Climate adaptation planning to support ecosystems and people in the Gila River Watershed, Arizona

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the RCP4.5 (orange; “RCP45 2065-2095”) and RCP8.5 (red; “RCP85 2065-2095”) emission scenarios. Color-coordinated shading around the ensemble mean represents the spread of monthly mean values for individual climate models and corresponds to the 10th-90th percentile of the 31-member ensemble distribution. The statistical significance of the projected changes are depicted through color-coordinated symbols on each line: diamonds mark the high-magnitude anomalies (>2 standard deviations from the historical mean) and the most robust of these anomalies, where more than 80% of climate models agree on the sign of the change, are further depicted with a hatched white circle.

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Executive Summary

Issues facing human populations in water-scarce regions are often complex and intertwined, reflective of the precarious nature of balancing consumptive water uses with maintaining natural ecosystems. With water-related stresses likely to be compounded by projected changes in climate, peoples of these regions are faced with the daunting task of maintaining or improving this precarious balance in increasingly unfavorable circumstances. Improving and maintaining these balances is likely to be facilitated through deliberate planning and actions, by cross-disciplinary collaborative groups and bodies.

Using the Gila and San Pedro River basins within Arizona as a case study, this report discusses the potential of climate adaptation planning to successfully address and mitigate the impacts of future climate change on ecosystems and peoples. To that end, we a) review existing literature to determine the extent to which stakeholder groups have, now or in the past, addressed or considered water and ecosystem-related problems and solutions in the context of climate change, b) identify and summarize the priorities and values of the residents and users of the river in a similar context via survey, and c) summarize future climate projections within the context of the priorities and issues revealed through steps a) and b).

We gathered data via 59 stakeholder climate adaptation planning documents, 56 web-based survey responses, and a suite of 31 spatially-downscaled General Circulation Models for future climate and hydrological projections. Project outputs include a thematic summary of regionally specific climate adaptation planning documents, an assessment of water and ecosystem-related concerns across a broad spectrum of stakeholders in the Gila River Basin, and high-resolution projections of future climate scenarios.

Results from both the literature review and stakeholder survey indicate 'water quantity' to be a top concern across the Gila and San Pedro River basins, specifically instream flow and water supply. While stakeholder documents reflected commitment to 'water management' and 'alteration and restoration'-based solutions, comparatively less explicit consideration of climate change exists: only 37% of survey respondents indicated they have a climate adaptation plan in place. Although the prevalence of such plans varied across the basin, nearly all survey respondents indicated climate projections would directly benefit their work. In response to this interest in regionally-specific climate projections, this report finds strong seasonal changes in the hydrograph of the Upper Gila, with spring season flows projected to decrease dramatically, by 37% of historical values, near the end of the 21st century. We found no significant trend in annual flow volume; however, variability from year-to-year is projected to increase.

Overall, this investigation suggests that stakeholders within the river basins are united by a concern for issues related to water quantity, interest in pertinent management-based solutions, and a similarly high valuation of collaboration, despite some concerns of competing goals and strategies. Despite a high willingness to collaborate (98% of respondents), past collaborative efforts were common (69%) but were not distributed equally across the basin. Most notably, there was an absence of collaborations between Tribal and non-Tribal communities. Tribal communities within the basin—such as the Gila River Indian Community (GRIC)—have robust climate adaptation plans, suggesting that outside organizations can benefit greatly from both GRIC's leadership and from engaging in collaborative work with Tribes. Overall, this report finds collaborative efforts, most notably those that seek to include Tribal Nations, to be underutilized, despite common concerns, goals, and willingness to collaborate. We thus strongly advocate for collaboration between stakeholder groups, particularly with the inclusion of Tribal Nations, in order to ensure that efforts to mitigate against and adapt to climate change in the Gila River basin are successful and equitable, and that the benefits of restoration and adaptation do not occur in isolation but are shared by the communities and people that are united by the river.

Plain-Language Summary

People and the environment are inextricably linked making natural resource management incredibly important but also complicated. In arid and semi-arid climates, water is often challenging to manage for the benefit of both people and nature. Balancing these concerns well is aided by deliberate planning, actions, and collaboration among diverse groups of stakeholders.

Using the Gila and San Pedro River basins within Arizona as a case study, this report discusses the potential of climate adaptation planning to address and mitigate the impacts of future climate change on people and ecosystems. We examined these themes by a) reviewing publicly available stakeholder documents, b) surveying stakeholders and rightsholders, and c) summarizing future climate projections.

Results from both the literature review and stakeholder survey show 'water quantity' is a top concern across the Gila and San Pedro River basins, specifically instream flow and water supply. Stakeholder documents showed a commitment to 'water management' and 'alteration and restoration'-based solutions. At the time of the survey, only 37% of survey respondents indicated they have a climate adaptation plan. However, almost all respondents indicated climate projections would directly benefit their work.

This report also details projected future values of monthly mean precipitation for the basin with resulting impacts for the Upper Gila River: spring river flows are projected to decrease dramatically, by 37% of historical values, near the end of the 21st century. We found no significant trend in annual flow volume, but variability from year-to-year is projected to increase.

Overall, our investigation suggests that stakeholders within the river basins are united by concerns related to water quantity, interest in management-based solutions, and a willingness to collaborate, even with some concerns of competing goals and strategies. Despite this high willingness to collaborate (98% of respondents), collaborative efforts between stakeholders were common (69%) but were not distributed equally across the basin. This is most notable in a lack of collaborations between Tribal and non-Tribal communities. The Gila River Indian Community (GRIC) located along the Gila River has a robust climate adaptation plan, suggesting that outside organizations can benefit from collaboration with GRIC and other Tribes.

This report advocates for increased collaboration between stakeholder groups within the Gila and San Pedro River basins, particularly collaborations that seek to include Tribal Nations. These efforts will aid climate change adaptation and will help ensure that the benefits of restoration and adaptation do not occur in isolation but are shared by the communities and people united by the river.

Summary of Major Points

- Both the literature review and stakeholder survey indicate 'water quantity' to be a top concern across the Gila River basin, specifically instream flow and water supply.

- Our models revealed strong seasonal changes in the hydrograph of the Upper Gila, with spring flows projected to decrease dramatically by 37% of historical values near the end of the century.

- Stakeholders are united by a concern for issues related to water quantity.

- Despite common concerns, goals, and willingness to collaborate, this report finds collaborative efforts, most notably those that seek to include Tribal Nations, to be underutilized.

- We strongly advocate for collaboration between stakeholder groups, particularly with the inclusion of Tribal Nations.

- The benefits of restoration and adaptation do not occur in isolation but are shared by the communities and people united by the river.

Project Report

1. Background

In the southwestern United States, rivers provide a wide range of ecological and cultural services (Jones et al. 2010). Riparian environments—the transitional zones between riverine and upland terrestrial habitats—are among the most productive, diverse, and dynamic ecosystems in dry landscapes (Naiman et al. 2010). Riparian zones host diverse plant communities, create essential habitat for migratory birds and endangered desert fishes (Naiman et al. 1993; Skagen et al. 1998; Fagan et al. 2002), and filter out toxic compounds (Zhang et al. 2010). Of course, rivers are also vital to people and society (Cooper et al. 2014; Zhu et al., 2015), and have aesthetic, cultural, and spiritual values (Vollmer et al. 2015). For example, rivers supply water for irrigated agriculture, for livestock, and for other industrial and municipal uses. However, beneficial use of rivers often results in altering river courses and streamflow: rivers are often dammed for flood control, storage, or hydropower, and diverted for off-stream use (Reisner 1993). These river alterations can result in the modification of natural streamflow to varying degrees and result in flows with little to no seasonal or interannual modulation (Poff et al. 2007), create artificial diurnal streamflow (e.g., from hydropeaking, Poff and Schmidt 2016; and treated wastewater discharge, Eppehimer et al. 2020), or eliminate perennial flow altogether (Stromberg et al. 2007).

In addition to river alterations and increased off-stream demand, rivers in the southwestern United States are also threatened by human-caused climate change. Higher temperatures are projected to decrease soil moisture and increase atmospheric water demand, leading to less runoff (USBR 2016). Additionally, increases in atmospheric water vapor holding capacity and changes to large-scale weather patterns are projected to change precipitation characteristics (Easterling et al. 2017). Streamflow is projected to decrease across the southwestern United States, including by up to 30% in the Colorado River basin by mid-century (Udall and Overpeck 2017).

Changes in streamflow impact both people and ecosystems. To adapt and prepare for projected climate and streamflow changes, some rights- and stakeholder groups are actively planning for future climate scenarios. These groups have identified the need for localized climate change data to support their planning process (Ferguson et al. 2016; Kalafatis et al. 2019). However, climate adaptation planning is challenging (Shi et al. 2015; Theobald et al. 2015), particularly given the many uses of rivers. Learning from the successes and barriers to climate change planning can benefit community action and collaboration for organizations or user groups with similar values (Burch 2010; Moser and Ekstrom 2010; Measham et al. 2011).

1.1 Objectives

Using the Gila River and its tributary, the San Pedro River, as a case study, we investigated the potential of climate adaptation planning to mitigate the impacts of future climate change on both ecosystems and people. We aimed to:

1) Review literature to determine the extent to which stakeholder groups are considering water and ecosystem-related problems and solutions in the context of climate change
2) Survey the priorities and values of the residents and users of the river
3) Project future climate and relate expected future conditions to the problems/solutions and priorities/values revealed by the literature review and survey

These objectives are detailed below.

1.1.1 Review of Stakeholder Climate Adaptation Literature

To better understand 1) the concerns of regional rights- and stakeholders regarding water and ecosystem-related issues in the context of climate change and 2) the extent to which these groups are (or are not) preparing for climate change and changing streamflow patterns, we analyzed rights- and stakeholder documents associated with climate adaptation planning. Identifying the similarities and differences in concerns and climate adaptation planning among user-groups and geographic sections of the Gila and San Pedro Rivers can provide a useful overview of how diverse groups are thinking about water and ecosystem-related issues in the context of climate change. By doing so, it is possible to summarize and communicate the successes and barriers to climate adaptation planning in the basin.

1.1.2 Survey of Gila and San Pedro River Stakeholders

The literature review shows climate adaptation planning in the basin. However, the scope of this approach does not capture concerns and plans that remain unpublished or undocumented. To more fully understand stakeholders' concerns about water and ecosystems in the context of climate change, we surveyed relevant user-groups to characterize hierarchies of concerns, pathways and barriers to implementation of adaptation plans, and multi-stakeholder collaboration.

1.1.3 Climate modeling

The literature review and survey provide us a deeper understanding of 1) how communities of the Gila and San Pedro River basins think about climate adaptation planning and 2) the most salient concerns across this diverse population. We use these perspectives of rights- and stakeholders to frame the way we communicate projected future climate scenarios in these basins. Through this process, we're able to provide an essential tool, missing for many, to inform climate adaptation planning. Although the general trend of climate change is consistent across the southwestern United States, the coarse spatial resolution of climate models can leave out important smaller-scale processes such as local precipitation extremes driven by topography. Stakeholders identified the need for localized, basin-level information on climate and its hydrological impacts. To address this need, we used spatially downscaled global circulation model (GCMs) outputs to drive a hydrologic model and simulate future hydroclimatic conditions. In the modeling experiment, we analyze and compare data under both historical conditions and future climate change scenarios[1]. These simulations allow for a better understanding of the regional impacts of climate change on temperature, precipitation, and streamflow changes in the Gila River watershed.

[1] Future climate scenarios are characterized and defined by the strength of their greenhouse gas forcing, which equates to the amount of global warming they cause. These scenarios are referred to as "representative concentration pathways", or RCPs. Specifically, we examine RCP4.5 and RCP8.5, which are commonly used future climate scenarios. For RCPs, the higher numbers represent higher greenhouse gas concentrations and thus more warming.

2. Study region

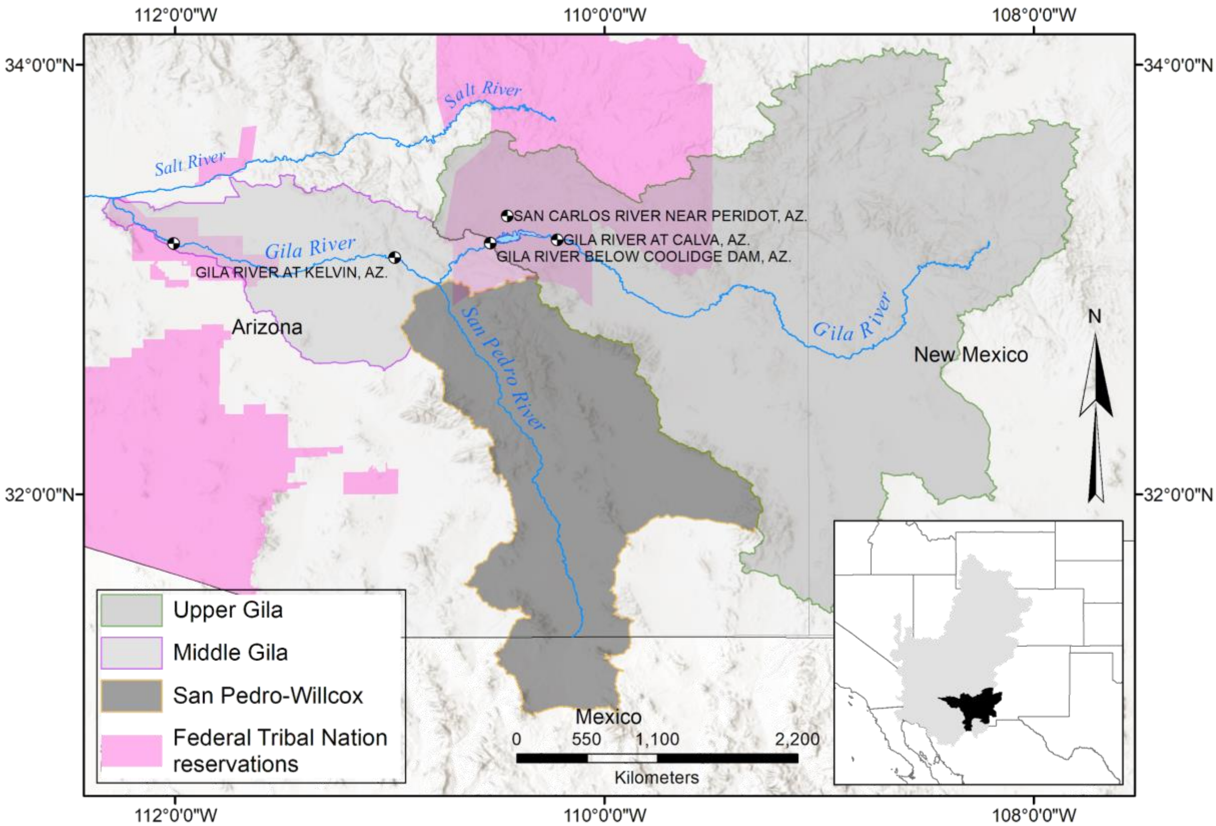

Figure 1: Gila River watershed, a major tributary in the Colorado River Basin (inset). Federally-recognized Tribal Nation reservations are shown in pink. The Gila River flows east to west through the Upper Gila River (green border) and Middle Gila River (magenta border) watersheds. The San Pedro River, a principal tributary to the Gila, flows south to north through the San Pedro watershed (gold border). For greater context, the Salt River follows east to west to a convergence with the Gila, just downstream of the Middle Gila watershed boundary. USGS stream gages are noted with dichromatic dots.

