Upper Gila, Salt, and Verde Rivers: Arid Land Rivers in a Changing Climate

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ABSTRACT: The major tributary of the lower Colorado River, the Gila River, is a critical source of water for human and natural environments in the southwestern United States. Warmer and drier than the upper Colorado River basin, with less snow and a bimodal precipitation regime, the Gila River is controlled by a set of climatic conditions that is different from the controls on upper Colorado River flow. Unlike the Colorado River at Lees Ferry in Arizona, the upper Gila River and major Gila River tributaries, the Salt and Verde Rivers, do not yet reflect significant declines in annual streamflow, despite warming trends. Annual streamflow is dominated by cool-season precipitation, but the monsoon influence is discernable as well, variable across the basin and complicated by an inverse relationship with cool-season precipitation in the Salt and Verde River basins. Major multiyear streamflow droughts in these two basins have frequently been accompanied by wet monsoons, suggesting that monsoon precipitation may partially offset the impacts of a dry cool season. While statistically significant trends in annual streamflow are not evident, decreases in autumn and spring streamflow reflect warming temperatures and some decreases in spring precipitation. Because climatic controls vary with topography and the influence of the monsoon, the impact of warming on streamflow in the three subbasins is somewhat variable. However, given relationships between climate and streamflow, current trends in hydroclimate, and projections for the future, it would be prudent to expect declines in Gila River water supplies in the coming decades.

SIGNIFICANCE STATEMENT: This research investigates the climatic controls on the Gila River and its major tributaries, the Verde and Salt Rivers, to gain insights on how trends in climate may impact future water supply. The Gila River is the major tributary of the lower Colorado River, but, unlike the situation for the upper Colorado River, no significant decreasing trends in annual streamflow are evident despite warming temperatures. Climate–streamflow relationships are more complex in this part of the Colorado River basin, and several factors may be buffering streamflow to the impact of warming. However, given the key climatic controls on streamflow, current and emerging trends in climate, and projections for the future, declines in streamflow should be expected in the future.

KEYWORDS: Watersheds; Streamflow; Drought; Climate change; Climate variability

1. Introduction

Water supplies in arid and semiarid regions are increasingly stressed by growing and changing demands, drought, and warming temperatures. Understanding how climate has influenced streamflow over the period of historic records provides baseline information that is critically important for anticipating how changes in climate will translate to changes in water supply. In the upper Colorado River basin (UCRB), research has shown that precipitation, particularly snowpack, is the most important factor controlling streamflow, but increasingly, temperatures are having an influence on the proportion of precipitation that results in streamflow (Woodhouse et al. 2016; Udall and Overpeck 2017; Xiao et al. 2018; Hoerling et al. 2019; Milly and Dunne 2020). In the lower Colorado River basin (LCRB), comparatively little research has been undertaken to examine climate–streamflow relationships.

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While the volume of water in the LCRB is much less than in the upper basin, the major lower basin tributary, the Gila River, is a critical source of water for natural and human systems in the region. Knowledge about how climate has influenced Gila River streamflow is important for gaining insights on how warming will impact this water resource in the future. To address this gap in knowledge, this research addresses the following questions: How has climate influenced the Gila River and its major tributaries, the Verde and Salt Rivers, and what are the implications of these climatic influences, given current trends, for future water supply?

a. Gila River basin setting

The Gila River basin is the largest watershed within the LCRB, draining about 15.7 million ha (60 500 mi²), an area slightly larger than one-half of the area of Arizona. The source of the Gila River headwaters is primarily in the central highlands of Arizona, at the southwestern edge of the Colorado Plateau. The main tributaries of this river are the Salt and Verde Rivers. The upper Gila River (i.e., that part of the Gila River system above the confluence with the Salt River) and these two rivers are addressed in this study. The upper Gila, Salt, and Verde River watersheds extend in an arc, from the upper Gila watershed in southwestern New Mexico to the

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FIG. 1. Location of Verde, Salt, and upper Gila River basins, with the locations of the three gauges used in this study marked by red stars. The inset shows the relative locations of the basins in the southwestern United States.

Verde watershed in northwestern Arizona (Fig. 1). Most of the headwaters fall within public lands (Gila National Forest in New Mexico, and the Tonto, Apache, Coconino, Kaibab, and Prescott National Forests in Arizona), whereas the most productive part of the Salt River is wholly within the White Mountain Apache Reservation and other parts of the Salt River and upper Gila, including San Carlos Reservoir, lie within the San Carlos Apache Reservation.

In all three basins, monthly streamflow reaches a peak in March, with a secondary and lower peak in August (Fig. 2, bottom). The mix of rain and snow is evident in the annual subbasin hydrographs, which show both increasing runoff throughout the entire winter, as well as a classic snowmelt runoff pattern (i.e., a steep decline) in the spring. In the Salt River, the March peak is sustained through April, reflecting a prolonged period of snowmelt, while streamflow quickly drops between March and April in the Verde and upper Gila Rivers. Cool-season streamflow (October–March) accounts for about 65% of the annual flow in the three basins (ranging from 58% in the Salt River to 73% in the Verde River), while monsoon-season flows (June–September) account for about 16%, varying from 13% in the Verde to 20% in the upper Gila River (Fig. 3, left).

Although April streamflow accounts for about 10% of the annual flow in the upper Gila and Verde Rivers and 17% in the Salt River, October–March is used as the cool season in this paper so as to correspond to the climatic cool season.

The entire Gila River basin lies within an arid region, but the aridity is tempered by the strong elevation gradient and varied topography (Crimmins 2007). Arizona's central highlands rise over 3000 m (10000 ft) in places, from the low deserts (less than 500 m) near Phoenix to 3475 m (11400 ft) Mount Baldy. Higher elevations are cooler and wetter with seasonal snow cover, which contributes roughly 60% of the total runoff according to the modeling study of Li et al. (2017). The region of highest annual precipitation is along the 100-mi-long (160 km) Mogollon Rim on the north edge of the Salt River basin, and the mountains directly east (upper Gila watershed) and northwest (Verde watershed) of the rim (Karnieli and Osborn 1988; Robles et al. 2020). In these three watersheds, cool-season moisture is conveyed from the Pacific Ocean in the form of cyclonic storms transported by midlatitude and subtropical jet streams (Sheppard et al. 2002; Woodhouse 1997) and via atmospheric rivers (Demaria et al. 2017). Cool-season climate variability is driven in part by El

FIG. 2. (top) Monthly average total precipitation, 1921–2019, (middle) mean monthly average temperature, 1921–2019, and (bottom) monthly average streamflow, 1945–2019, for the Verde (green), Salt (orange), and Gila (blue) River watersheds.

