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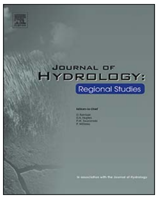

Shifts in historical streamflow extremes in the Colorado River Basin

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ABSTRACT

The global phenomenon of climate change-induced shifts in precipitation leading to "wet regions getting wetter" and "dry regions getting drier" has been widely studied. However, the propagation of these changes in atmospheric moisture within stream channels is not a direct relationship due to differences in the timing of how changing precipitation patterns interact with various land surfaces. Streamflow is of particular interest in the Colorado River Basin (CRB) due to the region's rapidly growing population, projected temperature increases that are expected to be higher than elsewhere in the contiguous United States, and subsequent climate-driven disturbances including drought, vegetation mortality, and wildfire, which makes the region more vulnerable to changes in hydrologic extremes. Here, we determine how streamflow extremes have shifted in the CRB using two statistical methods—the Mann-Kendall trend detection analysis and Generalized Extreme Value (GEV) theorem. We evaluate these changes in the context of key flow metrics that include high and low flow percentiles, maximum and minimum 7-day flows, and the center timing of streamflow using historical gage records representative of natural flows. Monthly results indicate declines of up to 41% for high and low flows during the June to July peak runoff season, while increases of up to 24% were observed earlier from March to April. Our results highlight a key threshold elevation and latitude of 2300 m and 39° North, respectively, where there is a distinct shift in the trend. The spatiotemporal patterns observed are indicative of changing snowmelt patterns as a primary cause of the shifts. Identification of how this change varies spatially has consequences for improved land management strategies, as specific regions most vulnerable to threats can be prioritized for mitigation or adaptation as the climate warms.

1. Introduction

Increased greenhouse gas emissions have caused a worldwide rise in both temperature means and extremes (Easterling et al., 2000). Global temperatures have risen by an average of 1 °C since the preindustrial age (Hansen et al., 2006), while increases in extremes have resulted in the maximum (minimum) historical means from the early 20th century occurring at greater (less) regularity during the latter part of the 20th century (Alexander et al., 2006). Given the expected increase in greenhouse gas emissions over the next century, such temperature trends are only anticipated to continue or even accelerate (Meinshausen et al., 2011). Indeed, comparisons of extreme temperatures from Global Climate Models (GCMs) to observed temperature data over the latter half of the 20th century support this conclusion (Zwiers et al., 2011). Understanding the direction, magnitude, and seasonality of impacts from these temperature changes on hydrology and associated ecosystems is thus paramount to mitigating risk from climate change (McDowell et al., 2017, in review).

The reported increases in mean and extreme temperatures have led to substantial changes in hydrology, resulting in a loss of

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hydrologic stationarity (Milly et al., 2008). This has manifested itself in all aspects of the water cycle above and below the ground surface, causing shifts in the mean and extreme values of precipitation (Karl et al., 1995; Karl and Knight, 1998; Asadieh and Krakauer, 2015), runoff and streamflow (Lins and Slack, 1999; Dai et al., 2009), evapotranspiration (Szilagyi et al., 2001; Szilagyi et al., 2001; Jung et al., 2010), water vapor (Seager et al., 2010), and soil moisture (Andreadis and Lettenmaier, 2006; Albergel et al., 2013). Groundwater is similarly affected, although the quantification of associated impacts are less clear due to the difficulty in isolating the competing impacts from land use change, such as the intensification of groundwater use for irrigation (Taylor et al., 2013). Given the motivation of understanding how water and energy supplies as well as associated critical infrastructure might be affected—as these are particularly vulnerable to floods and droughts—we focus our efforts here in understanding how historic streamflow extremes have already shifted. Ultimately, the results of these efforts will be used to compare with how streamflow extremes will change in the future.

Trends in extreme streamflow are often not as pronounced as extreme precipitation in areas where runoff is dominated by snowmelt. This is due to the offsetting effects of simultaneous declines in snowpack, which have been observed in areas such as the mountainous western United States (U.S.) (Mote, 2006). For example, there is a strong connection between high streamflow and the incidence of heavy precipitation events where they are becoming more common in the eastern U.S. (Groisman et al., 2001). However, due to the concurrent decreases in snowpack and snow cover extent in the more mountainous west, no such pattern exists in this part of the country in spite of the increase in heavy precipitation episodes also occurring in the region (Prein et al., 2016). The strong association with elevation and observed shifts in western U.S. streamflow center timing further indicates that snowmelt changes are largely contributing to this transformation (McCabe and Clark 2005; Regonda and Rajagopalan, 2004; Stewart et al., 2005; Mote, 2006; Clow et al., 2010; Dudley et al., 2017), likely offsetting any appreciable gains to high streamflow events from an increase in the frequency of heavy precipitation.