2.1 Gila River

The Gila River is an arid-region tributary to the Colorado River, originating in western New Mexico; it drains a 58,198 mi^2 basin encompassing much of southern Arizona (Waters 2008) (Figure 1). For the scope of this report, the basin can be dissected into two subbasins: the Upper and Middle Gila. The Upper Gila (Figure 1, green area; Figure 2A) encompasses roughly half of the Gila basin, and includes portions of New Mexico and Arizona (Steiner et al. 2000). The Middle Gila River (Figure 1, magenta area; Figure 2B and 2C) flows out of Coolidge Dam, through the Gila River Indian Reservation, and meets the Salt River just south of Phoenix. Drier conditions, paired with the completion of Coolidge Dam in 1928, disconnected the Middle Gila from the Upper Gila, diminishing flood frequency and overall streamflow (Huckleberry 1994) (Figure 3). The dam is owned and operated by the Bureau of Indian Affairs and was built to mitigate flood risk and meet irrigation needs for Tribal entities downstream (Dejong 2007). Dam outflow is largely determined by irrigation demand (Stromberg et al. 2007), resulting in inconsistent stream flow patterns.

The snowmelt-fed upper headwaters flow perennially, while the middle reach is intermittent (Uhlman et al. 2008). The Gila ultimately discharges into the Colorado River near Yuma, AZ (Waters 2008).

Because of the strong seasonality of precipitation in the southwesern U.S., groundwater is a critical hydrologic resource in the Gila River basin. Ecologically, high groundwater levels are important for maintaining riparian vegetation (Uhlman et al. 2008). However, groundwater pumping for domestic and agricultural use in Arizona has led to significant drawdown of the water table. To mitigate the overdraft of groundwater resources, groundwater recharge facilities are now operated in the Middle Gila River basin (Uhlman et al. 2008) to increase underground water storage for subsequent crop irrigation (Bark and Jacobs 2009). Recharge locations are dual purpose and serve as river restoration locations, where restored water flow creates a live river on the GRIC reservation (Gila River Indian Community 2015) and has increased native species recruitment (Westland Resources Inc. 2019).

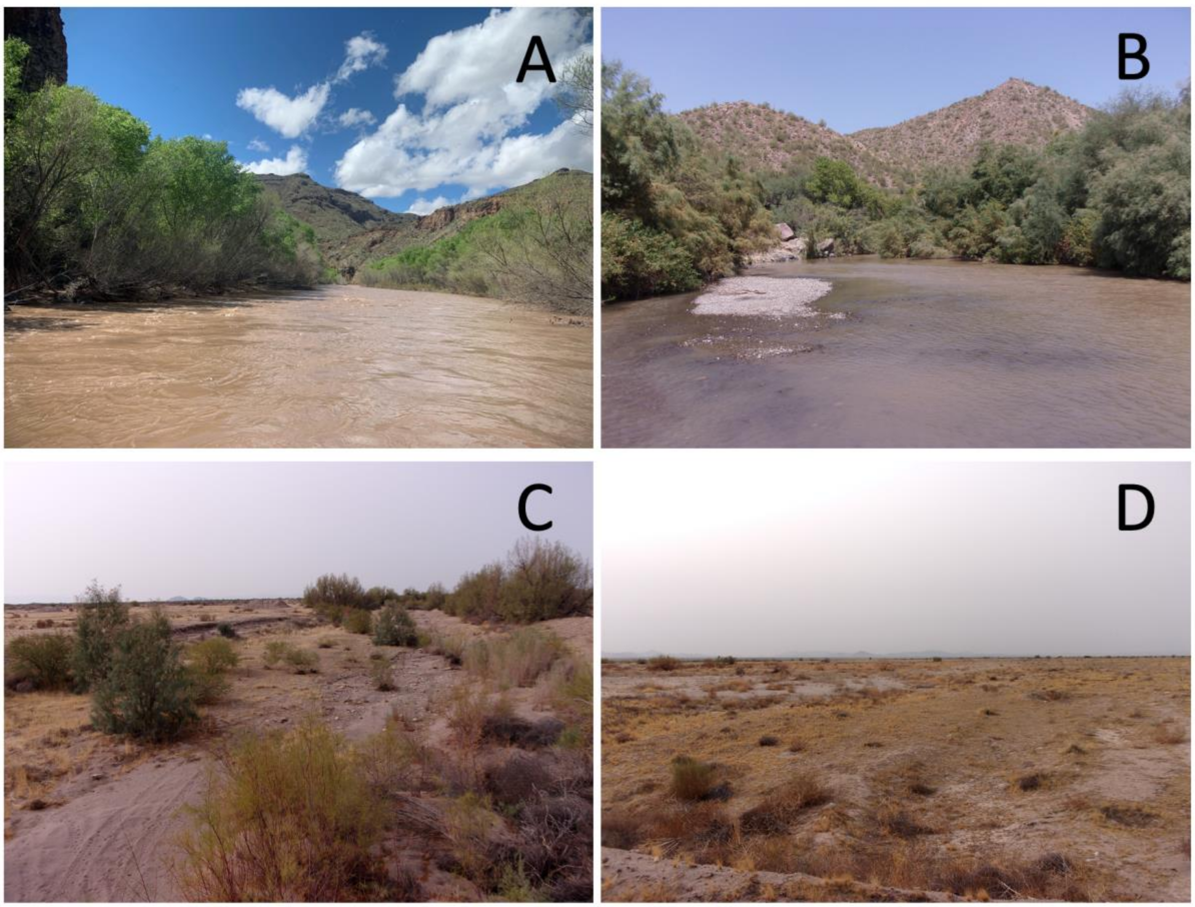

Figure 2: Photographs of the Gila River from the A) upper Gila near Clifton, AZ, B) middle Gila downstream from Coolidge Dam near Winkelman, AZ, C) middle Gila near the Gila River Indian Community, and D) lower Gila near Gila Bend, AZ. All photographs taken in October 2020 by Drew Eppehimer.

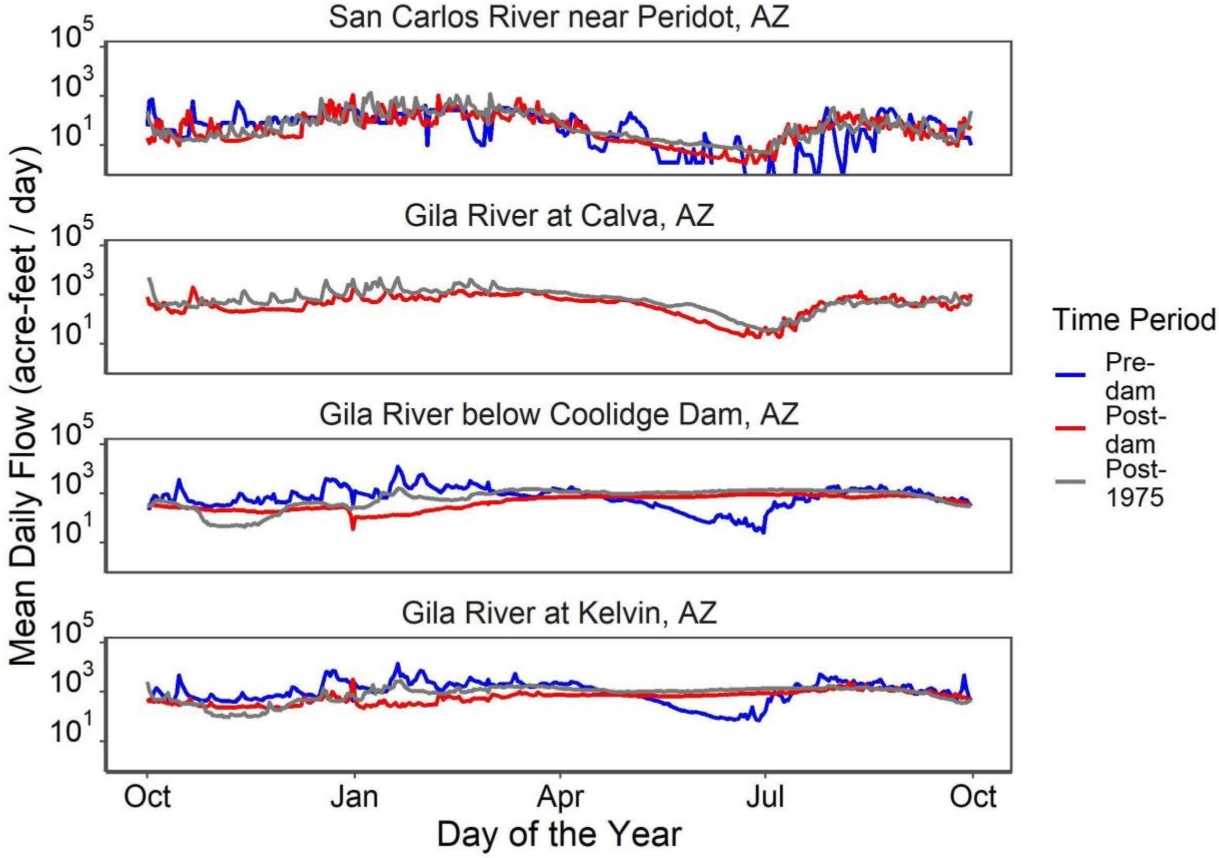

Figure 3: Mean daily flow hydrograph comparisons for three time periods: pre- and post-completion of Coolidge Dam (completed in 1928), and post-1975. In summary, this shows the following periods: pre-1928 (Pre-dam) (1914-1927 at Peridot, 1899-1905;1914-1927 at Coolidge Dam, 1911-1927 at Kelvin); 1928-1975 (Post-dam); 1975-present (Post-1975). From top to bottom the graphs represent observation stations located at increasing downstream distance along the Gila River. Coolidge Dam is located between the Gila River at Calva station and the Gila River below Coolidge Dam station.

2.2 San Pedro River

The San Pedro River, one of the last remaining undammed rivers in the desert southwestern United States, is a 143-mile long, largely undeveloped tributary to the Middle Gila River (Thomas and Pool 2006; Stromberg et al. 2007) (Figure 1, yellow area; Figure 4). It originates in Sonora, Mexico, just south of the border and flows northward through the San Pedro Riparian National Conservation Area before meeting the Middle Gila just downstream of Coolidge Dam. Streamflow in the San Pedro River results from storm runoff from seasonal monsoons (Serrat-Capdevila et al. 2007) and baseflow from groundwater upwelling (Thomas and Pool 2006). However, streamflow has diminished by more than 50% in the last century (Thomas and Pool 2006) and sections of the San Pedro River that were once perennial are now intermittent (Haney 2005). This reduction in perennial flow is attributed to decreased groundwater levels due to nearby groundwater pumping for agriculture, mining, and expanding urbanization (Haney 2005; Turner and Richter 2011).

Figure 4: Photographs of the San Pedro River from the A) upper San Pedro near Hereford, AZ, B) middle San Pedro near Benson, AZ, C) lower San Pedro near Mammoth, AZ, and D) lower San Pedro near Winkelman, AZ. All photographs taken October 2020 by Drew Eppehimer.

2.3 River users

Historically, the land along many central Arizona rivers has been farmed by the Hohokam and their descendants, the Akimel O'othom. The Akimel, the River People, lived in village clusters along the river and used irrigation to raise crops of corn, squash and two species of beans, in addition to the non-food crop of cotton (Hunt and Ingram 2014; Loendorf and Lewis 2017). Colonial settlers co-opted many of these Indigenous canal systems in the late 1860s (Dudley 2009). Today, both Tribal Nations and settler descendants continue to use the Gila and San Pedro rivers for agriculture. These river systems also provide value beyond consumptive off-stream water use. Many native riparian plants have important traditional and cultural value to local Tribal communities in the Gila and San Pedro basins (Phillips 1998; Long et al. 2003; Cohn et al. 2016) and rivers provide opportunities for birding, fishing, and other recreation. Rights- and stakeholders for the Gila and San Pedro rivers include, but are not limited to, the Bureau of Land Management, The Nature Conservancy, and Tribal Nations like the Gila River Indian Community.

3. Methods

3.1 Climate data contextualization and stakeholder adaptation

3.1.1 Systematic Literature Review

To assess the existing climate adaptation frameworks in place along the Gila River watershed, we reviewed a breadth of publicly available documents pertaining to stakeholder climate adaptation strategies in the Gila and San Pedro basins (e.g., scientific reports by federal agencies, municipal and local government planning documents, peer-reviewed literature) (*Appendix A)*. Documents were located and downloaded through Google Search in August 2020, regardless of their publication date, using search terms related to climate and planning, alongside singular search terms for a given stakeholder group and the region of interest (Table 1). We supplemented this search by asking academics, administrators, and Tribal Liaisons for relevant documents that may not be published online or otherwise found through our search. Overall, our analysis included 59 stakeholder documents (*Appendix A*). We used a thematic analysis (Attride-Stirling 2001) and coding scheme (Saldana 2016) to determine broad themes and identify emergent themes and unanticipated findings. With this technique, we identified issues of concern and related solutions (Tables 2 and 3).

Table 1. Search terms used in a systematic Google Search for stakeholder documents related to climate planning in the study area.

Category	Search terms
Climate	*(climate change OR warming OR drought OR "extreme events" OR water OR streamflow OR hazard) AND*
Planning	*(forecast OR predicted OR shortage OR scarcity OR adapt* OR management OR "action plan" OR mitigation) AND*
Region (only one region chosen per search)	*"Upper Gila", "Middle Gila", "Lower Gila", "San Pedro" AND*
State	*"Arizona" AND*
Stakeholder group (only one group chosen per search)	*~ "agriculture", "irrigation", "reservation", "tribe", "native", "municipal", "conservation", "NGO", "city"*

3.1.2 Literature Review Analysis

We used qualitative coding to identify a variety of concerns, as well as specific adaptation strategies (i.e., solutions) to address those concerns. We categorized issues based on those used in the survey (Table 2) and we used deductive coding (Saldana 2016) to categorize solutions (Table 3, *Appendix C*). Issue codes were further catalogued into the broad categories of water quantity, water quality, ecological concerns, socio-cultural issues, and other (Table 2). Solution codes were similarly catalogued into broad categories to ascertain general themes prevalent throughout the literature (Table 3).

Table 2. Issue codes used in the literature analysis.

Category	**Code**	**Definition**
Water quantity	Water supply	Broad mentions of water supply
	Agricultural water supply	Specific mentions of water supply for agricultural purposes/use
	Municipal water supply	Specific mentions of water supply for towns/cities/municipalities
	Instream flow	References to issues with or arising from past, present, and/or future alterations to instream flows
Water quality	Water quality	Broad mentions of water quality
	Groundwater	References to groundwater in any capacity
Ecological concerns	Ecosystem water stress	References to the adverse impacts to ecosystems as a result of water stress
	Stream vegetation	Specific mentions of concerns related to stream vegetation
	Fish populations	Specific references to issues concerning fish populations
	Bird populations	References to issues concerning bird populations
Socio-cultural issues	Socio-cultural issues	Broad mentions of socio-cultural issues in any capacity
Other	Other	Any issues that could not be adequately coded using the above 11 codes

Table 3. Solution codes used within a specific category and their definition. For more specific details on categorization, refer to *Appendix C*.