Niño–Southern Oscillation (ENSO) and underlying Pacific decadal variability, although the influence of ENSO is asymmetric, with cool ENSO events more often leading to dry conditions (Sheppard et al. 2002; Crimmins 2007). About 49% of the annual precipitation falls in the cool season, with the highest proportion in the Verde River basin (54%) and the lowest in the upper Gila River basin (42%) (Fig. 3, right).

In the warm season, the basin is influenced by the North American monsoon (NAM) system, which delivers precipitation from the eastern tropical Pacific and Gulf of Mexico, and to a lesser degree, from the Gulf of California (Adams and Comrie 1997). The monsoon onset progresses from northwestern Mexico into the southwestern United States, with average onset dates in the study area ranging from early July

in southwestern New Mexico to mid-July in central Arizona (Higgins et al. 1999). Research has linked early-monsoon-season precipitation to conditions in the northern and tropical Pacific (Castro et al. 2001; Grant et al. 2007), and later-season precipitation with sea surface temperatures off the California coast and Gulf of California (Grant et al. 2007). Remnant tropical storms can provide an additional moisture source in late August through October (e.g., Sheppard et al. 2002). The monsoon season accounts for over one-half of the annual precipitation (52%) in the upper Gila River basin, and near 40% in the other two basins (42% in the Salt and 38% in the Verde) (Fig. 3, right). April accounts for 3%–5% of the annual precipitation, and May and June, the driest months of the year, account for even less (together, 5%–6% of the annual total). In all seasons, but particularly in the warmer parts of the year, high temperatures drive a high rate of evapotranspiration, and as a result much of the precipitation that falls does not result in runoff (McCabe and Wolock 2020; Robles et al. 2017).

The Gila River is the most important surface water supply in the state of Arizona, along with the Colorado River. It provides about 20% of the state's supply, with the Salt and Verde Rivers currently providing about 40% of the water supply for the Phoenix metropolitan area (Feller 2007). The Gila River has long been a primary source of water for domestic and agricultural water needs in the region. Evidence of prehistoric irrigation systems documents the intensive use of water by the Hohokam who lived along the Gila River from about 450 CE to 1450 CE (Woodbury 1961; Haury 1976). The Gila River basin was the location of the first dam resulting from the National Reclamation Act of 1902, with the construction of Roosevelt Dam on the Salt River (August and Gammage 2010). In 2004, the Arizona Water Settlements Act addressed indigenous water rights on the Gila River with an allocation of over 801 million cubic meters (MCM) [650 thousand acre ft (KAF)] per year to the Gila River Indian Community (Akimel O'odham and Pee Posh tribes); however, only a small portion of that actually comes from the Gila River (Smith and Colby 2007; Bark and Jacobs 2009).

b. Prior work and knowledge gaps

While a large body of research has recently addressed the relationships between climate and streamflow in the UCRB (e.g., Nowak et al. 2012; Woodhouse et al. 2016; Udall and Overpeck 2017; McCabe et al. 2017; Xiao et al. 2018; Hoerling et al. 2019), fewer studies have specifically addressed the LCRB, and the Gila River basin in particular. Relative to the headwaters region of the UCRB, the Gila River headwaters are part of a region that is drier and warmer, with higher potential evapotranspiration (PET), lower runoff that peaks earlier in the spring, and much less of the annual precipitation falling as snow (McCabe and Wolock 2020). The runoff efficiency is lower, as might be expected given warmer temperatures and higher rates of PET, and the seasonality of precipitation is bimodal, with up to half of the total annual precipitation falling during the summer monsoon season (McCabe and Wolock 2020).

FIG. 3. (left) Percent of total annual streamflow for October–March and June–September by river for 1945–2019, and (right) percent of total annual precipitation for October–March and June–September by basin for 1921–2019.

A small number of papers has specifically examined the seasonality of streamflow peaks and associations with climate, while a larger body of work has investigated hydroclimatic trends in LCRB and Gila River basin. In a study of the high headwaters of the upper Gila River, [Pascolini-Campbell et al. \(2015\)](#) found two peaks in annual streamflow, with December–May flows accounting for 61% of total flow (related to winter/spring precipitation) and August–September accounting for 15% of the total flow (related to July–September precipitation). [Robles et al. \(2017\)](#) reported two peaks in Salt River annual streamflow as well, with 80% of the annual Salt River flow occurring between December and May. Most of the variability in annual flow was explained by precipitation (~71%), with temperature an inconsistent predictor. Although temperature trends were positive, large (up to nearly 3°C since 1914), and statistically significant for most months, [Robles et al. \(2017\)](#) found no trends in seasonal or annual precipitation, snow water equivalent (SWE), or annual flow in the basin over the years 1914–2012. Similarly, [Murphy and Ellis \(2014\)](#) found significant warming but no evidence in trends in LCRB precipitation or streamflow, while [Anderson et al. \(2010\)](#) detected no significant trends over the twentieth century in amount of precipitation, number of rainy days, or event coverage during the monsoon season across the part of Arizona that includes the upper Gila, Salt, and Verde River basins. However, over the past five decades, a decrease in annual and cool-season precipitation and frequency of precipitation days has been detected across the southern Rockies and Colorado Plateau, a region bordering the Gila River headwaters ([Zhang et al. 2021](#)). More recently, [Robles et al. \(2020\)](#) used modeled hydrology to investigate the lack of decreasing trend in streamflow despite warming temperatures. Their findings suggest that a seasonal offset between the period of peak streamflow generation in winter and the period of greater evaporative losses in spring may be ameliorating the impacts of increasing temperatures on streamflow.

