Journal of Hydrology 523 (2015) 768–780

Contents lists available at ScienceDirect

Journal of Hydrology

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

Modeled intermittency risk for small streams in the Upper Colorado River Basin under climate change

Lindsay V. Reynolds [a,b,*], Patrick B. Shafroth [b], N. LeRoy Poff [a,c]

[a] Department of Biology, Colorado State University, Fort Collins, CO 80523, USA
[b] U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave., Bldg. C, Fort Collins, CO 80526, USA
[c] Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523, USA

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 15 January 2015
Accepted 9 February 2015
Available online 17 February 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Yasuto Tachikawa, Associate Editor

Keywords:
Surface water hydrology
Streamflow permanence
Ecological flows
Drought
Arid lands

SUMMARY

Longer, drier summers projected for arid and semi-arid regions of western North America under climate change are likely to have enormous consequences for water resources and river-dependent ecosystems. Many climate change scenarios for this region involve decreases in mean annual streamflow, late-summer precipitation and late-summer streamflow in the coming decades. Intermittent streams are already common in this region, and it is likely that minimum flows will decrease and some perennial streams will shift to intermittent flow under climate-driven changes in timing and magnitude of precipitation and runoff, combined with increases in temperature. To understand current intermittency among streams and analyze the potential for streams to shift from perennial to intermittent under a warmer climate, we analyzed historic flow records from streams in the Upper Colorado River Basin (UCRB). Approximately two-thirds of 115 gaged stream reaches included in our analysis are currently perennial and the rest have some degree of intermittency. Dry years with combinations of high temperatures and low precipitation were associated with more zero-flow days. Mean annual flow was positively related to minimum flows, suggesting that potential future declines in mean annual flows will correspond with declines in minimum flows. The most important landscape variables for predicting low flow metrics were precipitation, percent snow, potential evapotranspiration, soils, and drainage area. Perennial streams in the UCRB that have high minimum-flow variability and low mean flows are likely to be most susceptible to increasing streamflow intermittency in the future.

1. Introduction

The effects of climate change on river discharge in the western US are of strong interest to scientists, resource managers and policy makers. Some studies have revealed that peak streamflow timing has shifted to earlier in the spring over the last century and that runoff is likely to continue to occur earlier under most future climate scenarios (Hodgkins et al., 2003; Stewart et al., 2005; Rood et al., 2008; Clow, 2010). In addition, streamflow magnitude during late spring and summer has also shown a marked decline over the last century (Zhang et al., 2001; Burn and Hag Elnur, 2002; Rood et al., 2008; Leppi et al., 2011). According to several studies, mean annual streamflow is projected to decrease significantly over the next 100 years in the southwestern US (Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009; Jerla et al., 2012; Seager et al., 2013). However, some have suggested strong seasonal signatures will be associated with this change in average conditions, with winter precipitation and streamflow increasing (especially in northern latitudes) and late summer and fall precipitation and streamflow declining (especially in southern latitudes) under climate change in western North America (Milly et al., 2005; Cayan et al., 2008; CWCB, 2010; Seager et al., 2013). In arid and semiarid regions of the western US where intermittent streams are common, some studies show potential increases in minimum flow (Döll and Schmied, 2012) but most studies predict that minimum flows will decrease and the number of zero-flow days will increase in the future (Das et al., 2011; Leppi et al., 2011; Jaeger et al., 2014). Decreased minimum flows could lead some perennial streams to shift to intermittent streamflow regimes under climate-driven changes in timing and magnitude of precipitation and runoff, and increases in temperature.

Decreasing flows and the potential for streams to shift streamflow regime from perennial to intermittent could have significant implications for human water use as well as riverine ecosystems

* Corresponding author at: Department of Biology, Colorado State University, Fort Collins, CO 80523, USA. Tel.: +1 970 226 9174.
E-mail address: reynoldsl@usgs.gov (L.V. Reynolds).

http://dx.doi.org/10.1016/j.jhydrol.2015.02.025
0022-1694/

(Arthington et al., 2013). Changes to key hydrologic factors, such as minimum flow duration and riparian water tables, are likely to affect important ecological functions. In the southwestern US, it has been shown that both riparian plant and aquatic macroinvertebrate community structure depend on the dominant hydrologic regime (intermittent vs. perennial streams) and ecoregion (desert vs. mountain streams) (Stromberg et al., 2005, 2010; Shaw and Cooper, 2008; Brasher et al., 2010; Miller and Brasher, 2011). A critical first step to proactive management of these river basins is to better understand hydrologic thresholds associated with shifts from perennial to intermittent streamflow, so that we can model where such thresholds are likely to be crossed under potential future climate regimes.

In this study, we establish basic hydrologic relationships for small streams in the Upper Colorado River Basin (UCRB) and then build upon those relationships to understand how hydrology may shift under future projected climate change. Our first objective was to understand historic relationships between inter-annual variability in climatic factors (annual precipitation and temperature) and streamflow intermittency along gaged streams that already experience some intermittency. We focused our research on streams in the UCRB, a region that is projected to experience large future climate shifts (Christensen and Lettenmaier, 2007; Clow, 2010; Seager et al., 2013).