Category	**Code**	**Definition**
Water management	Water management	Broad references to water management
	Flow management	Specific mentions of management of instream flows
	Groundwater management	Specific references to groundwater management
	Artificial recharge	Mentions of any artificial recharge techniques
Alteration and restoration	Watershed management and restoration	Mentions of management or restoration either at the watershed scale or of watershed components other than water/flow
	Process-based restoration	Broad references to process-based restoration techniques
	Infrastructure	References to the installation, adaptation, operation, and/or maintenance of infrastructure as a solution to an issue
Legal actions	Legal action	Broad mentions of various legal strategies or actions as a solution for any of the aforementioned issues
Research & Planning	Research and monitoring	References to the need for future or additional research and/or monitoring
	Planning	References to or recognition of a need for planning
Engagement & Collaboration	Education and outreach	Broad mentions of education or any sort of outreach as a solution to the above issues
	Stakeholder engagement	Specific mentions of stakeholder engagement as a solution to the above issues
	Tribal engagement	Specific mentions of tribal engagement as a solution to the above issues
	Collaboration	References to collaboration as a solution for any or several of the above issues

3.1.3 Survey Data and Analysis

We used a survey to better understand the current perspectives of stakeholders within the Gila and San Pedro River corridors. The survey was approved the University of Arizona IRB (protocol #2006740963). Unfortunately, we were unable to survey Tribal Nations, because Tribal research review panels ceased convening because of the COVID-19 shutdowns. Using contact information for relevant stakeholder groups obtained from publicly accessible sources, we distributed this survey (*Appendix D*) via email, using Qualtrics software. Our survey was open for 21 days from August 12 - September 2, 2020. The survey contained 14 questions, which included multiple choice, select all that apply, and ranking questions, as well as three open ended response questions (*Appendix D*). Respondents remained anonymous, but described themselves based on their geographic location (upper, middle, lower portions of the San Pedro and Gila Rivers) and by their professional affiliation in relation to a river. Survey respondents were asked to identify their priorities and concerns about the river, climate adaptation plans, and collaboration efforts. We used basic summary statistics to document the respondents' professional affiliations and location along the rivers and examine the most salient trends in responses. We also used a thematic analysis (Attride-Stirling 2001) and coding scheme (Saldana 2016) to determine broad themes in the open-ended responses.

3.2 Climate modeling

Though large-scale signals of climate change are consistent across the western United States, local topography (e.g., narrow mountain ranges) and atmospheric processes (e.g., convective towers) exist on spatial scales too small to be represented faithfully by coarser-scale climate models. As a result, local precipitation extremes are smoothed due to averaging over a larger area in general circulation model (GCM) experiments (Stone and Risbey 1990; Pierce et al. 2014). Local terrain is particularly important for precipitation processes that are known to impact precipitation intensity in the western U.S., such as upslope fluxes of water vapor (Neiman et al. 2002; Ralph et al. 2006). Because the spatial resolution of GCMs does not resolve the topographical features of even the most dramatic of mountain ranges, let alone the smaller mountains of the upper reaches of the Gila River basin, a regionally-specific analysis is required to produce meaningful simulations of hydrometeorological and hydrological information. Various dynamic and statistical methods are available for such spatial downscaling of the more coarse GCM output to the finer resolution grids more capable of resolving these regional-to local-scale processes.

3.2.1 Localized Constructed Analogs (LOCA)

We used the results of a statistical downscaling and bias correction technique, the Localized Constructed Analogs (LOCA) method (Pierce et al. 2014). We make use of results from Pierce et al. (2015) who applied this technique on the output of 31 Coupled Model Intercomparison Project Phase 5 (CMIP5) climate change scenarios. The LOCA process incorporates a multiscale matching scheme to pick appropriate analog days from observations to downscale GCM-projected daily weather patterns. LOCA grid cells are downscaled using a single analog day (a day that varies from place to place in the grid). This methodology results in reduced smoothing, but is particularly advantageous for investigating extreme precipitation days (Pierce et al. 2014). In summary, the LOCA dataset provides bias-corrected, realistically detailed, daily projections of precipitation and surface air-temperature on a 4.3-mile horizontal grid.

3.2.2 LOCA + Land Surface Model + Streamflow routing

While the LOCA dataset is useful for understanding projected temperature and precipitation data, further processing by a large-scale hydrologic model is required to simulate projected runoff and, eventually, streamflow. Previous work by Pierce et al. (2015) uses the LOCA dataset to force, or provide the necessary meteorological inputs to, the Variable Infiltration Capacity (VIC) hydrological model (Liang et al. 1994). The results from the VIC model simulation then provide a suite of near-surface, surface, and subsurface hydrological and energy-balance variables, including gridded runoff and subsurface baseflow data. We applied these simulations into a final post-processing step used to route gridded runoff and baseflow to streamflow estimates. While there are several well-regarded models available for streamflow routing, their aim is identical: to simulate the flow of water across and below the land surface to discreet stream channel nodes, or locations. For our purposes, we used the MizuRoute streamflow routing model (Mizukami et al. 2016) to route the LOCA/VIC outputs to co-located streamflow nodes at existing U.S. Geological Survey (USGS) streamflow gages. The overlapping period between the historical model simulations and the USGS observations were then used for model validation and secondary bias correction using the Preserve Ratio (PresRat) method (Pierce et al. 2015).

The final routed LOCA/VIC dataset provides daily simulations of streamflow into the San Carlos reservoir, from 1950-2100. These projections include 31 GCMs under three greenhouse gas emission scenarios, including one historical (1950-2005) and two future (2005-2100) scenarios which include both a future under lower greenhouse gas emissions (RCP 4.5) and higher greenhouse gas emissions (RCP 8.5). In addition to streamflow, we also simulated other variables at a daily time step, including temperature, snow water equivalent (SWE), and precipitation.

3.2.3 Streamflow modeling challenges in the San Pedro and Middle Gila basins

Although this report offers daily projections of streamflow into the San Carlos reservoir at the terminus of the Upper Gila, we were unable to produce projected streamflow data for the San Pedro and Middle Gila rivers due to the impacts of human intervention on natural streamflows. Water releases from the San Carlos reservoir dictate the streamflow of the Middle Gila. Because we were unable to simulate reservoir operation in conjunction with our hydrological modeling work, we were unable to produce any meaningful projections of streamflow below the San Carlos reservoir. Although streamflow in the San Pedro is not subject to reservoir operations, we were unable to successfully model this stretch of river likely due to both surface diversions and groundwater pumping, which are prevalent in the San Pedro (Gungle et al. 2016). Although surface diversions are a substantial component of the Upper Gila, we were able to account for them in our secondary bias correction process, and thus were able to produce streamflow projections for the Upper Gila.

4. Results

4.1 Literature

We reviewed 59 stakeholder documents (*Appendix A)* encompassing a variety of literature types to identify relevant issues, which were coded using phrases taken directly from the survey document (*Appendix D*, Question 4). The most commonly-mentioned issues across both the Gila and San Pedro (excluding the catch-all “Other” code) were water supply (36 and 97 mentions, respectively), instream flows (28 and 86 mentions), and groundwater (18 and 61) (*Appendix C,* Table C2). Based on our analysis, the most common specific concern for each basin was water supply. Overall, water quantity—encompassing the codes of water supply, instream flows, groundwater, agricultural water supply and municipal water supply—was by far the most frequently mentioned issue category (Table 4). Notably, mentions of ecological concerns that are dependent on water supply (e.g., stream vegetation, 24 and 44 mentions, or fish populations, 2 and 9 mentions) were sparse relative to the more direct concerns of water supply or instream flows. This disparity suggests that rights- and stakeholder groups within the Gila Basin are predominantly concerned with water quantity and less explicitly concerned with more "indirect" problems that arise as a result of water scarcity.

The most commonly-mentioned specific solutions to the identified issues were 1) watershed management and restoration (35 and 74 mentions for the Gila and San Pedro, respectively) and 2) water management (27 and 65 mentions) (*Appendix C,* Table C2). This analysis suggests that most stakeholders are primarily and predominantly interested in addressing problems of concern with solutions involving management and restoration (Table 4). Notably, formal codification of collaboration or stakeholder and Tribal engagement as solutions was relatively absent in the reviewed documents; mentions of engagement and collaboration as an explicit solution to identified concerns were distinctly fewer than mentions of solutions related to water management or alteration and restoration (Table 4). In particular, of the 59 stakeholder documents reviewed, only 5 documents - 8% of the total - reported active collaboration with a Tribal Nation. Often, these collaborations were with the main Tribal Nation in the region, the Gila River Indian Community (GRIC).

Table 4. Issue and solution broad categories and their total mentions by river system

	Total mentions			Total mentions	
Issue category	**Gila River**	**San Pedro River**	**Solution category**	**Gila River**	**San Pedro River**
Water quantity	87	244	Water management	57	156
Ecological concerns	49	96	Alteration and restoration	69	98
Water quality	4	13	Legal actions	25	55
Socio-cultural issues	11	1	Research and planning	18	66
			Engagement and collaboration	35	51

Sankey plots for both rivers reveal how the issues and solutions identified in the analysis relate to one another (Figures 5 and 6). The size of the boxes containing each code reflect the frequency with which they are mentioned within the reviewed documents; the width of the connections or "tendrils" between the issue and solution boxes (i.e., left- and right-hand side of the figure) are proportional to the frequency with which each solution was mentioned in conjunction with a specific issue. Water supply and instream flows are mentioned most often (i.e., have the thickest boxes) (Figures 5 and 6). Interestingly, solutions mentioned in conjunction with these concerns are highly diverse—tendrils connect to most of the solution code boxes—but there appears to be very little formal codification of collaboration or tribal or stakeholder engagement as a solution. Overall, for both rivers, stakeholder documents most frequently identified water management as a solution to water supply concerns. However, there was no similar consensus for instream flow concerns: diverse solutions were mentioned, with the two most frequent being water management and flow management.

In summary, results of a thematic analysis of existing stakeholder documents related to climate adaptation planning revealed commonality in concerns between user groups, with instream flows and water supply the major issues, as well as a similar commitment to pursuing a variety of solutions to these problems. Broadly speaking, river users in the basin are united by both a common consideration of water quantity concerns as being most paramount, and a common commitment to actively addressing those concerns and working towards solutions designed to mitigate them. Unfortunately, user documents also reflect a notable dearth of solutions that explicitly articulate collaboration or engagement, especially with Tribal communities.

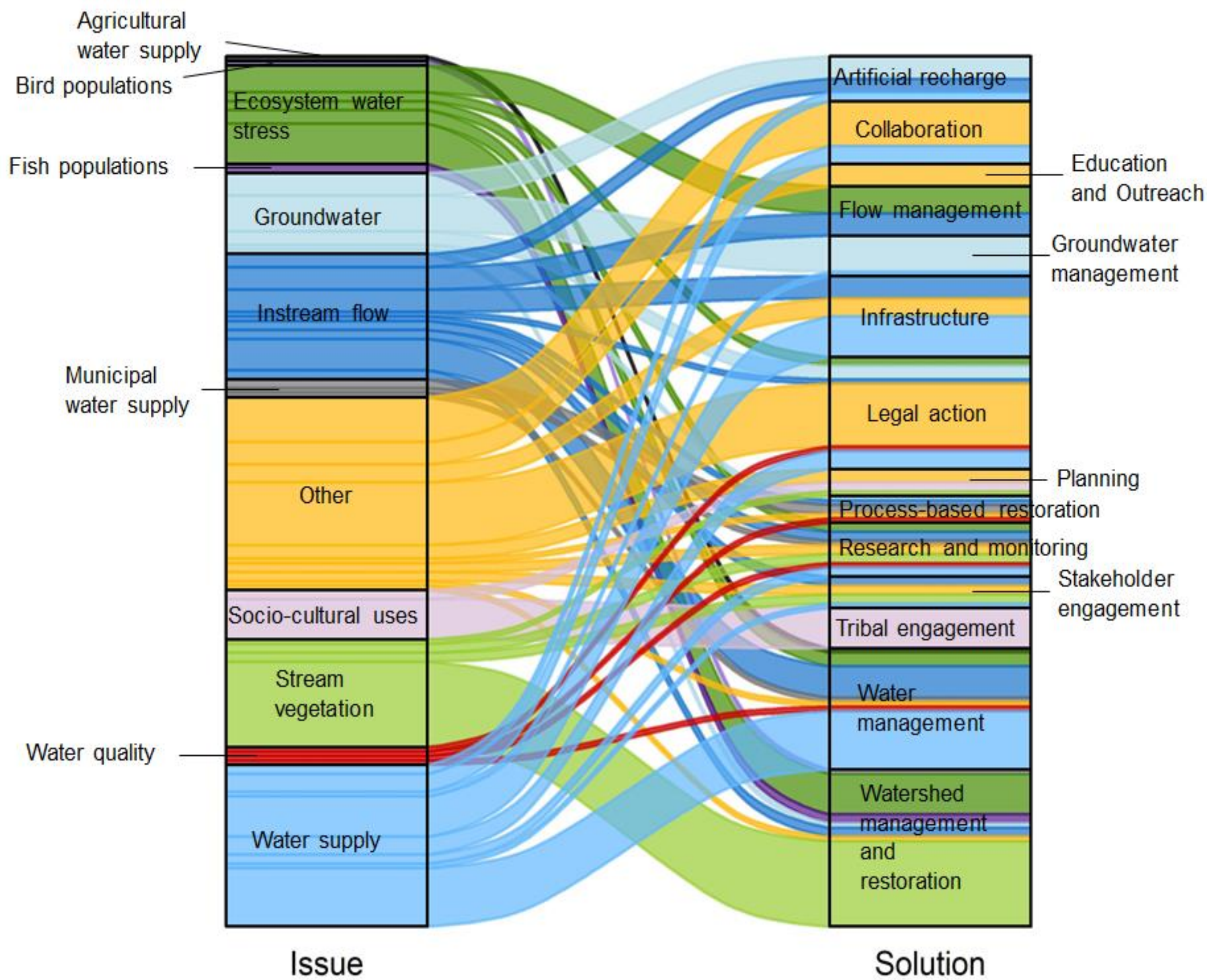

Figure 5. Sankey plot linking river issues on the left with their respective solutions identified in stakeholder documents related to the Gila River watershed. The width of the columns is proportional to their frequency in the literature review.