Other studies more clearly indicate the influence of warming temperatures on hydroclimate in this region, including a decrease in Salt River basin soil moisture since 1980 ([Svoma et al. 2010](#)) and an increase in snow level since the 1930s in the Salt and Verde River basins ([Svoma 2011](#)). Snow season

length has decreased significantly since the early 1980s over a region that includes the Gila River headwaters ([Zeng et al. 2018](#)), and a trend toward an earlier date of maximum SWE has also been documented ([Musselman et al. 2021](#)). Warming summer temperatures have been linked to a significant trend in warm-season drought across the LCRB over the past century ([Ellis et al. 2010](#)), while increases in length of mean and longest dry interval have been detected across the southern Rockies and Colorado Plateau since the mid-1970s ([Zhang et al. 2021](#)).

With regard to projected changes, in a study of the Salt and Verde River basins, [Ellis et al. \(2008\)](#), using output downscaled from six GCMs, found warming of 2.4°–5.6°C under 2050 greenhouse gas concentrations, with highly variable changes in precipitation and runoff, and an 85% probability of lower runoff in the two basins. A recent pilot study on the Salt and Verde River Reservoir system found that projected warming was not great enough to cause management concern about water supplies ([Broman et al. 2020](#)). With current Phoenix metropolitan area demands (~800 KAF yr⁻¹; 987 MCM yr⁻¹) being significantly less than long-term-average Verde and Salt inflows (~1000 KAF yr⁻¹; 1230 MCM yr⁻¹), the system appears resilient to significant flow declines ([Murphy and Ellis 2014, 2019](#)). Since 2000, however, Salt and Verde inflows have been about 800 KAF yr⁻¹ (987 MCM yr⁻¹), which matches recent demands. Climate change projections for the southern U.S. Southwest region indicate overall warming conditions and a suggestion of declining precipitation, with strong agreement among models for spring precipitation only ([Kunkel et al. 2013](#)). Along with these changes, a commensurate increase in aridity and longer, more severe droughts are projected ([Gonzalez et al. 2018](#), and references within), potentially leading to permanent conditions where demands exceed supplies.

These studies, while valuable, reveal an incomplete understanding of the relationships between Gila River streamflow and climate. One of the most intriguing findings is that temperatures are warming, yet no long-term trends in annual streamflow have been detected in this region. In contrast, a number of recent studies on the upper Colorado River have altered our understanding of human impacts on river flow,

TABLE 1. Gauge records used for this study.

Gauge name	USGS gauge	Years
Verde River below Bartlett Dam, Arizona	09510000	1914–44
Verde River below Tangle Creek above Horseshoe Dam, Arizona	09508500	1945–2019
Salt River near Roosevelt, Arizona	09498500	1914–2019
Gila River at head of Safford Valley near Solomon, Arizona	09448500	1921–2019

with four studies now attributing up to half of the approximately 20% flow loss since 2000 to anthropogenic warming (Udall and Overpeck 2017; Xiao et al. 2018; Hoerling et al. 2019; Milly and Dunne 2020). Given the influence of warming temperatures on UCRB flow, what is the role of temperature on streamflow in the warmer, drier Gila River basin? The Gila River is a critical water supply for this arid region, and the management of this river system will be increasingly challenging under a warming climate with potentially more severe and prolonged drought. An improved understanding of the influence of climate on streamflow will provide baseline information for anticipating streamflow response to changing conditions.

2. Data

a. Gauge data

Water-year (October–September) and monthly streamflow records for the Verde, Salt, and upper Gila Rivers were used. The Gila River watershed includes the Verde and Salt Rivers, and the Verde River flows into the Salt River, but the records used here are above those confluences, reflecting geographically independent watersheds (Fig. 1). The gauges for which streamflow records were used capture the headwaters flow, which account for most of the total volume of flow. These gauges are located above major reservoirs (except for the early part of the Verde River record), although smaller diversions exist above these gauges and groundwater pumping in hydrologically linked aquifers may influence the records. In addition, land-use history and natural disturbance such as fire can have an influence on streamflow in this region (Wine and Cadot 2016; Robles et al. 2017). These factors introduce some uncertainty in the reliability of the gauge records for which estimates of natural flow are not available.

Gauge data were obtained from the U.S. Geological Survey (USGS) Water Data for the Nation (<https://waterdata.usgs.gov/nwis>). The gauge record for the Salt River near Roosevelt, Arizona (above Roosevelt Dam), starts in 1914 and was used through 2019 for this study (Table 1). For the Verde River, two records were combined: the gauge below Bartlett Dam for 1914–44 and the gauge below Tangle Creek, above Horseshoe Dam, from 1945 to 2019. The Verde River below Bartlett Dam annual flows are virtually identical to the few years of a gauge record for the Verde River above Bartlett Dam, and very similar to Verde below Tangle Creek and above Horseshoe Dam, but the some of the monthly values clearly reflect dam operations. Consequently, for analysis with monthly values, only data from the gauge below Tangle Creek and above Horseshoe Dam were used. The record for

the upper Gila River at the head of Safford Valley near Solomon, Arizona, is the longest and most complete record available, capturing most of the headwaters' streamflow including the upper Gila itself as well as the San Francisco River. While the Verde and Salt River records extend back to 1914, this upper Gila River record starts in 1921, so the full period analyses for annual streamflow in this study use 1921 as the start date. The Gila River near Safford contained missing data for 1933–34, which were estimated using linear regression and flow records from the Gila River near Redrock, New Mexico, and the San Francisco River near Glenwood, New Mexico, after Meko and Hirschboeck (2008). Monthly streamflow values are used in trend analysis, for 1950–2019.

b. Climate data

Two gridded climate data products were evaluated for this study, Parameter–Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2008) and nClimGrid (Vose et al. 2014) monthly precipitation and temperature. Both datasets are based on observations interpolated to a grid; PRISM data are on a 4 km × 4 km grid and nClimGrid data are on a 5 km × 5 km grid. Grid points for the hydrologic unit code (HUC)-8 regions that included and were above the gauge (except for the Animas HUC in the upper Gila, which does not contribute flow to the Gila River) were averaged to generate basin monthly average temperature and total precipitation. Comparisons of the two datasets indicated small differences with no consistent biases in correlation results, so PRISM data were used for most analyses. Results for trend analysis are shown for both datasets, and although small differences exist, they do not impact the results.