In spite of some evidence for weaker extreme streamflow trends due to the observed competing changes in snow, broad spatial and temporal patterns have still been recognized across North America. For example, increases in streamflow were generally reported for minimum flow percentiles over much of the conterminous U.S. (Lins and Slack, 1999) or centered in the eastern U.S. (McCabe and Wolock, 2002; Ahn and Palmer, 2015), while decreases were observed in the Pacific Northwest (Ahn and Palmer, 2015; Kormos et al., 2016). Such trends were more variable for maximum flow percentiles, although a tendency towards increased variability in high flows was noted for the continental U.S. (Ahn and Palmer, 2015). By contrast, in Canada a greater number of decreases in streamflow maximums were observed, while the direction of trends were more variable for streamflow minimums (Zhang et al., 2001; Burn et al., 2010). The reduction in maximum flows is again related to decreases in or earlier peak snowmelt, which leads to a more gradual rise in peak streamflow and dampening of the overall hydrograph (Zhang et al., 2001). Similar to what was found across Canada, within boreal basins of Alaska and the Yukon Territory decreases in annual maximum streamflow were particularly pronounced in snowmelt-dominant basins, while more statistically significant increases were observed in minimum flows (Bennett et al., 2015).

The Colorado River Basin (CRB) is located within the intermountain region of the western United States and serves as an excellent setting to analyze shifts in hydrologic extremes for a variety of factors. The region recently underwent one of the largest droughts observed in the historical record (Piechota et al., 2004) and based on future temperature increases simulated in Global Climate Models (GCMs), more severe droughts than what have been observed in the paleoclimate record are anticipated by 2100 (Woodhouse et al., 2010). Other climate change impact studies indicate a CRB-wide reduction of 8–11% in streamflow due to changes in climate (Christensen and Lettenmaier, 2007), as well as a 6–11% decline in annual streamflow by 2100 from vegetation and climate disturbances in the San Juan sub-basin of the CRB (Bennett et al., 2017, in review). Even higher reductions were projected using a range of emission scenarios for other CRB sub-basins (Ficklin et al., 2013). Additional impacts include a ~30% decline in runoff (Barnett and Pierce, 2009), and longer-lasting, higher-severity droughts (Cayan et al., 2010; Woodhouse et al., 2016). Moreover, the high rate of population growth coupled with the projected temperature increases are expected to further strain water supplies and make critical water and energy supply infrastructure particularly vulnerable to floods and droughts (MacDonald, 2010; Stewart et al., 2015).

Two leading statistical methods used to understand changes in hydrologic extremes include the non-parametric Mann-Kendall trend analysis (Mann, 1945; Kendall, 1975) and the Generalized Extreme Value (GEV) theory (Coles, 2001). The Mann-Kendall trend analysis has been applied in previous studies to understand shifts in hydrologic extremes (Lins and Slack, 1999; Zhang et al., 2001; Miller and Piechota, 2008; Villarini et al., 2009; Burn et al., 2010; Cheng et al., 2014; Sagarika et al., 2014; Bennett et al., 2015). However, as this statistical method was not specifically developed for analysis of extremes and provides no means of determining changes in the probability of different flow magnitudes—both of which are important for quantifying risk in water resource management and engineering design—the GEV analysis offers a good compliment to this approach. GEV theory can be applied to determine changes in extreme streamflow metrics in either a stationary or nonstationary setting by using time-dependent parameters in the GEV distribution (Katz, 2013). As such, similar to the Mann-Kendall analysis, the GEV is also used to detect trends in extremes.

In this study, we evaluate changes in extreme streamflow in the CRB using the Mann-Kendall and GEV statistical approaches. The Mann-Kendall trend analysis was applied to extreme streamflow metrics and the center timing of streamflow, which were derived from historical daily discharge to determine the size and direction of changes at annual, seasonal, and monthly timescales. Next, the Generalized Extreme Value (GEV) analytical approach was used to estimate how the high- and low-flow tails of streamflow maxima and minima are changing in the region and to assess changes in extreme flow return intervals (Zhang and Zweirs, 2013). The Mann-Kendall and GEV results were both evaluated against the respective elevation and latitude of the streamflow gages to identify shifts associated with changing snow and snowmelt patterns due to their strong spatial dependency. We examined changes in extremes using exclusively unimpaired gages to isolate the source of the change to climatic factors alone due to the high vulnerability to impacts from changing climate within the CRB region.

This study differs from previous studies by providing the first investigation of streamflow extreme shifts and the drivers of change