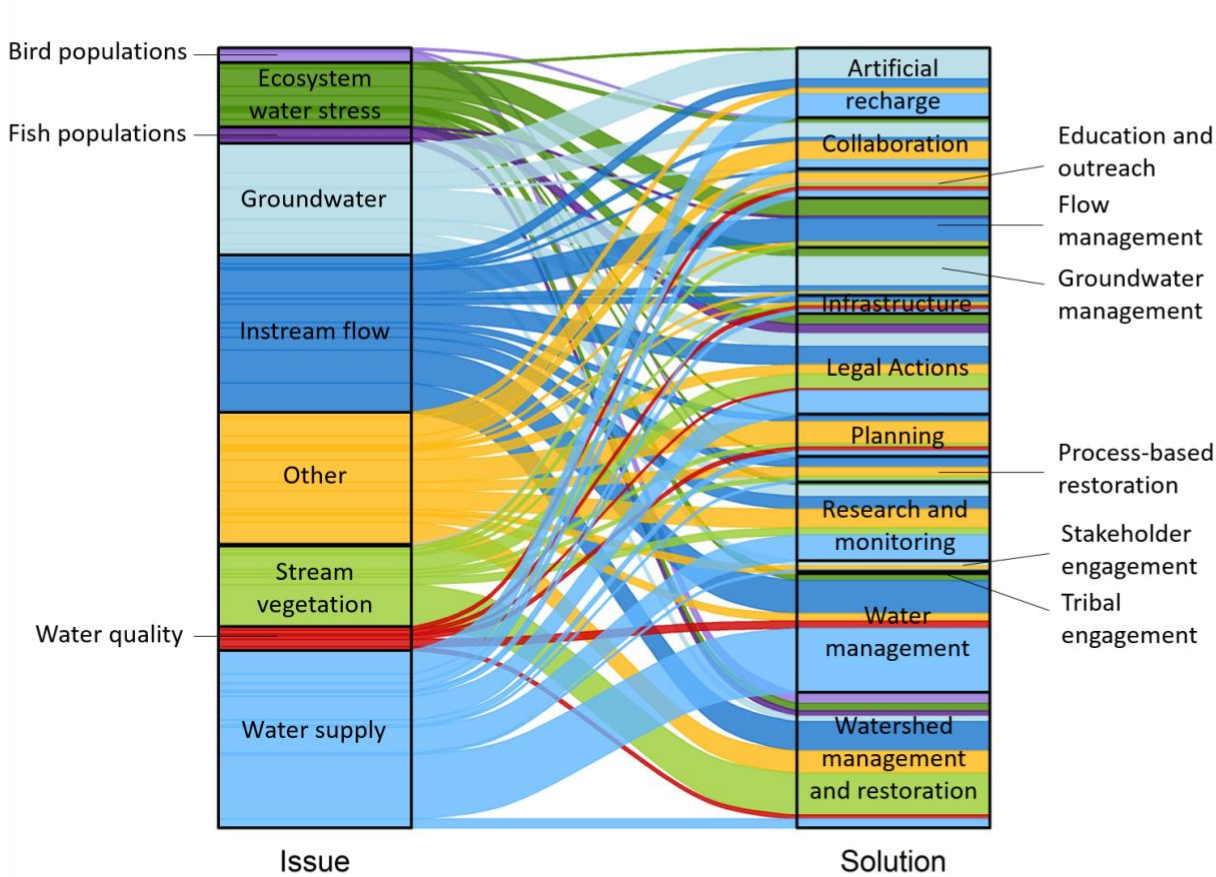

Figure 6. Sankey plot linking river issues on the left with their respective solutions identified in stakeholder documents related to the San Pedro River watershed. The width of the columns is proportional to their frequency in the literature review.

4.2 Survey

We received a total of 56 survey responses, a response rate of 30%. More respondents were from the San Pedro River (n=30) than the Gila River (n=22). In both river systems, the Middle sections were underrepresented: four respondents from the Middle San Pedro and one respondent from the Middle Gila (Fig 7). Respondents self-identified as at least one of nine categories: NGO/non-profit (31%), federal (18%), state (9%), researcher (8%), city (7%), farmer/rancher (7%), recreation (7%), industry (3%), and other (11%). Several professional groups were represented in each geographic area with the exception of the Middle Gila River (Fig 7). Unfortunately, no participants in our survey self-identified as Tribal members. This was due largely to constraints imposed by the COVID-19 pandemic, mentioned previously. The Gila River Indian Community (GRIC) forms a large and important constituency and user group within the Middle Gila River. GRIC has published its own climate adaptation plans, and previous interviews with the Tribe have illustrated their desire to partner with a diversity of collaborators to advance their adaptation efforts (NNCAP 2017).

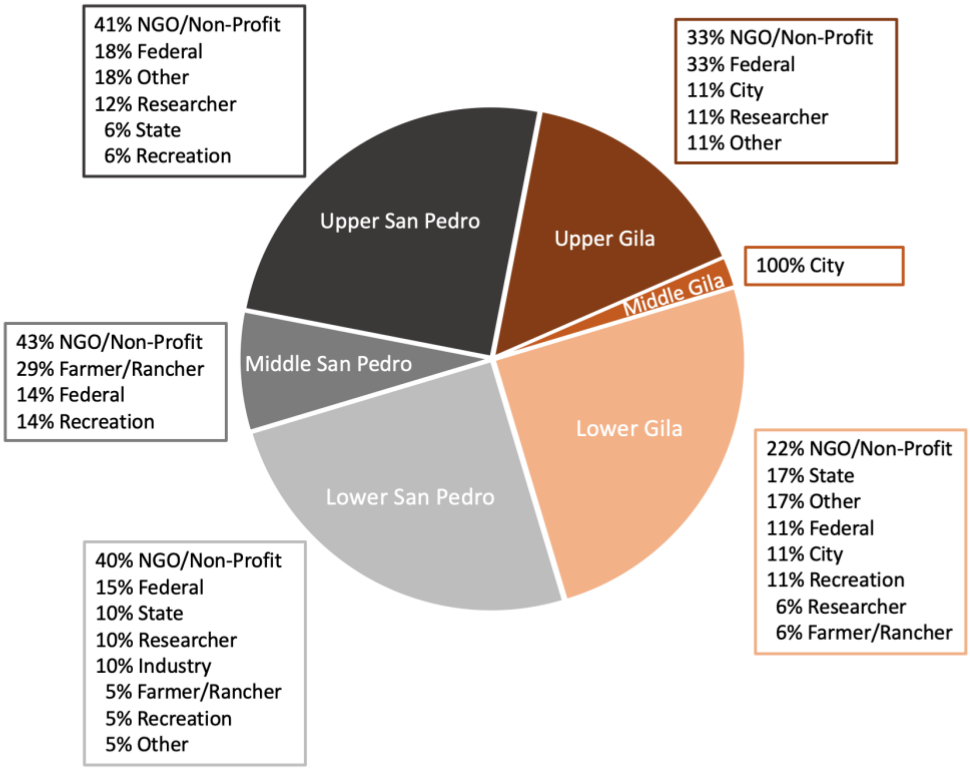

Figure 7. Proportional breakdown of survey respondents by geographical river section and associated professional affiliation by percent, N=56. Gila River is denoted by shades of orange, and the San Pedro River is denoted by shades of gray.

For both rivers, a majority of respondents (71%) identified water quantity factors as their primary concern, of which instream flows, ecosystem water-stress, and groundwater were the most common responses. Specifically, instream flow was disproportionately identified as the primary concern in the Upper San Pedro, Lower San Pedro, and Lower Gila Rivers (Figure 8). Instream flow was also identified as a primary concern by nearly every user group with the exception of city professionals (Figure 9). Of the nine different professional categories, concerns regarding instream flow, ecosystem water-stress, groundwater, and vegetation were shared by ≥5 stakeholder groups, indicating potential for future collaboration (Figure 9).

Only 37% of respondents stated that their community/organization had a climate adaptation plan, of which the majority of plans (62%) focused on water quantity issues. Climate adaptation plans were most common in the Upper Gila (60% of respondents), Lower Gila (86%), and Upper San Pedro (71%). Of those that did not have a plan, 75% acknowledged they needed one. Ninety-six percent of respondents indicated that climate projections would be directly beneficial to them and that this information would primarily help restoration efforts (23% of total respondents). For example, one individual working in the Upper Gila River stated that this information would "provide a better understanding of changes to [native] fish communities... [such as] how climate change might impact the current balance of fish communities as a result of changing flow patterns and temperature," and an individual in the Lower San Pedro River stated that it "would help define native planting palettes… to survive changing climate conditions in the future."

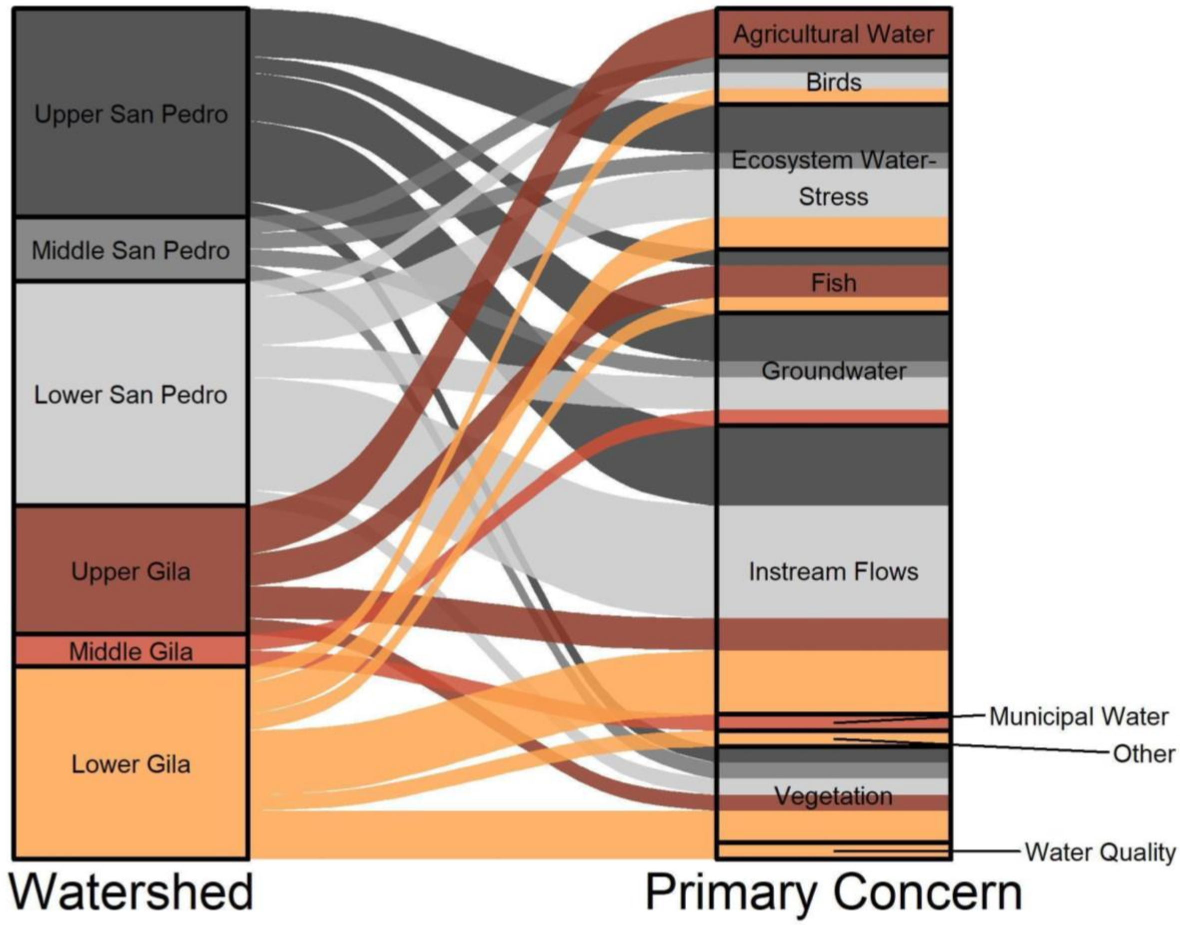

Figure 8. Sankey plot linking the survey respondents by geographic river section on the left with their primary concern about the river on the right. The width of the columns is proportional to the number of respondents and their responses, n=52.

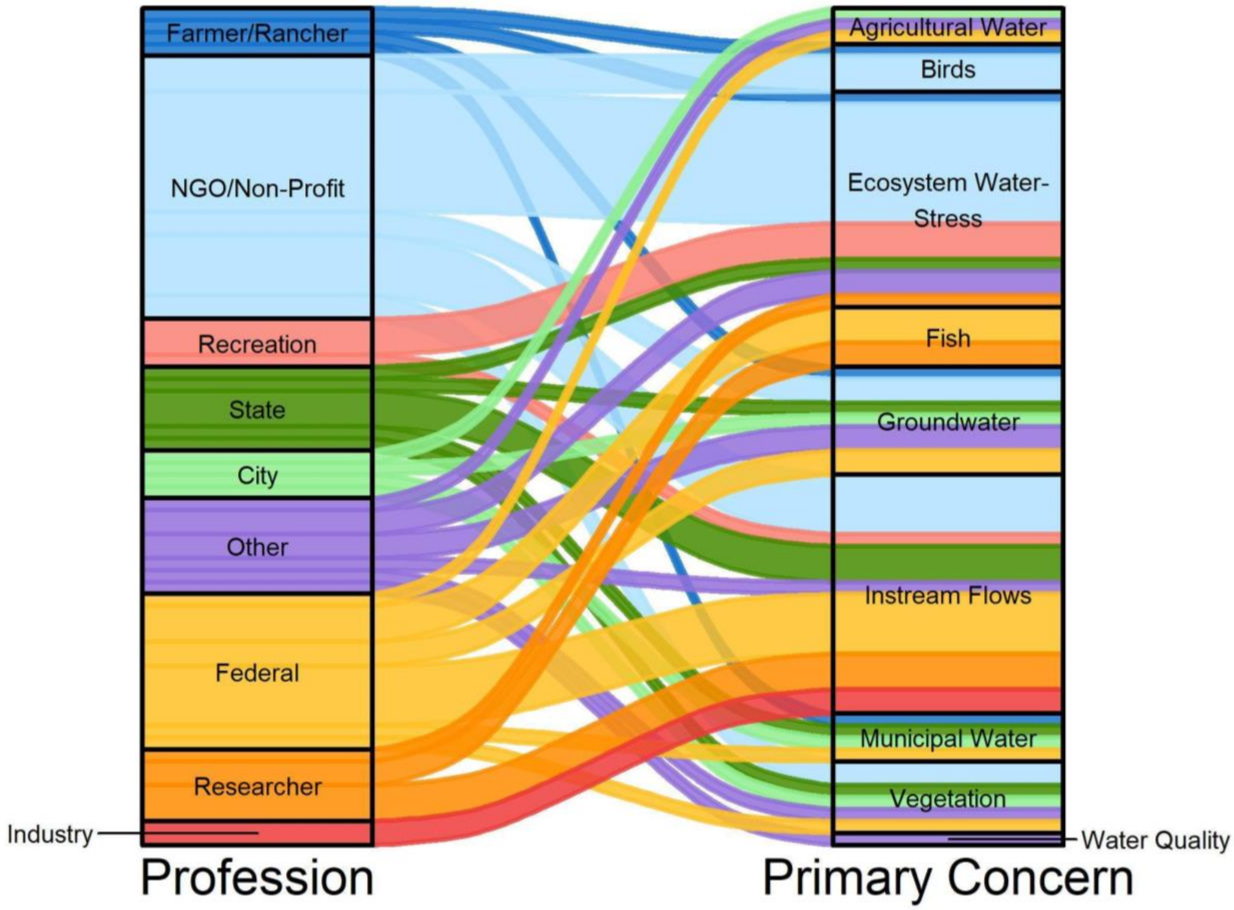

Figure 9: Sankey plot linking survey respondent profession on the left with their primary concern about the river on the right. The width of the columns is proportional to the number of respondents and their responses, n=70 (note: some respondents worked for multiple organizations, so the number of professions represented here is greater than the number of survey participants).