In several analyses, climate and streamflow data were converted to percentile values to allow a comparison between streamflow and climate in the analyses of droughts and low-flow years. The percentile scale ranges from 0 to the 100th percentile, with the 50th percentile representing the median.

3. Analysis and discussion

a. Basin hydroclimate

Basin geography and climatic characteristics vary among the Verde, Salt and upper Gila River basins, resulting in differences in magnitude of streamflow. Although the upper Gila has the largest drainage area (20 450 km² above the Solomon gauge), it has the lowest average annual flow (393 MCM; 319 KAF), while the Salt River basin is the smallest (above the gauge near Roosevelt 11 152 km²) but has the highest average annual flow (709 MCM; 575 KAF), with the Verde River between the two, in terms of basin size and average

TABLE 2. Gauge and basin characteristics, 1921–2019.

	Verde River	Salt River	Upper Gila river
Basin area	17 168.27 km ²	17 724.2 km ²	39 347.33 km ²
Avg basin elev	1576 m	1574 m	1644 m
Percent of area 2743 m and above	<1%	3%	1%
Gauge ^a elev	618 m	663 m	932 m
Basin area above gauge	15 172 km ²	11 152 km ²	20 450 km ²
Avg water-year flow	504 MCM	709 MCM	393 MCM

^a For gauges in Table 1.

annual streamflow (15 172 km² above Horseshoe Dam and 504 MCM; 409 KAF) (Table 2). Elevation differences are likely an influence (the Salt River basin has the highest proportion of its area above 2743 m, or 9000 ft), but an examination of the average climate of the three basins reveals some additional reasons for these differences.

All three basins reflect the strong bimodal precipitation regime, but the seasonal proportions vary. Precipitation totals for both cool and monsoon seasons are higher and temperatures are lower for the Salt River basin relative to the other two basins (Fig. 2, top and middle). In both the Salt and Verde River basins, more precipitation falls in the cool season than in the monsoon season (Fig. 3, right). In contrast, the upper Gila River basin is the driest (Fig. 2, top) and receives a greater proportion of annual precipitation in the monsoon season (Fig. 3, right). Precipitation that falls during the warmer months contributes less to streamflow than cool-season precipitation due to evapotranspiration losses. These factors help explain the difference in flow volume despite basin area of the Salt and upper Gila Rivers. The Verde River basin is similar in size to the Salt River basin, but it is drier and warmer, with much less of the basin at higher elevations (Table 2, Fig. 2). Consequently, conditions are less conducive for retaining a winter snowpack in this basin. However, the uppermost one-third of the Verde River basin only contributes to the flow intermittently, so the runoff-producing part of the basin is smaller than reflected by the full basin area. With this consideration, the flow per runoff-producing area in the Verde River basin is similar to that of the Salt River basin.

b. The influence of climate on streamflow

Because topographic and climatic characteristics of the three basins lead to differences in average annual flow, climate–streamflow relationships were examined to determine if climatic controls on streamflow varied as well. The relationships between streamflow and monthly climate were evaluated using correlation analysis for precipitation and partial correlation analysis for temperature to determine the climatic variables most strongly associated with annual streamflow. Partial correlations evaluate the association between temperature and streamflow, while accounting for the correlation between precipitation and temperature. To assess whether these influences were different in wet and dry years, relationships between seasonal climate (total precipitation and average temperature for October–March and June–September) and water-year flow were compared among the three gauges

for all years and years in which streamflow was above and below median, using correlations and partial correlations as with the monthly values. In all analyses, Pearson correlation coefficients were assessed at $p < 0.05$ (assuming each year represents one degree of freedom).

At all three gauges, correlations between annual streamflow and the months of cool-season precipitation (October–March) are positive (correlation coefficient $r = 0.23$ – 0.66) and statistically significant (Fig. 4, top). Salt and Verde River streamflow show a weak negative correlation with July (significant) and August (not significant) precipitation. This negative correlation is related to the inverse relationship between cool- and monsoon-season precipitation (Salt: $r = -0.30$, Verde: $r = -0.34$, significant at $p < 0.0001$; in comparison, upper Gila: $r = -0.16$; $p = 0.103$) that is not completely understood, but likely driven in part by seasonal land surface feedbacks (e.g., Grantz et al. 2007). This inverse relationship may play a role in years when flows are greater or less than would otherwise be expected given winter precipitation and during multiyear droughts, as described in the following sections.

The highest partial correlations between flow and temperature are negative, for April, June, and July (r from -0.23 to -0.32) for all three gauges (Fig. 4, bottom). November temperatures are also negatively correlated with Salt and Verde flow.

FIG. 4. (top) Correlations between water-year streamflow at the three gauges and monthly precipitation, and (bottom) partial correlations with temperature in the respective basins, for 1921–2019. Gray horizontal lines indicate the 0.05 significance level.

FIG. 5. Correlations between water-year streamflow at the three gauges and seasonal precipitation and temperature in the respective basins for 1921–2019. Gray horizontal lines indicate the 0.05 significance level.

These negative relationships suggest that warm temperatures in the late autumn reduce soil moisture, while warm April temperatures hasten the melting of the remaining snowpack and lead to higher rates of evapotranspiration and drying of soils, resulting in reduced flows. Negative correlations between streamflow and temperature in the early monsoon season also suggest enhanced evapotranspiration rates.