Our second objective was to model minimum flow metrics from existing daily discharge time series. Hydrologic modeling efforts that aim to simulate future streamflow conditions generally predict synthetic metrics (such as mean annual flow), which do not lend insight into possible future minimum flows (Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009). Where modeling of minimum flows is attempted, estimates are generally associated with a large degree of error (Wenger et al., 2010) although recent efforts have shown considerable improvement (Leppi et al., 2011; Jaeger et al., 2014). Our approach was to examine existing streamflow gage data to relate historic low flow measures to commonly modeled flow metrics (mean daily flow, peak flow, and peak flow timing). We reasoned that annual timing of peak runoff, mean daily flow, and annual maximum flow would explain some variation in the observed annual minimum flows across these sites and thus provide a basis for estimating the likelihood of future low flows and the vulnerability of perennial streams becoming intermittent under future changes in mean flows, peak flows, and peak flow timing (Poff and Ward, 1989).

Our third objective was to understand the distribution of low flow hydrology across the landscape by spatial modeling of several selected streamflow metrics using environmental variables such as climate, geology, soils and land cover. With an understanding of the environmental conditions that are likely to drive variation in low flow across the landscape, we can suggest where thresholds of stream intermittency currently exist and where future vulnerabilities may occur in a drying climate (Snelder et al., 2013).

2. Methods

2.1. Study area

The Colorado River is one of the most intensively managed river systems in the world and a vital water resource in the western US, supplying water for cities, agriculture, energy production, and natural ecosystems across seven states and two countries (Sabo et al., 2010). The Upper Colorado River Basin (UCRB) extends from southwestern Wyoming to northern Arizona and New Mexico, and includes the western half of Colorado and the eastern half of Utah (Fig. 1). The headwater streams of the basin form at high elevations in the Wind River, Uinta, Wasatch and Rocky Mountains. Annual precipitation varies widely across the region with the higher elevations receiving as much as 67 cm and lower elevations receiving 13–25 cm (Hereford et al., 2002). Precipitation in the headwaters is dominated by snow accumulation from November to March/April, which subsequently melts during the late spring and early summer months and average peak snow thickness varies widely with elevation and land cover (Clow et al., 2012). Correspondingly, higher elevation and northern streams in the basin are characterized by snowmelt peak runoff in the late spring that decreases to base flow in the late summer and early fall (Poff and Ward, 1989). Streams in the southern portion of the basin may experience a second streamflow peak in mid-to-late summer associated with rainfall from the North American Monsoon, and this monsoon rainfall is often the primary driver of annual flow in smaller, southern UCRB streams (Hereford and Webb, 1992; Ely, 1997; Hereford et al., 2002; Gochis et al., 2006).

2.2. Gage selection

We identified streamflow gages within the UCRB from the National Hydrography Plus Data Set (NHD+, http://www.horizon-systems.com/nhdplus/index.php) and acquired information on all USGS gages that operated between 1895 and 2009 for a total of 1146 gages. We eliminated gages that failed to meet several specific criteria. First, gages not on streams or rivers (e.g., canals and diversions) were eliminated, as were gages on large rivers. We defined large river reaches with a subjectively-chosen threshold of mean daily flow greater than 28 m^3/s and eliminated them because they are unlikely to shift hydrologic regime from perennial to intermittent. Next, we narrowed our sample to gages with at least 8 years of data, based on a detailed period-of-record analysis in our study region that determined 8 years to be a minimum record length necessary for certain low, mean and peak flow statistics to be reliable (Moline, 2007). We used some of the same low flow and high flow timing metrics that passed Moline's period-of-record ANOVA tests as well as mean flow metrics that are more stable year-to-year. Most of our gage records covered the second half of the twentieth century, at least overlapping the years 1975–1990, and included both dry and wet years (Cayan et al., 1998; Hereford et al., 2002; Appendix 1). Length of record for our study gages ranged from 8–83 years (median = 36 years). Sixteen perennial and fourteen intermittent stream gages had lengths of record 8–20 years, 26 perennial and 11 intermittent stream gages had lengths of record 21–40 years, and 44 perennial and four intermittent stream gages had lengths of record 41–83 years (Fig. 1, Appendix 1).

To identify gages with flows largely unaltered by human activities we gathered information from a variety of sources. We began by including those classified as unimpaired in the Hydro-Climate Data Network (HCDN, http://water.usgs.gov/GIS/metadata/usgswrd/XML/hcdn.xml). We compiled information about impacts for each gage location from USGS Annual Stream Gage Data Reports, The Nature Conservancy's database on stream diversions, the National Hydrography GIS layer, and the GAGES II dataset (Horizons System, 2006; TNC, 2010; USGS, 2010; Falcone, 2011). We eliminated stream gages with upstream dams and reservoirs, and with diversions greater than 20% of mean daily flow during the growing season (May–September). We chose 20% diverted flow as a threshold because "reference" streams are commonly defined on a sliding scale of impairment and there is not a widely-accepted standard for "minimally impacted streams" (Stoddard et al., 2006). We included 30 gages (25 perennial and 5 intermittent) that Falcone (2011) categorized as "non-reference" because they either had (a) more than 8 years of data between 1975 and 1990, which met our criteria, but less than 20 years of data, which failed Falcone's criteria, or (b) small diversions that we accounted for