One crucial aspect of climate adaptation planning and restoration is collaboration with other stakeholders. Ninety-eight percent of respondents stated that collaboration is important to their community/organization, and 69% indicated that they have collaborated with other groups in the past. The Upper and Lower San Pedro River were disproportionately represented: 70 and 75% of respondents from these sections had collaborated with others. Of all respondents who had not engaged in collaboration, resource limitations (such as funding, time, and staff capacity) were the most common explanation. When asked about what helped make the collaborations successful, common goals (41%) and facilitation (22%) were the most common responses, with one individual from the Lower San Pedro River noting that "identifying common ground, transparency, and neutral facilitation" were important. Further reinforcing this finding, when asked to identify challenges and barriers to collaboration, the most common response was problems resulting from different priorities (43%). Describing their own experience, one respondent from the Lower San Pedro River noted that groups "were too narrowly focused on their interests alone and expressed little interest in recognizing other important uses of the river."

4.3 Climate Modeling

Under the RCP8.5 higher emissions scenario, the 31-ensemble member model simulations unanimously project that temperature will increase significantly by the end of the 21st century. In each of the Upper Gila, Middle Gila, and San Pedro subwatersheds, the average increase in monthly mean temperature is projected to be approximately 4°F during winter and 5.5°F during the summer between 2036-2065. By the end of the century, these average seasonal increases rise to 7°F and 9.5°F, respectively. These end of-century levels exceed the largest historical temperature anomalies during the months of September and October.

Model simulations from the RCP4.5 lower emissions scenario project that temperatures will still increase substantially by the end of the century, though less than in the RCP 8.5 scenario. The average increase in monthly mean temperature for both the Upper Gila and San Pedro watersheds by mid-century (2036-2065) is projected to be approximately 3.5°F during winter and 4.5°F during the summer. By the end of the century, these seasonal increases rise to 4.5°F and 5.5°F, respectively, also exceed the largest historical temperature anomalies seen during the months of September and October.

Although much of the Gila River watershed is an arid lowland desert, the snowpack that exists in the headwaters of the Upper Gila is projected to decrease substantially as a result of rising temperatures. Under the RCP8.5 scenario, annual peak snow water equivalent (SWE), a measure of how much water is contained in the snowpack, is projected to decrease nearly 3-fold between the historical period and the middle of the century, and 5-fold into the later part of the century. Though these reductions are smaller under RCP4.5 conditions, they are still severe; projected mid- and late-century snowpack decreases are 2.2 and 2.6-fold, respectively. The timing of peak SWE, which determines the timing of the spring snowmelt and associated streamflow, is also projected to shift significantly, from a historical peak around February-March to a future peak around January. To exacerbate matters, increasing temperatures and declining snowpacks are projected to occur contemporaneously with decreased precipitation (both rain and snow) throughout winter and spring (Collins et al. 2013), although the degree of certainty associated with the precipitation change is low compared to the certainty associated with temperature and SWE changes.

Unsurprisingly, increases in temperatures and decreases in snowpack are manifested in the hydrograph of the Upper Gila River (Figure 10). Our modeling experiments project a decrease of monthly total streamflow during April and May, with more than 80% of the climate models in agreement. By late century, under RCP8.5, springtime March-May flows are projected to decrease by 37% (23%, RCP4.5) with respect to the historical period, with April and May flows decreasing up to 60% (50%, RCP4.5). As compared to the historical means, other trends in the hydrograph are less certain. For example, although the multi-model mean streamflow for the fall and winter suggests an increase from the historical baseline, these increases are not consistently projected across the 31-member ensemble, suggesting greater uncertainty. Uncertainty in projected winter and fall precipitation and streamflow leads us to conclude that there is no statistically significant trend in total annual streamflow in the Upper Gila basin, but rather a statistically significant shift in the timing of streamflow, where peak flows might occur 1-2 months earlier in the year. Notably, however, our modeling experiment suggests that the average year-to-year variability will increase compared to the historical period of 1950-2005. Accompanying figures for temperature and precipitation can be found in *Appendix E*.

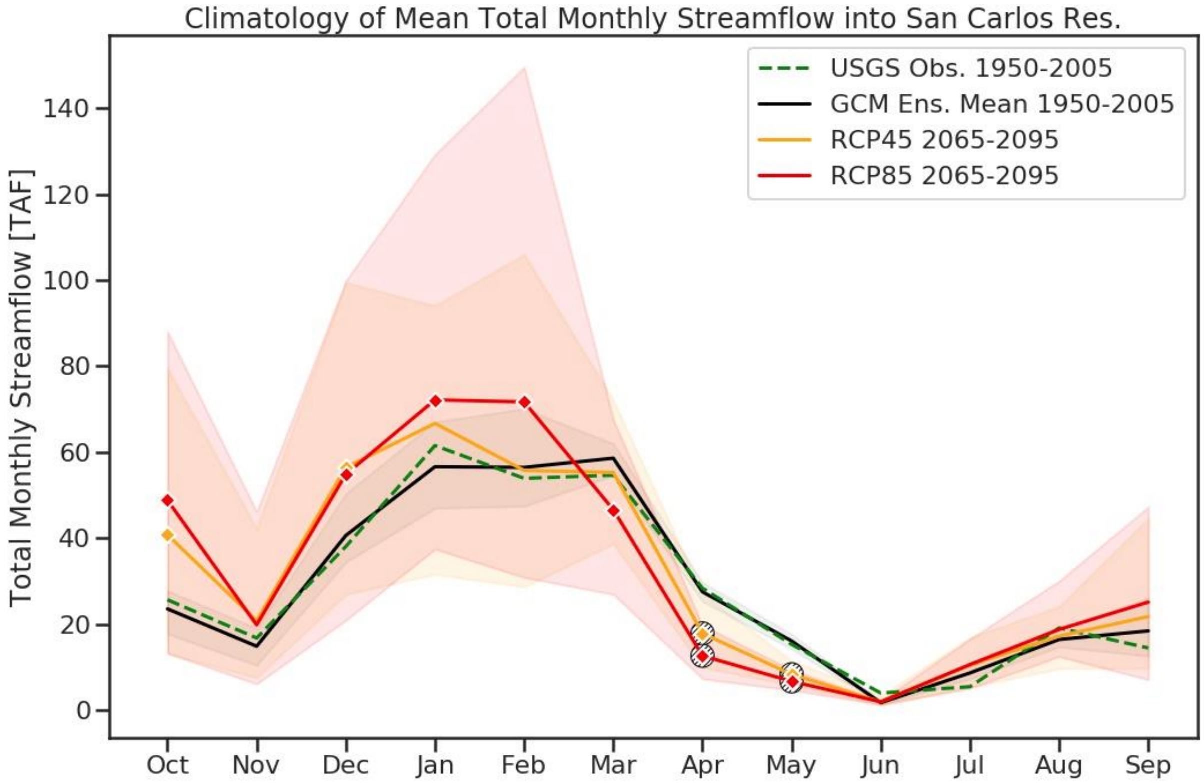

Figure 10. Climatology of the mean monthly total streamflow into the San Carlos Reservoir (Upper Gila and San Carlos rivers). Historical observations from USGS gages are shown in dashed green. The 31-ensemble mean monthly total streamflows are shown in solid lines, with the modeled historical period (black; "GCM Ens. Mean 1950-2005"), and end-of-century (2065-2095) model projections for both the RCP4.5 (orange; "RCP45 2065-2095") and RCP8.5 (red; "RCP85 2065-2095") emission scenarios. Color-coordinated shading around the ensemble mean represents the spread of monthly mean values for individual climate models and corresponds to the 10th-90th percentile of the 31-member ensemble distribution. The statistical significance of the projected changes are depicted through color-coordinated symbols on each line: diamonds mark the high-magnitude anomalies (>2 standard deviations from the historical mean) and the most robust of these anomalies, where more than 80% of climate models agree on the sign of the change, are further depicted with a hatched white circle.

5. Conclusions

Overall, our investigation suggests that stakeholders within the Gila and San Pedro River basins share a concern for issues related to water quantity, a common desire to solve identified problems via management, and a similarly high valuation of collaboration, despite some concerns of competing goals and strategies between surveyed stakeholders. Results from both the literature review and stakeholder survey indicate 'water quantity' is a top concern across the river basins, specifically instream flow and water supply. While stakeholder documents reflected the commitment to 'water management' and 'alteration and restoration', we found comparatively less explicit consideration of climate change: only 37% of survey respondents indicated they have a climate adaptation plan in place. Although the prevalence of such plans varied across the basin, nearly all survey respondents indicated climate projections would be directly beneficial to their planning. We found strong seasonal changes in the hydrograph of the Upper Gila, with spring flows projected to decrease by 37% of historical values near the end of the century; projected flow changes are likely due to increasing temperatures driving decreased snowpack. Although there is no significant trend in total annual flows, interannual (year to year) flow variability is projected to increase. Community-based resource management can enhance the resiliency of communities and ecosystems alike (Tompkins and Adger 2004), and research shows that local planning efforts are better informed by local data. Contextualizing climate change information with direct knowledge of stakeholder and rights-holder priorities will give local communities previously unavailable data to better inform climate adaptation plans.

While collaboration is important to many of these communities and organizations, some survey respondents thought that their goals and strategies differed significantly, and they perceived limited commonality. However, our survey results indicate that common concerns do exist across a diversity of user groups. Additionally, despite most respondents indicating they believe collaboration is important, an analysis of the existing stakeholder documents revealed limited formal codification of collaboration as an explicit solution to specific concerns, and relatively little collaboration among the entities we surveyed has included Tribal groups. We recommend that future collaborative efforts in the Gila and San Pedro Rivers strive to include Tribes, such as GRIC. Furthermore, as identified by responses in our survey, use of neutral facilitators should dramatically increase collaborative success, by facilitating the identification of common goals shared by a diverse network of river users. Our analysis of existing climate planning documents and survey of stake- and rights-holders within these basins has highlighted areas of mutual agreement, which can be used to facilitate future collaborations that would support the long-term success of a diverse river community.

6. Acknowledgements

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Appendices

Appendix A

Table A1. A table of the 59 stakeholder documents including key white, grey, and peer-reviewed literature pertaining to stakeholder climate adaptation strategies in the Gila and San Pedro Basins used in the literature review.

Organization/Agency	Title	Year
Arizona Department of Emergency and Military Affairs	State of Arizona Hazard Mitigation Plan	2018
Arizona Department of Environmental Quality	Gila River - Centennial Wash to Gillespie Dam	2015
Arizona Department of Water Resources	Arizona Drought Preparedness Plan	2018
Arizona Department of Water Resources	Arizona Drought Preparedness Annual Report	2018
Arizona Town Hall	Keeping Arizona's Water Glass Full	2015
Arizona-Sonora Desert Museum	Sonorensis	2018
Bureau of Land Management	San Pedro Riparian National Conservation Area Analysis of the Management Situation Report	2017
Bureau of Reclamation	New Mexico Unit of the Central Arizona Project Draft Environmental Impact Statement Volume 1	2020
City of Sierra Vista	Vista 2030: Sierra Vista General Plan	2014
Coalition of organizations	Green Budget 2013	2012
Coalition of organizations	Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change, Southwest	2000
Coalition of organizations	San Pedro Conference Proceedings	1999
Coalition of organizations	Southline Transmission Line Project: Final Environmental Impact Statement	2015
Colorado College State of the Rockies Project	State of the Rockies Report Inclusive River Governance for a Changing West	2017
Defenders of Wildlife	Losing Our Heritage: Budget Cut Impacts and Our Environment, Green Budget 2014	2014
Department of Defense	Proceedings from the Southwest Region Threatened, Endangered, and At-Risk Species Workshop	2007
Department of Game and Fish	State Wildlife Action Plan for New Mexico	2016

Desert Landscape Conservation Cooperative	Climate Smart Landscape Conservation Planning and Design Phase I Report	2016
Encourage Capital; Squire Patton Boggs	Liquid Assets: Investing in Impact in the Colorado River Basin	2015
Federal Agencies	Federal Resource Management and Ecosystem Services Guidebook	2016
Fort Huachuca	Integrated Natural Resources Management Plan and Environmental Assessment	2002
Gila Watershed Partnership of Arizona	Upper Gila River Ecological Resiliency Improvement Project	2017
Good Neighbor Environmental Board	Climate change and resilient communities along the U.S.-Mexico border: The role of federal agencies	2016
Good Neighbor Environmental Board	The Environmental, Economic, and Health Status of Water Resources in the U.S.-Mexico Border Region	2012
GRIC; Salt River Project	Arizona's Water Futures: Challenges and Opportunities, 85th Arizona Town Hall	2004
Liverman D, Merideth R, and Holdsworth A	Climate Variability and Social Vulnerability in the U.S.-Mexico Border REgion: An integrated assessment of the water resources of the San Pedro River and Santa Cruz River Basins	1997
National Drought Information System	Drought Preparedness for Tribes in the Four Corners Region Workshop	2010
National Federal Lands Conference	Catron County Comprehensive Land Plan	1992
Pima County	Pima County Multi-Species Conservation Plan Appendices (Final)	2019
Pima County	Drought Management Plan Review: Vulnerability Assessment in Drought Mitigation Report	2014
Pima County	Multi-Jurisdictional Hazard Mitigation PLan	2017
Southwest Native Nations	Southwest Tribal Climate Change Assessment Final Report	2017
State of Arizona	State of Arizona Hazard Mitigation Plan	2013
The Audubon Society	Water and Birds in the Arid West	2017
The Dialogue on Water and Climate	Climate changes the water rules: How water managers can cope with today's climate variability and tomorrow's climate change	2003
The Nature Conservancy	Gila River Flow Needs Assessment	2014
U.S. Customs and Border Protection Dept of Homeland	Programmatic Environmental Assessment Considering Deployment of Unmanned Aerial Vehicles by the Office of	2005

Security	Border Patrol, Customs and Border Protection, in Arizona and New Mexico	
U.S. Department of Agriculture	Riparian Research and Management: Past, Present, Future: Volume 1	2018
U.S. Department of Agriculture	Riparian Research and Management: Past, Present, Future Volume 2	2020
U.S. Department of Agriculture	Vulnerability of Species to Climate Change in the Southwest: Threatened, Endangered, and At-Risk Species at Fort Huachuca, Arizona	2013
U.S. Department of Agriculture	Merging Science and Management in a Rapidly Changing World: Biodiversity and Management of the Madrean Archipelago III	2012
U.S. Department of the Interior	Chihuahuan Desert Rapid Ecoregional Assessment	2017
U.S. Department of the Interior Bureau of Reclamation	San Carlos Irrigation Project Facilities Phase 2 Rehabilitation, Reaches 1–3	2017
U.S. Environmental Protection Agency	Climate Change Impacts in the Southeastern United States	2010
U.S. Fish and Wildlife Service	Southwestern Willow Flycatcher Final Recovery Plan/Five Year Report	002/201
U.S. Fish and Wildlife Service	Biological and Conference Opinion Letter to Fort Huachuca Colonel McFarland	2014
U.S. Fish and Wildlife Service	(Corrected) Programmatic Biological Assessment for Ongoing and Future Military Operations and Activities at Fort Huachuca, Arizona (PBA)	2014
U.S. Fish and Wildlife Service	Endangered and Threatened Wildlife and Plants; Threatened Status for the Northern Mexican Gartersnake and Narrow-Headed Gartersnake; Final Rule	2014
U.S. Fish and Wildlife Service	Endangered and Threatened Wildlife and Plants; 12-month Finding of a Petition to List a Distinct Segment of the Roundtail Chub (Gila robusta) in the Lower Colorado River Basin; Proposed Rule	2009
U.S. Geological Survey	Hydrologic requirements of and consumptive ground-water use by riparian vegetation along the San Pedro River, Arizona	2005
U.S. Geological Survey, Mexican state and national commissions	International Conference of Water Scarcity, Global Changes, and Groundwater Management Responses	2008
University of Arizona	Sustainability of Semi-Arid Hydrology and Riparian Areas; Final Report	2010

University of Arizona	Weather, Climate, and Rural Arizona: Insights and Assessment Strategies	2012
University of Arizona Water Resources Research Center	Upper Gila River Watershed Assessment	2018
University of Arizona Water Resources Research Center and Northern Arizona University Watershed Ecohydrology Program	Desert Flows Assessment	2016
University of Arizona, sponsored by Gila River Indian Community and Salt River Project	Arizona's Water Future: Challenges and Opportunities	2004
Water journal - special issue	Water Governance, Stakeholder Engagement, and Sustainable Water Resources Management	2017
Western States Water Council	Meeting Briefing Materials	2019
Western Water Policy Review Advisory Commission	Aquatic Ecosystems Symposium	1997

Appendix B

Supplemental Figure: Photograph of the lower Gila River near Buckeye, AZ. This portion of the river is supported by treated effluent discharge and agriculture return flows.