These relationships are summarized in correlations/partial correlations between water-year streamflow, and precipitation and temperature in the cool and monsoon seasons (Fig. 5, left panel). The close association between cool-season precipitation and water-year streamflow at all gauges is evident ($r > 0.80$), as is the negative correlation between flow and monsoon-season precipitation for the Salt and Verde River gauges ($r = -0.22$). Partial correlations for temperatures indicate significant negative associations between streamflow and temperatures in the monsoon season only, for all three gauges ($r < -0.30$). These partial correlation results suggest that correlations between streamflow and cool-season temperature are not independent of the correlations between precipitation and streamflow, likely due at least in part to the correlation between cool-season temperature and precipitation (Verde: $r = -0.36$; Salt: $r = -0.33$; Gila: $r = -0.35$; $p < 0.001$).

Relationships are somewhat different in years of below- and above-median flow. In below-median-flow years (Fig. 5, middle panel), correlations between streamflow and cool-season precipitation are positive, but weaker than for all years, especially for the upper Gila River ($r = 0.38$). In these years, upper Gila River flow is more strongly correlated with monsoon-season precipitation ($r = 0.45$), while the Salt and Verde flow records show no significant correlation with precipitation in

this season. Similar to all years, partial correlations between streamflow and temperature in below-median years are evident in the summer but are only statistically significant for the Verde and upper Gila Rivers. In above-median-flow years, the pattern of correlation with precipitation is very similar to all years, again emphasizing the importance of cool-season precipitation. Partial correlations again indicate a negative relationship between streamflow and temperature in the monsoon season but are only significant for the Gila River basin.

These analyses indicate that while cool-season precipitation is the strongest driver of annual streamflow over all years, some seasonal and basin-scale differences exist for above- and below-median-flow years. Of the three basins, the Salt and Verde Rivers have the strongest associations with cool-season precipitation in all years and in above-median-flow years; correlations are still strong but slightly lower in below-median-flow years. In contrast, while upper Gila annual flow is also strongly correlated with cool-season precipitation in all years and above-median-flow years, in below-median-flow years, flow is influenced almost equally by precipitation in cool and monsoon seasons. The stronger correspondence between upper Gila flow and monsoon precipitation is likely a consequence the larger proportion of annual precipitation coming in summer in this basin. In the Salt and Verde Rivers, negative correlations (although weak or nonsignificant) characterize the relationship between flow and monsoon precipitation due the inverse relationship between cool- and monsoon-season precipitation. Annual streamflow does not appear to be related to cool-season temperatures once the correlation between temperature and precipitation is accounted for, but there is an association between monsoon-season temperatures (particularly in the earlier part of the season; Fig. 4, bottom) and streamflow. The importance of warm-season temperature to annual flow is also found in the UCRB (Das et al. 2011; McAfee et al. 2017; McCabe et al. 2017), suggesting that the influence of temperature is related to evapotranspiration and drying of soils rather than on snowmelt.

c. Analysis of unusual years

Correlation analysis can obscure relationships that may not occur on a regular basis or that act to reinforce or reduce the impact of other climate variables on streamflow. For example, while there is an indication of the importance of monsoon conditions in below-median-flow years in the upper Gila River (Fig. 5), the inverse relationship between cool- and monsoon-season precipitation may obscure the monsoon's influence on streamflow in the other two basins. Because cool-season precipitation is such a dominant driver of streamflow, investigating years with less streamflow than might be anticipated given the cool-season precipitation amount (and the reverse, years with higher flows that might be expected from the cool-season precipitation) may reveal less commonly occurring but influential climate factors. We investigated this potential by examining climatic conditions (temperature and precipitation) in water years with flow volume higher or lower, relative to the cool-season precipitation amount, by a percentile ranking difference of 20 or more (equivalent to a

Flow > P	# yrs	Flow	Cool season P	Oct-NovP	Dec-MarP	Apr-MayP	Jun-SepP	Oct-NovT	Dec-MarT	Apr-MayT	Jun-SepT
Verde	5	53	28	54	26	56	86	46	65	38	19
Salt	4	58	26	59	16	55	73	42	66	55	38
Gila	10	53	18	32	21	39	90	66	70	59	41
Verde high	3	68	43	59	42	62	10	32	40	43	54
Flow < P	# yrs	Flow	Cool season P	Oct-NovP	Dec-MarP	Apr-MayP	Jun-SepP	Oct-NovT	Dec-MarT	Apr-MayT	Jun-SepT
Verde	6	20	47	75	35	42	44	50	68	70	79
Salt	4	21	47	74	31	40	39	35	56	61	69
Gila	9	20	50	58	48	40	17	45	51	51	71

FIG. 6. Average seasonal precipitation P and temperature T conditions corresponding to years when flow is higher or lower relative to cool-season precipitation [(top) flow > P by at least one quintile; (bottom) flow < P by at least one quintile]. The first four columns show river, numbers of years, average flow, and cool-season precipitation, in percentile for each set of years. The middle set of four columns shows seasonal precipitation conditions averaged for those years, and the last set is the average seasonal temperature conditions, in percentile. Colors corresponding to quintile: blues and greens = wet and cool, respectively; oranges and pinks = dry and warm, respectively; white = near median. Quintile value ranges: 0–19th, 20–39th, 40–59th, 60–79th, and 80–99th.

quintile category of change). Seasons examined included October–November, December–March, April–May, and June–September. Two types of years were evaluated: those with lower flows relative to the precipitation amount and those with higher flows relative to the precipitation amount.

Years with relatively large differences between annual flow and cool-season precipitation of either type are uncommon in the Salt River basin (8% of years); another indication that cool-season precipitation is the major influence in this basin. In the Verde, these years are somewhat more common (14% of years), while in the upper Gila, the two types occurred in nearly 20% of years (Fig. 6). In general, years with higher-than-expected flow (flow > P) correspond to near-median streamflow and dry to very dry cool-season conditions, particularly in December–March. In these years, the monsoon season was wet, with below-median temperatures (Fig. 6, top), suggesting that the monsoon conditions helped alleviate the effects of dry and warm December–March on annual flow. The Verde River had an additional subset of these years (*Verde high* in Fig. 6) in which streamflow was high and cool-season precipitation was slightly below median, with wet, slightly cool April–May, and dry monsoon, but all of these events occurred in the early part of the record (1923, 1924, 1926).

In the years with less flow than expected (flow < P), annual flows were low while cool-season precipitation was near or slightly below the median (Fig. 6, bottom). In the Verde and Salt River basins, these years were characterized primarily by warm temperatures, particularly in the spring and monsoon seasons (April–September). Wet autumn conditions were likely responsible for the near-median cool-season moisture since the December–March period was dry. In the Salt River basin, monsoons were dry, coinciding with conditions in the upper Gila River basin where these years were characterized by very dry, warm monsoon seasons.

Despite the weakly negative correlation between streamflow and monsoon precipitation in the Salt and Verde Rivers (Figs. 4 and 5), these results suggest the monsoon-season conditions may have an influence on streamflow in some years.

Specifically, wet, cool monsoon seasons appear to offset the impact of a dry cool season, resulting in near-median flows in all three basins in a handful of years. Conversely, elevated temperatures in all three basins and dry monsoons conditions in the Salt and upper Gila appear to contribute to very low flow, despite near-median cool-season moisture. The higher frequency of these types of years in the upper Gila River basin again supports a greater influence of the monsoon on this basin's climate. This is further emphasized by the pattern of these years over time (Fig. 7). A loose cluster of these unusual years occurred after 1990, but most of these (9 of 14 years) are unique to the upper Gila basin. In this basin, six near-median-flow years occurred despite very dry winters, and five low-flow years occurred in years with slightly above median cool-season precipitation over this time period. As indicated above, in the upper Gila, these unusual years appear to be a result of monsoon conditions, which were extremely wet in the first case, and extremely warm and dry in the second.

d. Multiyear droughts and the associated climatic conditions

Given the importance of cool-season precipitation, particularly to Verde and Salt River streamflow, periods of low flow

FIG. 7. Occurrence of a year (colored bar) with flow greater relative to cool-season precipitation (top half of graph) or less relative to cool-season precipitation (bottom half of graph) by one quintile or more in each of the three basins.

TABLE 3. Multiyear (>2 yr) droughts in the three streamflow records, 1921–2019. Average percentile values for annual flow for the years in each drought period are shown along with each drought's duration in number of years.

Verde			Salt			Gila		
Years	Avg	No. of years	Years	Avg	No. of years	Years	Avg	No. of years
1946–48	27.3	3	1938–40	36.3	3	1934–36	37.0	3
1953–56	31.2	4	—	—	—	1943–48	25.0	6
1970–72	29.7	3	1953–57	25.6	5	1953–57	24.0	5
1999–2004	20.5	6	1970–72	30.7	3	1969–71	13.3	3
2011–16	22.7	6	—	—	—	2002–04	20.3	3
			2011–16	20.7	6	—	—	—

are expected to coincide with dry winters. Other climatic factors may be involved, including the impact of warmer temperatures on low flows, as has been documented as an increasingly important factor in UCRB droughts (Woodhouse et al. 2016; Udall and Overpeck 2017; Hoerling et al. 2019; Milly and Dunne 2020). The role of monsoon moisture may be an additional factor, with the potential to either exacerbate or ameliorate the impact of a dry cool season on streamflow. To investigate the climate conditions associated with multiyear droughts, we identified droughts in the streamflow records (the period of consecutive years of streamflow below the median, lasting three years or more), then examined the range of climate conditions that have accompanied these events. Streamflow, cool- and monsoon-season precipitation, and temperatures, in percentile values, were averaged for the years in each period of drought to assess the corresponding climate conditions for the different droughts.

Between four and five droughts were identified in the three gauge records, ranging from three to six years, with some variability in timing (Table 3). All three gauge records reflect multiyear droughts in the 1950s and early 1970s. The other droughts are shared by two of the three gauge records in overlapping periods in the 1930s, 1940s, 2000s, and 2011–16. The droughts identified are sensitive to the median as a threshold, and it is worth noting that all three streamflow records reflect below-median conditions in average percentile values over the years 1938–40, 1943–48, 1999–2004, and 2011–16.

As expected, a common feature among all droughts and basins is the concurrence of dry winters with streamflow drought, although the relative magnitudes of the deficits in these two variables vary somewhat (Fig. 8). Another common feature is the extremely warm temperatures for twenty-first century droughts (including 1999–2004) (>69 th percentile). Only in the upper Gila, in the 1930s, are the twenty-first century drought temperatures (in the cool season) exceeded. Temperatures during drought events are variable otherwise, with cool-season temperature below the median in two cases (i.e., 1940s drought in the Verde and upper Gila River basins and the 1970s drought in all three basins). Monsoon conditions during these droughts are also variable. All of the Salt River droughts and three of the five Verde River droughts occur during periods of near- to above-median monsoon moisture (especially the 1970s drought). Two of the Verde River droughts coincided with drier monsoon conditions, in the 1940s and early 2000s. In contrast, droughts in the Gila occur with both very low cool-

season and monsoon precipitation. This is yet another indication of the importance of monsoon precipitation to Gila River annual flow, unlike the other two basins. The sole exception to this occurred in the 1930s but that drought was also the least dry with nearly 40% of annual flow and precipitation in both seasons just below the 50th percentile.

The results cited above suggest that droughts are becoming much warmer throughout the Gila River basin, similar to the UCRB, and perhaps more severe. In particular, the droughts since 1999 in the Verde and Salt Rivers are the longest (6 years) with the lowest flow ($\sim 20\%$ of average), while in the Gila River, the short 2002–04 drought had the second lowest flow. Although by no means conclusive, there is a hint of worsening drought conditions in all three basins in terms of severity and in two basins in terms of length. As in the Colorado River, it is likely that warm temperatures are exacerbating the impacts of moisture deficits on streamflow, suggested by cool-season precipitation levels that are higher relative to streamflow deficits in the most recent period of drought (Fig. 8). However, unlike the UCRB, there is a tendency for wet summers to follow dry winters in the Verde and Salt River basins (Fig. 4, top), with the potential for a very wet summer to at least partly offset the effect of a dry winter. The upper Gila River basin, it is clear that multiyear periods of low flow are the result of both cool- and monsoon-season precipitation deficits.

e. Trends in climate and streamflow

Given the associations between streamflow and climate, recognizing trends in hydroclimatic variables over past decades can provide insights on the influence of climate on flow in the future. Warming temperatures are documented across the southwestern United States (Gonzalez et al. 2018), but long-term trends (over the past century) in precipitation, numbers of rainy days, SWE, and annual flow have not been detected in the Gila River basin (Anderson et al. 2010; Murphy and Ellis 2014; Robles et al. 2017). However, studies that assess trends over more recent decades have found significant decreasing trends in moisture-related variables such as precipitation, frequency of precipitation days, and length of snow season in regions that include the Gila River basin (Musselman et al. 2021; Zhang et al. 2021). Here we examine changes in streamflow and climate over five periods (1950–2019, 1960–2019, 1970–2019, 1980–2019, and 1990–2019)

FIG. 8. Multiyear droughts in the three gauge records, with water-year streamflow, along with cool-season and monsoon precipitation and temperatures, averaged for the years in each period of drought for the (top) Verde River, (middle) Salt River, (bottom) upper Gila River. Values are in percentile and are color coded to correspond to the different variables.

to assess how climatic trends, and specifically, warming temperatures, correspond to trends in streamflow. Multiple temporal subsets were used to evaluate the robustness of trends over different time periods with very different starting conditions. Trends were evaluated using both PRISM and nClim-Grid datasets, for annual and monthly streamflow, and monthly mean temperature and total precipitation. Trends were assessed using the nonparametric Mann–Kendall test for

the significance of trend and Sen's estimation of slope to evaluate the size of the trend (Helsel et al. 2020). Results are very similar for both datasets. A slightly warm bias in the nClim-Grid data for the upper Gila was the most noticeable difference (6 of 65 tests indicated significant warming in this dataset and not in the PRISM data).

1) TEMPERATURE AND PRECIPITATION

As expected, statistically significant and large warming trends (exceeding 2°C in many periods) are evident across all three basins, particularly for March, April, and June (Fig. 9). The March trends are especially noteworthy, ranging from approximately 2° to almost 4°C across all basins and most time periods. The summer months of July, August, and September are among the months with the least warming (0.5° – 2°C), although trends are significant in many cases. Annual trends are of a similar magnitude. There are nonsignificant but still substantial warming results for most other months and periods. May is the only month that shows slight and nonsignificant cooling (from 1990 to 2019 in all three basins); this is the only cooling in the entire set of tests. Of the 390 significance tests (two datasets, 13 annual/monthly tests, five periods, and three basins), 68% show significant warming and none show significant cooling (31% show nonsignificant warming and 2% nonsignificant cooling).

Trend analysis of precipitation shows general drying, but few trends are statistically significant. On an annual basis, all three basins show a statistically significant decline (five of six tests) during 1980–2019 (up to 30%), likely due to a number of extremely wet years in the 1980s and 1990s following by dry conditions in the 2000s. March stands out as the only month for which all three basins show statistically significant trends for several periods. Declines ($>60\%$) occur during 1970–2019 and 1980–2019 in all three basins (also 1990–2019 in the Salt River basin). Precipitation declines are also evident across all basins in October, November, April, and June, although not significant (except for one period for June in the Verde). It is noteworthy that the large warming previously noted in March, April, and June coincides with precipitation reductions in those months. The drying in those months may be promoting at least part of the substantial warming through a positive feedback. In a few months and periods, there is a suggestion of wetting, the most notable being July in the Verde and Salt River basins over the most recent period. The Verde River basin shows an increase of over 100% in this month, but the trend is not significant. Of the 390 significance tests, 6% show significant drying and none show significant wetting (66% show nonsignificant drying and 28% nonsignificant wetting).

2) STREAMFLOW

As was the case in several recent studies (Murphy and Ellis 2014; Robles et al. 2017), we found no statistically significant declines in annual streamflow, except for one period, 1980–2019, which as mentioned above, appears to be driven by exceptionally wet years in the 1980s and 1990s and the dry conditions of the 2000s (Fig. 9). On a monthly basis, the majority of tests reveal declines over all basins and periods

FIG. 9. Trends in monthly temperature, precipitation, and streamflow for the (top left) Verde, (top right) Salt, and (bottom left) upper Gila Rivers, annual and monthly values, for five periods (1950–2019, 1960–2019, 1970–2019, 1980–2019, and 1990–2019). Temperature trends are changes in degrees Celsius over the period. Precipitation and streamflow trends are percent change over the period. Results are shown for PRISM (lighter shade) and nClimGrid (darker shade) temperature and precipitation datasets. Values with asterisks are months with significant trends at $p < 0.05$ for both datasets.

although many are not statistically significant. Significant declines in Salt and Verde River flow in April, May, and June range from 20% to 85% over most of the five periods with most of the declines over 40%. Significant decreasing trends (10%–50%) are also evident in these two rivers in the months of October and November over most periods. In the upper Gila, significant declines in monthly streamflow are less consistent for these two set of months, occurring in only one to three of the periods (declines range from 60% to 80%). Very few positive trends in monthly streamflow were detected, and only three were statistically significant. These were for the upper Gila River, in December, January, and February, for the 1950–2019 period only (increases of about 50%). Of the 195 significance tests (five periods, 13 monthly/annual periods, and three gauges), 32% show statistically significant declines and 2% show statistically significant increases (56% show nonsignificant decreases, and 10% nonsignificant increases).

To summarize, it is clear that temperatures are warming across the Gila River basin. The rate of warming is greatest in

March, but summer temperatures (June–September), the most closely associated with annual streamflow, are also warming significantly, although at a lower rate. Few trends in precipitation are statistically significant, but even so, trends are largely negative. March does show several periods of significant decreasing precipitation across all three basins over the past 40–50 years. These trends in climate (and associated impacts) translate to declines in streamflow at monthly time scales. In all three basins, spring (April, May, and June) streamflow is declining. March precipitation decreases and strong temperature increases do not correspond to a statistically significant decrease in March streamflow, but declining April, May, and June streamflows suggest a lagged streamflow response, perhaps related to depleted cool-season moisture stored in the soil. Similarly, the significant declines in streamflow evident in the autumn months may be due to summer warming and October and November drying (though the drying trends are not statistically significant).

The Salt River basin, with a larger area likely to be accumulating winter snowpack, may be more susceptible to warming impacts, as in the UCRB, than the other two basins. This basin has a larger proportion of statistically significant declines in annual and monthly streamflow and a greater average rate of decline relative to the upper Gila River basin (21 trend tests with an average of -58% as compared with 15 trend tests with an average of -38%). In contrast, the Verde River basin has an even higher proportion of significant declines in streamflow (30 statistically significant trend tests), but with a -40% decline on average. The Verde River, with more of its watershed at lower elevations, less snowpack, but a similar proportion of runoff from cool-season precipitation as the Salt River, may be more sensitive to the impacts of warming temperatures on evapotranspiration. However, the higher proportion of significant decreasing trends in Verde River streamflow may also be an indication of the groundwater pumping in this basin (Murphy and Ellis 2014).

4. Conclusions

Topographic and regional climate variations across the Gila River basin result in differences in relationships between streamflow and climate in the upper Gila, Salt and Verde Rivers. Although cool-season precipitation is the dominant control on annual streamflow, the tendency for an inverse relationship between cool- and monsoon-season precipitation in the Verde and Salt River basins could mitigate the effects of dry winters, particularly during multiyear droughts. The analyses presented here are only suggestive of the possible buffering effect, which is like to diminish as summer temperatures increase. The increased precipitation during wet monsoons is a key factor, but cooler summer temperatures during wet monsoons are likely to be equally if not more important. Monsoon-season temperature and precipitation are inversely correlated (weak, but statistically significant; r from -0.201 to -0.302), but the most recent multiyear drought experienced wet monsoon conditions with temperatures were above the 80th percentile, likely diminishing the buffering effect.

Evidence of the impact of the extremely wet monsoon of 2021 suggests some of ways a very wet monsoon can alleviate effects of an extremely dry prior cool season (and dry prior monsoon, in this case). Although June 2021 was extremely warm, July and August temperatures were moderate, and monsoon-season precipitation at the end of August was in the 90th percentile over much of the state (https://cals.arizona.edu/climate/misc/SWMonsoonMaps/current/swus_monsoon.html). Monsoon precipitation had a measurable influence on the Salt River Project (SRP) reservoir system, bringing levels up to 71% of capacity from a record low of 66% between mid-July and mid-August (<https://www.abc15.com/weather/impact-earth/srp-lake-levels-up-thanks-to-wet-monsoon>). Severe drought conditions across the State of Arizona were alleviated, with monsoon moisture reducing the areal extent of the state in the worst two drought categories from 90% at the beginning of July to 59% at

the end of July (<https://www.climate.gov/news-features/event-tracker/western-drought-2021-spotlight-arizona>). Clearly, even an exceptionally wet monsoon will never make up for an extremely dry cool season, but it can help moderate impacts. A question for further study is whether warm temperatures will erase any benefit of very wet monsoons in the future. Summer months are warming at a slower rate than those of autumn and spring but do show statistically significant positive trends.

The upper Gila is different from the Salt and Verde basins, as monsoon precipitation is a more important contribution to annual flow, particularly in lower-flow years. An inverse seasonal precipitation relationship is not as evident in this basin, but in 20% of years, monsoon conditions have either ameliorated the impacts of a dry winter or reduced the annual flow in a near-average winter. This has happened with increasing frequency over the past several decades.

Similar to past research, we find no consistent statistically significant decreasing trend in annual streamflow in any of the three basins despite temperature trends that indicate significant warming. Little evidence of trend exists in the cool-season precipitation months of December and January or the monsoon months, July–September. For now, the fact that critical winter precipitation and early season runoff occur when evapotranspiration is low may be shielding annual streamflow from the impact of warming, as suggested by Robles et al. (2020) and supported by McCabe and Wolock (2020) who found that precipitation exceeds PET only in the months of December–March. However, a closer look at annual and monthly trends suggests that the shielding effect may be short-lived. While few trends in annual or monthly streamflow are statistically significant, the vast majority show declines. Significant spring streamflow declines reflect the months of greatest warming, March, April, and June. Summer warming, not as great as in spring but consistently significant over almost all intervals of time, has the potential to impact annual flow (e.g., Das et al. 2011) and may be a key factor in the significant decreasing trends in autumn streamflow, likely representing base flow.

Looking to the future, warming and drying conditions are projected for the region. Warming is already evident, consistent with projections. Projections for changes in precipitation are less certain, but a recent report projects a 3%–4% decrease in annual precipitation across the three basins by midcentury (Bureau of Reclamation 2021). A synthesis of dynamically downscaled climate model projections suggest spring precipitation decreases are the most certain (Kunkel et al. 2013), evident in the March drying trend in this study. Changes in monsoon are less certain. Projections suggest a later monsoon season, but with low confidence, with some studies indicating no changes in total precipitation amount (Seth et al. 2013; Cook and Seager 2013; Wang et al. 2021) while another indicates significant reductions (Pascale et al. 2017).

Although several factors may be helping to shield the entire Gila River system from the impacts of warming, as temperatures increase, reductions in water supply from the

Gila River are likely. Current water resource management in the Phoenix metropolitan area appears to be cushioned to the impacts of reductions of streamflow, largely because of declining demands (Murphy and Ellis 2019; Broman et al. 2020). However, drought conditions since the turn of the twenty-first century place additional stresses on this critical water supply. Since 1995, the Salt and Verde Rivers have been in the worst cumulative deficit of net basin supply relative to modeled demand (900 KAF; 1110 MCM) since the 1500s (Murphy and Ellis 2019). More work is needed to fully understand relationships between warming temperatures and seasonal precipitation and their impact on this important source of water for the arid Southwest, but the current absence of a substantial decrease in streamflow may be short-lived.

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Data availability statement. All data used in this study are openly available from the University of Arizona Research Data Repository (<https://doi.org/10.25422/azu.data.16822399>).

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