Appendix C

Table C1: An expanded table of the thematic codes presented in Tables 2 and 3. These more specific codes were used to identify issues and solutions in the initial review of the documents and then placed under the appropriate "broader" codes that are presented in Tables 2 and 3. Final issue codes were analogous to concerns asked about in the survey (*Appendix D*, question 4); solution codes were created using deductive coding (Saldana 2016).

Artificial Recharge	**Process Based Restoration**	**Water Management**	**Groundwater Management**	**Flow management**
Artificial recharge: effluent	Process-based restoration: beaver reintroduction	Regulation	Pumping/ Use regulation/ management	Instream flow management
Artificial recharge: excess water	Constructed wetland	Water harvesting	Water conservation	Streamflow restoration & management
Artificial recharge: floodwater	Process-based restoration: natural infrastructure	Dam management	Groundwater management	Flow regime-based water management
Artificial recharge: irrigation tailwater	Process-based restoration: levee setback	Effluent re-use	Groundwater pumping	Flow recommendations: species based
Artificial recharge: stormwater	Weather modification	Pond elimination/ management		Flow recommendations: regime based
Stormwater recharge		Impoundment management		Maintain/ increase streamflow permanence
Wastewater recharge		Source-water protection: seeps/springs		Riparian restoration/ management
Groundwater recharge		Conjunctive use: general		Restoration/maintenance of natural flow regime
Artificial water		Water treatment		Return flow management: agriculture

Effluent		Water conservation		Return flow management: stormwater
		Conjunctive use: pump water from mines		Restoration/ maintenance of natural flow regime
		Conjunctive use: groundwater pump to supplement during drought		
Watershed Management + Restoration	**Infrastructure**	**Planning**	**Collaboration**	**Legal action**
Watershed restoration	Reservoir construction	Risk assessment	Partnerships and collaboration	Federal designation
Vegetation restoration	Green infrastructure	Mitigation	Local user association	Water rights
Watershed restoration & management	Green infrastructure: permeable parking lots	Targeted mitigation	Collaborative decision support software	Water permits
Watershed management/ restoration	Green infrastructure: riparian buffers	Watershed planning/ forecasting	Database	Alternative source acquisition
Riparian restoration/ management	Well installation	Water management planning	Centralized data + resources	Land acquisition/ conservation & management
Watershed management/ restoration	Low impact development	Best Management Practices: urban water management	Decision support tool	Landscape conservation/ conservation easements/ land acquisition
Grazing management	Water infrastructure	Managed retreat: residential		Water policy
Geomorphological restoration		Managed retreat: farmland		Policy implementation
Invasive/exotic removal		Crop specialization		Forbearance agreements

Forestry management				Federal designation
Land management				Water leases
				Water marketing
				Water bank: AZ water protection fund
				Environmental water right
				Conservation easements
				Pollution permits
Education + Outreach	**Stakeholder Engagement**	**Research & monitoring**	**Tribal Engagement**	
Education	Stakeholder collaboration, coordination & communication	Research and development	Archeology/ Tribal knowledge	
Program development		Monitoring and reporting	Quantify cultural impacts	

Table C2. Total mentions of each issue and solution code in the reviewed documents, organized by river system

	Total Mentions			Total Mentions	
Issue Code	**Gila River**	**San Pedro River**	**Solution Code**	**Gila River**	**San Pedro River**
Agricultural water supply	1	0	Artificial recharge	10	38
Bird populations	1	8	Collaboration	14	28
Ecosystem water stress	22	35	Education and outreach	5	16
Fish populations	2	9	Flow management	11	27
Groundwater	18	61	Groundwater management	9	26
Instream flow	28	86	Infrastructure	18	10
Municipal water supply	4	0	Legal action	25	55
Other	43	72	Planning	6	23
Socio-cultural uses	11	1	Process-based restoration	6	14
Stream vegetation	24	44	Research and monitoring	12	43
Water quality	4	13	Stakeholder engagement	7	6
Water supply	36	97	Tribal engagement	9	1
			Water management	27	65
			Watershed management and restoration	35	74

Appendix D

Survey

Consent Agreement:

I have read (or someone has read to me) this form, and I am aware that I am being asked to participate in a research study. I have had the opportunity to ask questions and have had them answered to my satisfaction, and I voluntarily agree to participate in this study.

a) Yes
b) No (if No, please discontinue)

I am not giving up any legal rights by agreeing to participate. I will be given a copy of this form upon request.

Survey:

Please respond to this survey in your professional capacity to the best of your ability. The responses to questions 1-4 may be used to show general uses, priorities, and concerns for each river system in a publicly accessible infographic or written summary. For example, responses to questions 2-4 will be presented as work, issues, and concerns general to the river system identified in question 1. Responses to questions 5-14 will only be used to explore general trends in climate adaptation planning and barriers associated with the planning process.

1. In which river system are you primarily involved? (Example: a water rights holder on the Middle Gila, a NGO focused on restoration in the Upper San Pedro, etc.) (Please pick one):

a) Upper Gila River (New Mexico to Coolidge Dam)
b) Middle Gila River (Coolidge Dam to the Salt River)
c) Lower Gila River (Salt River to Colorado River)
d) Upper San Pedro River (Sonora, Mexico to north boundary of San Pedro Riparian NCA)
e) Middle San Pedro River (north boundary of San Pedro Riparian NCA to Soza Wash)
f) Lower San Pedro River (Soza Wash to Gila River)

2. Which of the following most closely aligns with the type of professional work that you do? Select all that apply:

a) Farmer/rancher
b) Non-governmental organization
c) Non-profit organization
d) Researcher
e) Professional
    i) Federal
    ii) State
    iii) Local
f) Outdoor recreation
    i) If so, what focus? _________
g) Industry
h) Other: _______________

3. What is your main use of the river? Select all that apply:

a) Recreation
b) Agriculture
c) Restoration
d) Regulatory
e) Municipal (e.g. drinking water)
f) Socio-cultural uses
g) Industrial (e.g. gravel mining)

h) Other _________

4. What are your main concerns about the river? (Rank top 4 with 1 indicating most important):

___Fish populations
___Stream vegetation (in stream and banks)
___Water quality
___Bird populations
___Instream flows
___Socio-cultural uses
___Groundwater
___Ecosystem water-stress
___Municipal water supply
___Agricultural water supply
___If you believe there is anything we missed that is of importance to you, write below: _______________

5a. Does your community/group have a plan to address changing stream/climate conditions for your river (e.g. Climate Adaptation & Resiliency Plan, Water Conservation Plan, Gila River Flow Needs Assessment Plan, Climate Adaptation Menu)?

a) We have a plan
b) We do not have a plan

5b. If not, do you think your community/group needs one?

a) Yes, we need a plan
b) No, we do not need a plan
c) Unsure
d) NA

6. Would having information about long-term, predicted changes in patterns of streamflow, air temperature, precipitation, etc. be useful for your community/group?

a) Yes
b) No
c) Unsure
d) Other: _______

7. (Open-ended answer) How might long-term predicted changes in patterns of streamflow, air temperature, precipitation, etc., inform climate adaptation planning for your community/group?

NOTE: If you participated in a planning process that might be affected by climate change, or feel that a plan that considers climate change would benefit your group, please continue. If not, please submit survey.

8. In your climate adaptation plan, what objectives are prioritized? (Rank top 4 with 1 indicating most important).

___Fish populations
___Stream vegetation (in stream and banks)
___Water quality
___Bird populations
___Instream flows
___Socio-cultural uses
___Groundwater
___Ecosystem water-stress
___Municipal water supply
___Agricultural water supply
___Concern not mentioned, fill in here: ___________

9. Is collaborating with other stakeholder and rightsholder groups important to your community/organization?

a) Yes
b) No

c) Unsure
d) Other:_______

10. Has your community/group collaborated with other stakeholder groups in achieving your climate adaptation goals in the past?
a) Yes
b) No
c) Unsure
d) Other: _______

11. Does your community/group plan on collaborating with other stakeholder groups in achieving your climate adaptation goals?
a) Yes
b) No
c) Unsure
d) Other:_______

12. (Select all that apply) If not, what is preventing you from collaborating?

a) Funding
b) Staff capacity
c) Time limitations
d) Understanding climate change
e) Plan implementation
f) Knowing who to reach out to/engage with
g) Lack of facilitation
h) Lack of common goals with other groups
i) Other:________

13. (Open-ended answer) If you have worked with other rights- or stakeholder groups, what do you think helped make these collaborations successful?

14. (Open-ended answer) If you have worked with other rights- or stakeholder groups, what do you think created challenges to collaboration?

Thank you for your participation! We really appreciate you taking time to complete this survey.

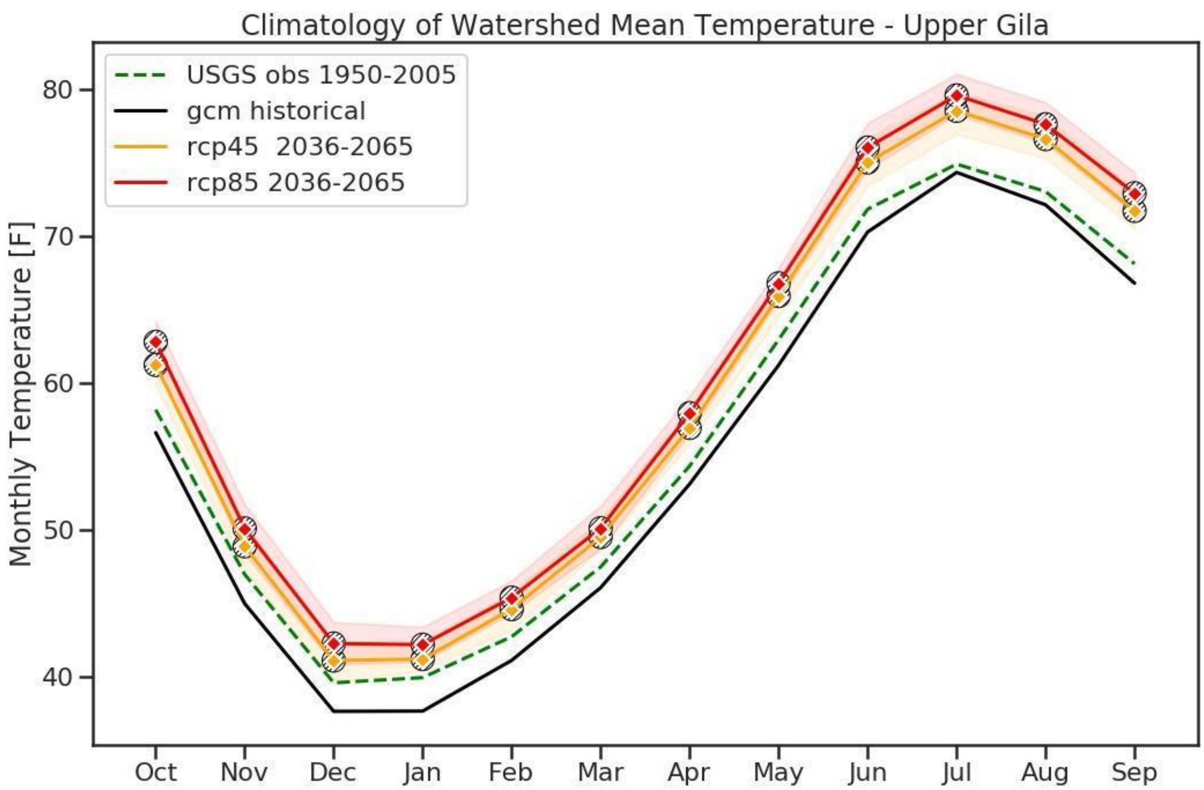
If you work on more than one of the river sections listed in question 1, you are welcome to take this survey again.

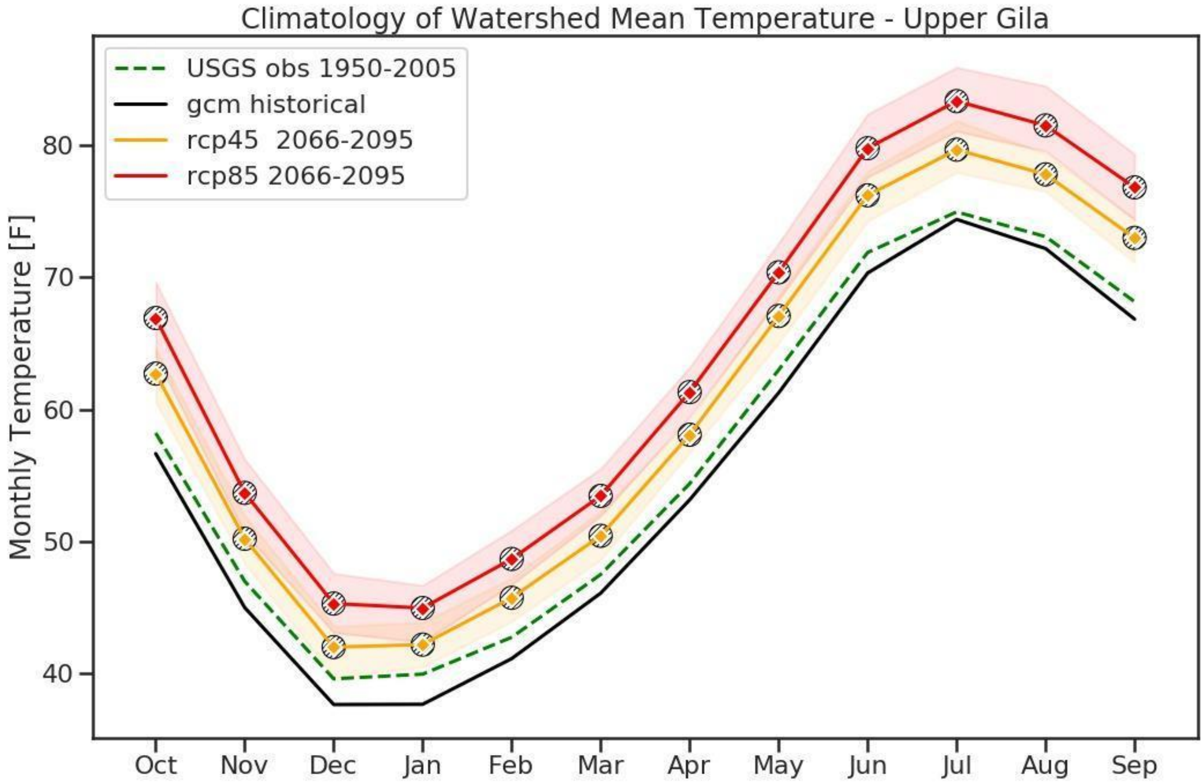
Please contact the survey team if you have any questions, comments, or concerns.

Appendix E

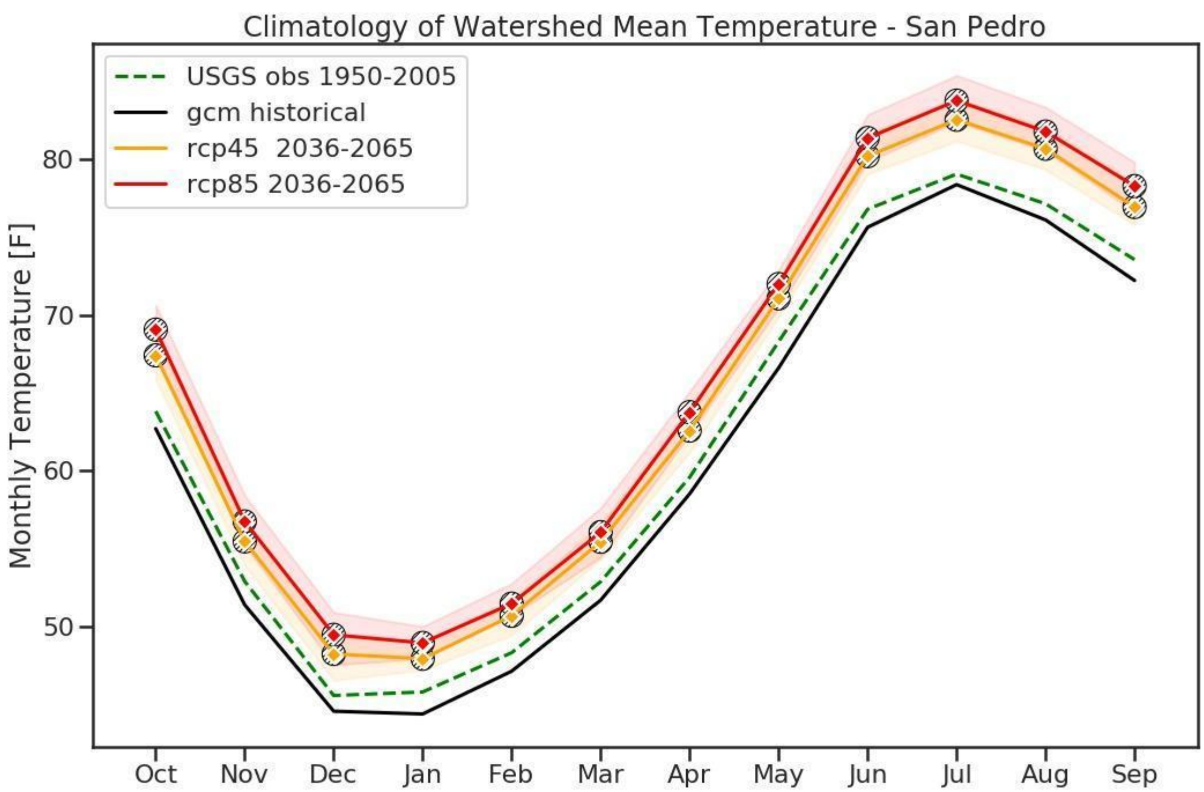
The figures below provide a more detailed overview of hydrometeorological changes beyond streamflow that are driven by global warming. As in Figure 10, the figures are intended to be interpreted in a similar manner (see Fig. E1 caption) and reflect changes in monthly mean variables across the 31 members of the CMIP 5 ensemble.

Figure 10. Climatology of the mean monthly total streamflow into the San Carlos Reservoir (Upper Gila and San Carlos rivers). Historical observations from USGS gages are shown in dashed green. The 31-ensemble mean monthly total streamflows are shown in solid lines, with the modeled historical period (black; "GCM Ens. Mean 1950-2005"), and end-of-century (2065-2095) model projections for both the RCP4.5 (orange; "RCP45 2065-2095") and RCP8.5 (red; "RCP85 2065-2095") emission scenarios. Color-coordinated shading around the ensemble mean represents the spread of monthly mean values for individual climate models and corresponds to the 10th-90th percentile of the 31-member ensemble distribution. The statistical significance of the projected changes are depicted through color-coordinated symbols on each line: diamonds mark the high-magnitude anomalies (>2 standard deviations from the historical mean) and the most robust of these anomalies, where more than 80% of climate models agree on the sign of the change, are further depicted with a hatched white circle.

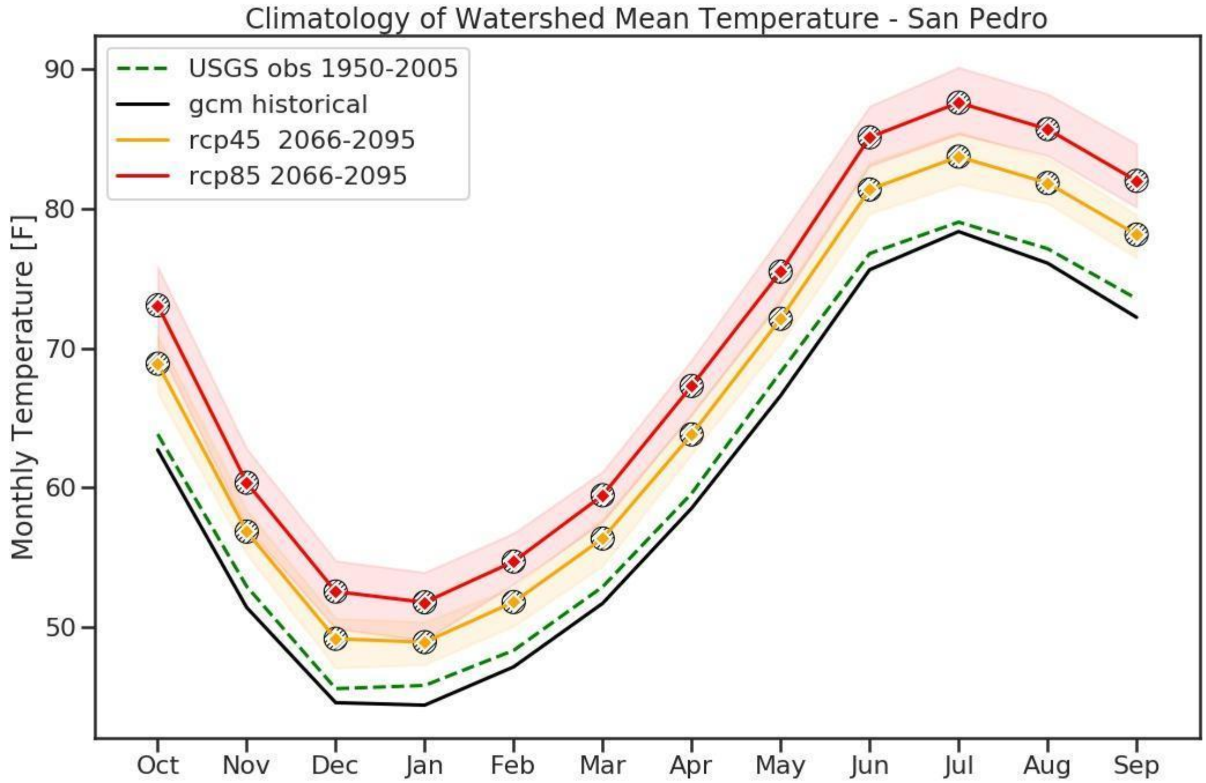




Climatology of Watershed Mean Temperature - Upper Gila
USGS obs 1950-2005
gcm historical
rcp45 2066-2095
rcp85 2066-2095
Monthly Temperature [F]
40
50
60
70
80
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep



Climatology of Watershed Mean Temperature - San Pedro
USGS obs 1950-2005
gcm historical
rcp45 2036-2065
rcp85 2036-2065
Monthly Temperature [F]
50
60
70
80
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep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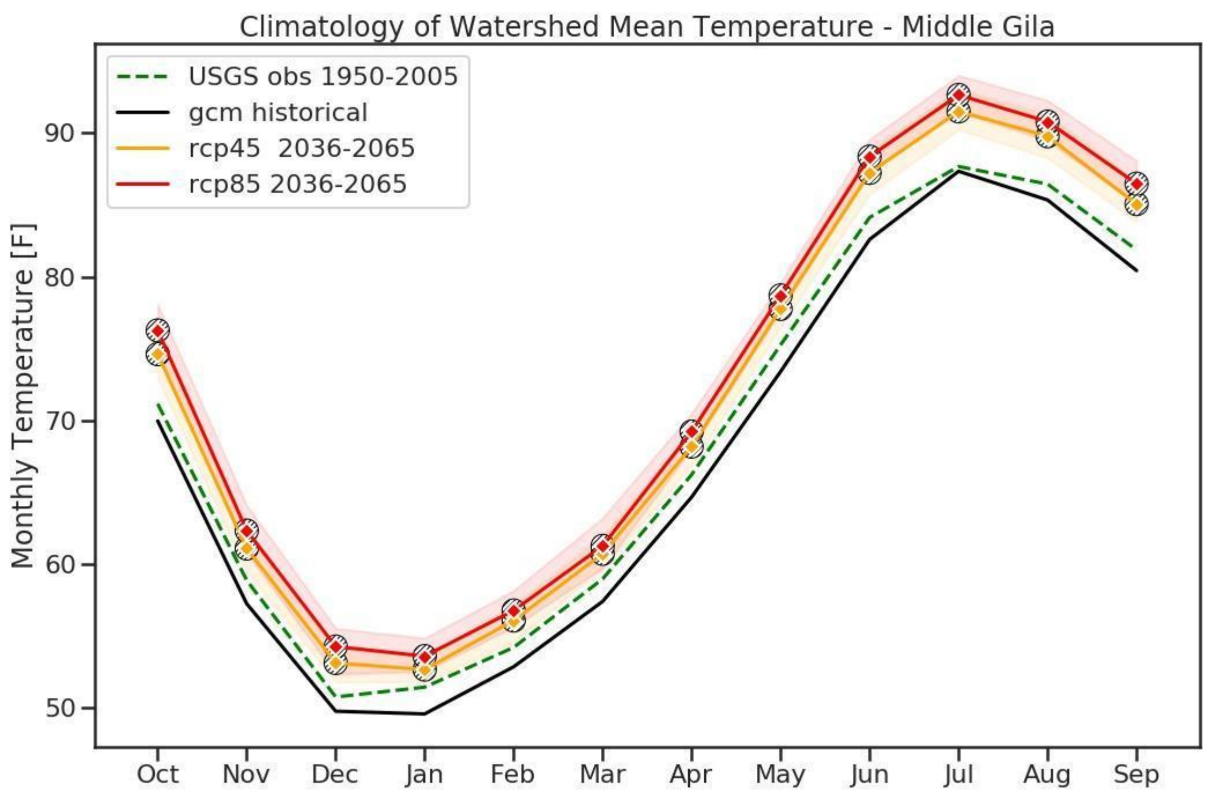
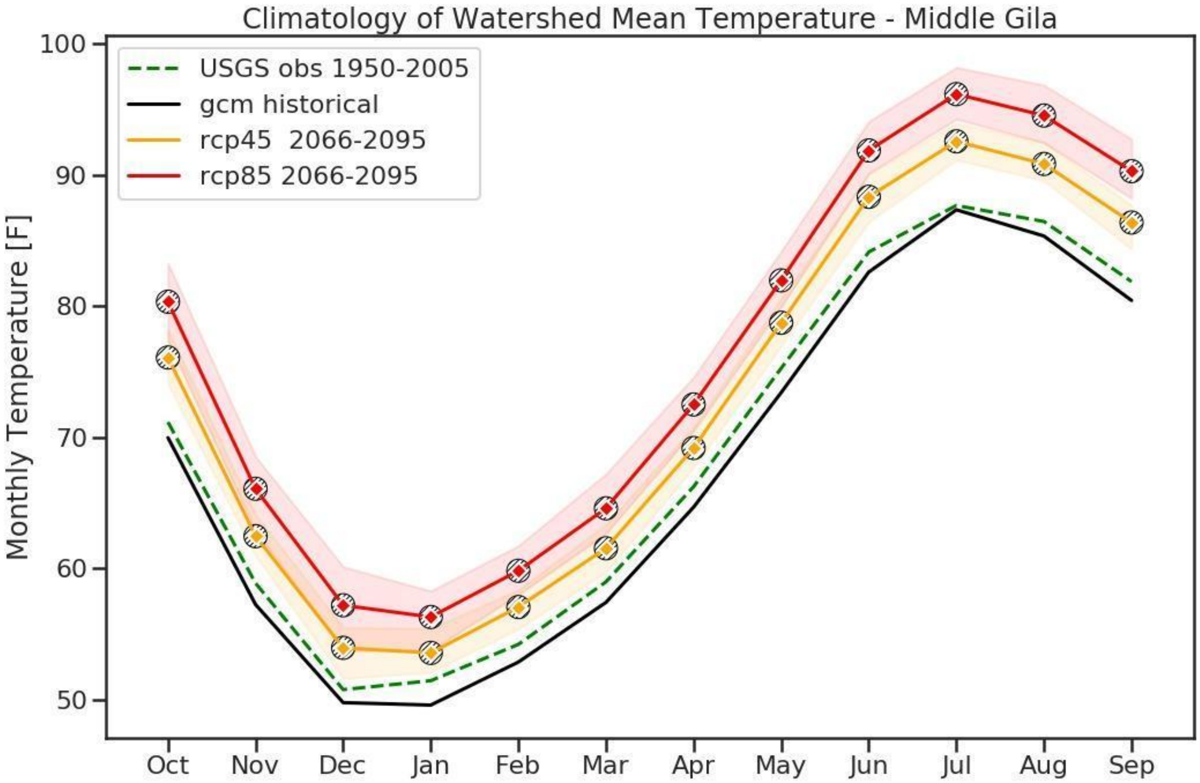
USGS obs 1950-2005
gcm historical
rcp45 2066-2095
rcp85 2066-2095
Monthly Temperature [F]
90
80
70
60
50
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Climatology of Watershed Mean Temperature - Middle Gila
USGS obs 1950-2005
gcm historical
rcp45 2036-2065
rcp85 2036-2065
Monthly Temperature [F]
90
80
70
60
50
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep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USGS obs 1950-2005
gcm historical
rcp45 2066-2095
rcp85 2066-2095
Monthly Temperature [F]
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90
80
70
60
50
Oct
Nov
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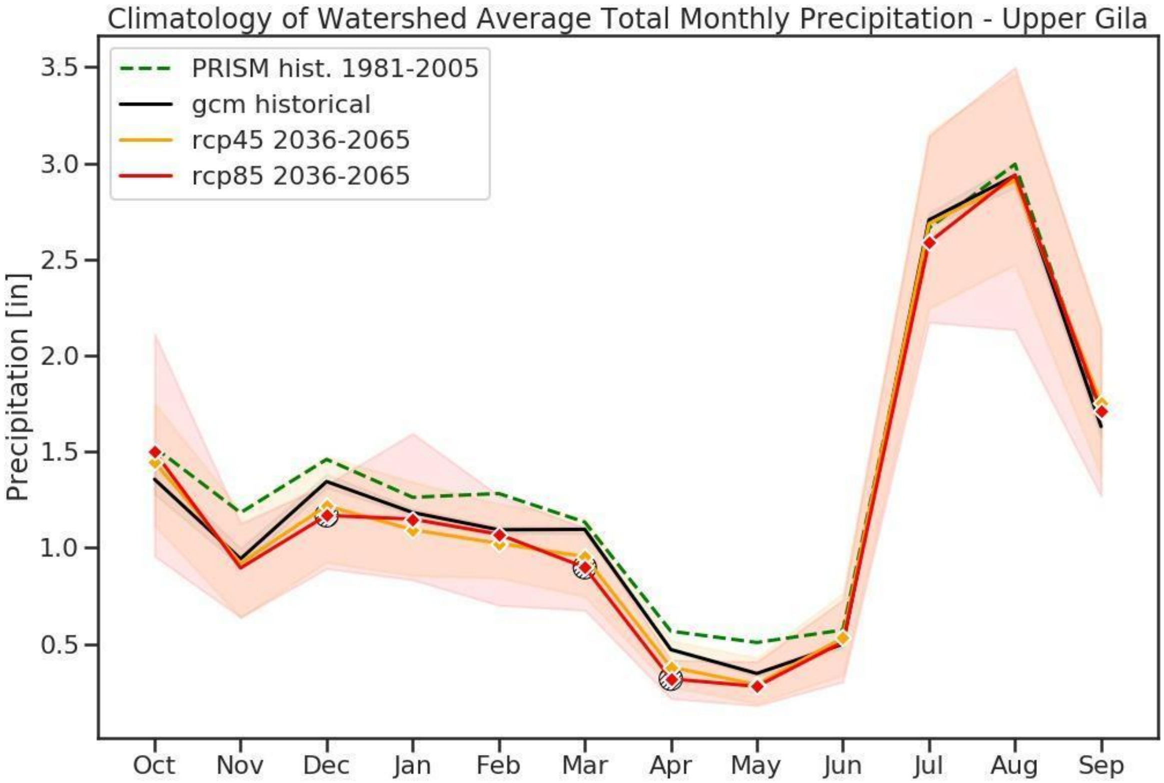
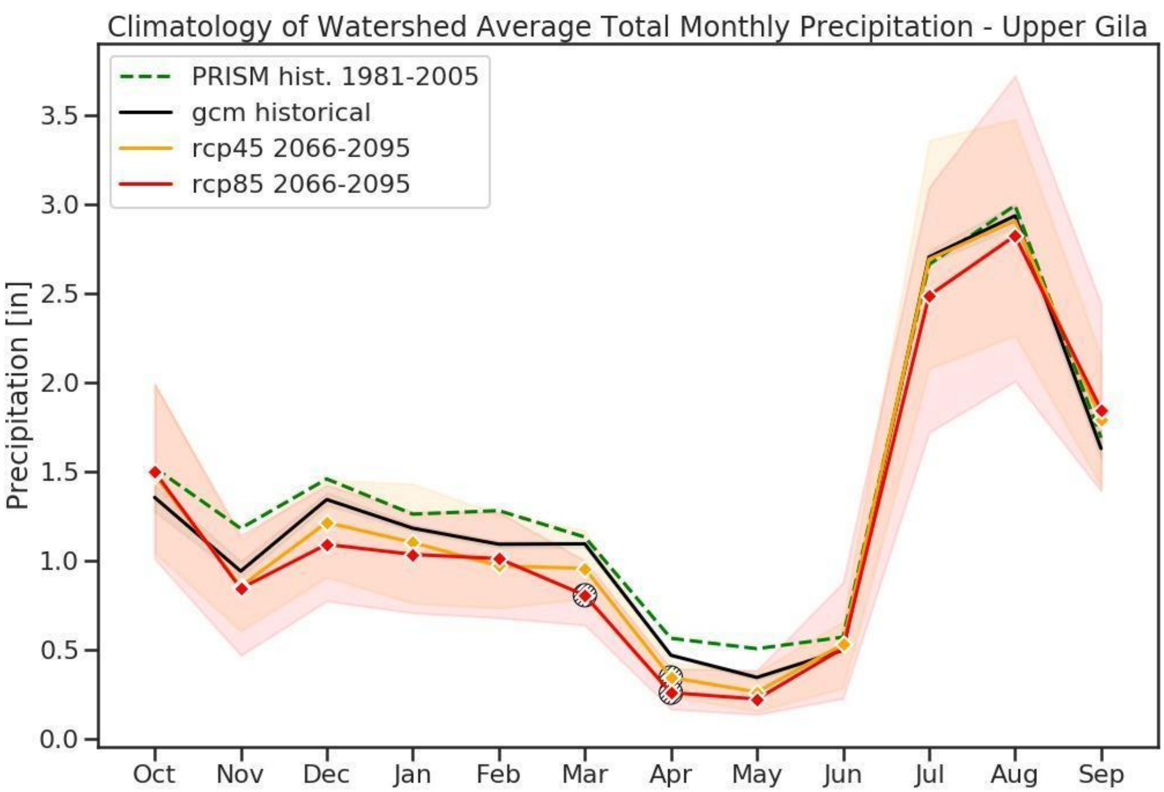
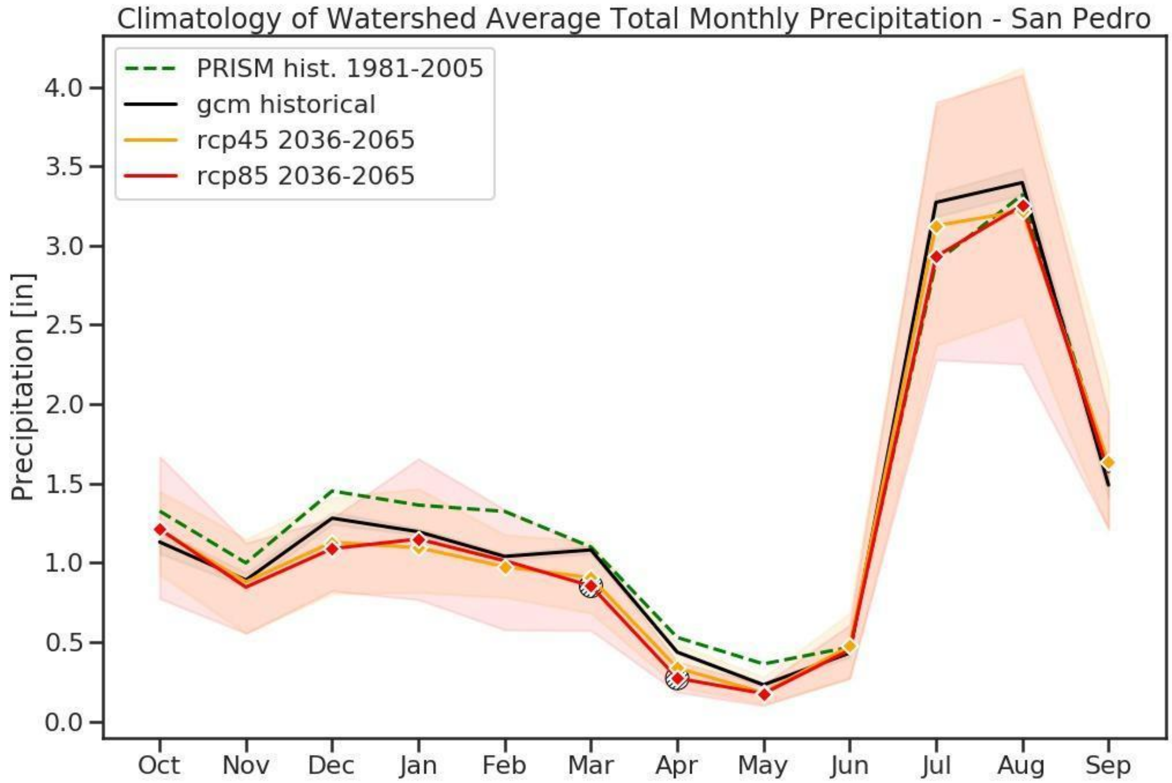
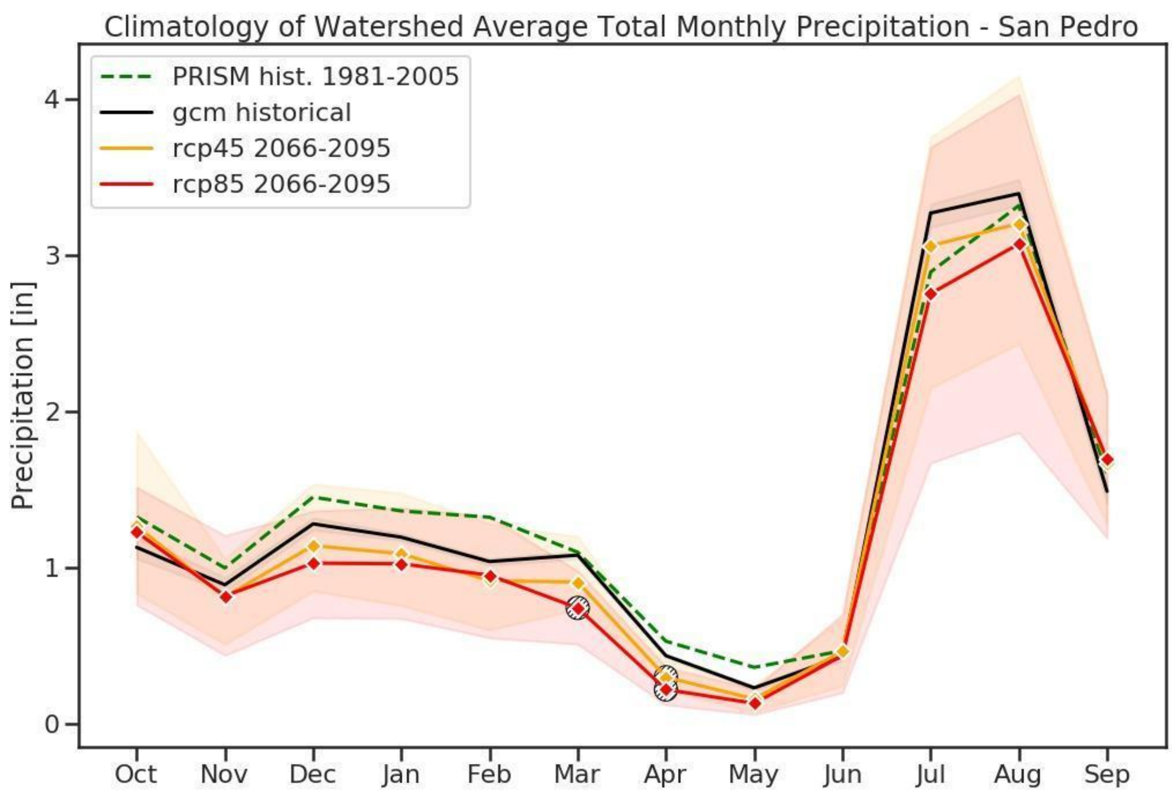
Jul
Aug
Sep


Climatology of Watershed Average Total Monthly Precipitation - Upper Gila
PRISM hist. 1981-2005
gcm historical
rcp45 2036-2065
rcp85 2036-2065
Precipitation [in]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Climatology of Watershed Average Total Monthly Precipitation - Upper Gila
PRISM hist. 1981-2005
gcm historical
rcp45 2066-2095
rcp85 2066-2095
Precipitation [in]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Climatology of Watershed Average Total Monthly Precipitation - San Pedro
PRISM hist. 1981-2005
gcm historical
rcp45 2036-2065
rcp85 2036-2065
Precipitation [in]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Climatology of Watershed Average Total Monthly Precipitation - San Pedro
PRISM hist. 1981-2005
gcm historical
rcp45 2066-2095
rcp85 2066-2095
Precipitation [in]
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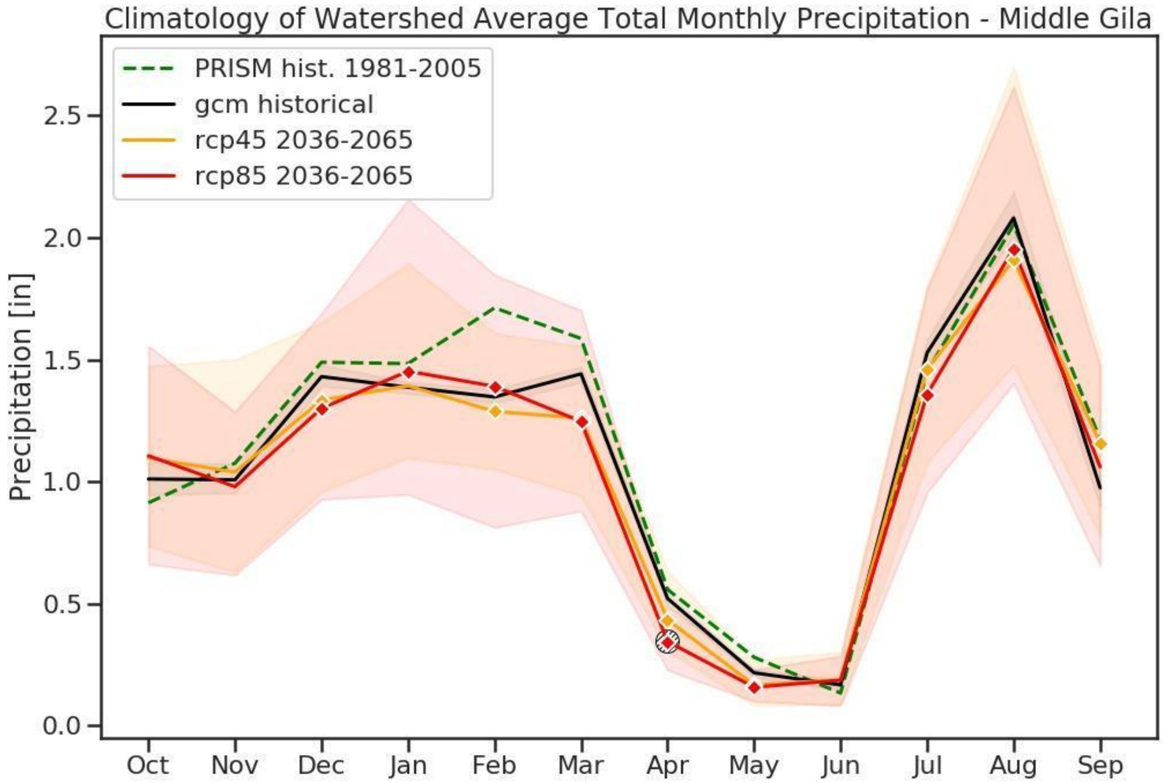
1
2
3
4
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Climatology of Watershed Average Total Monthly Precipitation - Middle Gila
PRISM hist. 1981-2005
gcm historical
rcp45 2036-2065
rcp85 2036-2065
Precipitation [in]
0.0
0.5
1.0
1.5
2.0
2.5
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep