Streamflow Projections for the upper Gila River

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Contents

1. Introduction

This paper discusses two approaches to estimating projected streamflows in the upper Gila River over the next few decades. One approach employs dynamical models of the climate system and surface hydrologic system to calculate projected changes in streamflows. The second approach uses statistics of current observed climate variability to develop an empirical model for use in projecting future flows. This paper follows an earlier document, entitled "Observed and Projected Climate Changes and Their Effects on Snow-fed Rivers in Southwestern North America" (hereafter referred to as the Review Paper), that was submitted to the New Mexico Interstate Stream Commission (ISC) in March 2013. Taken together these papers have been drafted for the purpose of providing guidance to the ISC on projected future flows in the Gila River, for use regarding decisions on water allocations within New Mexico related to the 2004 Arizona Water Settlements Act.

The Gila River has its headwaters in the Gila Wilderness of southwestern New Mexico (Figure 1) and flows in a general westward direction into southern Arizona as a tributary of the Lower Colorado River (Thomson 2012). The Gila River is fed by winter snowpack at high elevations near its headwaters. Summer flows are augmented by warm season season rainfall associated with the North American Monsoon circulation. The Gila River is arguably the southernmost snow-fed river in North America. Future flows on the upper Gila River will be controlled by climatic variability and change in the surface water budget with regard to precipitation (P) in winter and summer, and by temperature-driven variability and change in water losses due to evapotranspiration off the surface (E). On a large scale, climate models project that the surface water budget P-E across the Southwest will tend toward drier conditions (a negative change in P-E) during the 21st Century (Seager et al. 2008), leading to projections of diminished future streamflows in southwestern rivers as described in the Review Paper.

The Review Paper summarized recent research on future flows in the Colorado and Rio Grande basins. Several studies have indicated that annual flows in major southwestern snow-fed rivers could decline by approximately 20% by the end of the 21st Century. Substantial quantitative uncertainties are inherent in this general projection, although there is a very strong consensus that flows are expected to decrease as the result of the significantly warmer temperatures projected to occur in the middle of the North American continent this century. The projected temperature increase is a very robust projection that is generated by all modern climate models in response to much-increased concentrations of greenhouse gases that are currently observed and will inevitably continue to increase for the foreseeable future (IPCC 2007; Karl et al. 2009). Precipitation projections across the Southwest are considerably less robust (Gutzler and Robbins 2011; Cook and Seager 2013), but the possibility of diminished precipitation plays a secondary role to the effect of increasing temperature on projections of diminished future streamflow (Hurd and Coonrod 2008, 2012). Additional uncertainty due to the interannual and decadal variability of precipitation, which will be emphasize in this report, has received very little attention to date in studies of century-scale climate change.

Section 2 of this paper reviews historical flows on the upper Gila River, including means, variability and trends in the data record. We have chosen to focus on the flow record at the Gila gage (USGS gage number 09430500). We also review historical climatic variability of temperature and precipitation in southwestern New Mexico.

Downscaled climate change projections generated by dynamical models have recently been applied to the watershed of the upper Gila River. Section 3 assesses a new set of such streamflow projections generated by the Bureau of Reclamation as part of its West Wide Water Assessment projection (Reclamation 2011a, 2011b). We analyze runoff at the location of the Gila gage yielded by these projections, and assess the quality and possible limitations of these dynamical projections. We consider the Reclamation projections to represent the current state of the art in dynamical streamflow projections of western rivers.

Section 4 then develops an empirical projection of flow at the Gila gage. Average temperature in the upper Gila basin is projected to increase significantly in coming decades, and may depart altogether from the historical envelope of variability in the instrumental record by mid-century. The magnitude of streamflow change driven largely by this projected temperature change can be estimated by statistical analysis of the effects of temperature changes on streamflow in the current climate, taken together with projections of precipitation variability and change.

The results in Sections 3 and 4 represent distinct and complementary ways to estimate projected streamflow change in the upper Gila River. Each approach -- one derived from dynamical models, the other from statistical extrapolation using observed data -- includes considerably uncertainty. However we will show that these two approaches yield similar estimates of change for the period 2021-2050 in the upper Gila River, which bolsters confidence that either approach yields reasonable and actionable projections.

Principal conclusions are then summarized in Section 5. We include both an estimate of average future flows, and -- importantly -- place the projected change into context of natural variability. The projection of estimated change, and its magnitude relative to decadal and interannual variability, are offered as an element of water management planning for the upper Gila River in New Mexico.

2. Historical streamflow at the Gila River Gila gage

To set projected flows into historical context, we first review the observed seasonal and interannual record of streamflow on the upper Gila River. This paper will focus on observed and projected flows at the Gila gage (USGS gage 09430500) on the upper Gila River. The location of the Gila gage is shown by a red square in Figure 1. Annual average (mean) flow at the Gila gage for the entire period of record, Water Years 1929-2012, is 155.6 cubic feet per second (cfs), or 113×10^3 acre-feet per year (113 kaf/yr).

The 82-year average (median) flow for each calendar day in this record is shown as the thick black line in Figure 2. Flows average about 60 cfs from October through December, then increase to about 100 cfs by the end of February. The Spring season snowmelt runoff peak occurs in March and April, when the median flow peaks near 200 cfs. Flows then steadily decrease to less than 50 cfs by the end of June. A secondary peak in the seasonal hydrograph of median flows, about 80 cfs, occurs near the end of the Water Year in August-September, as rainfall associated with the summer monsoon replenishes flow in the upper Gila River.

The shape of the seasonal hydrograph at the Gila gage is quite robust in the historical record. Median flows based on just the first half (WY 1929-1970) and second half (WY

1971-2012) of the observed record are shown in Figure 2 as thin green and red lines, respectively. Low flow periods in the hydrograph, in October-November and June-early July, are nearly the same in both halves of the data record. However the median flows during higher flow periods (December-March, April-May, and late July-August) are greater in the latter half of the record. Annual average (mean) flow for the 1929-1970 period is 128 cfs, and for the following 1971-2012 period is 183 cfs, a fluctuation of ±18% about the 82-year average. It is worth noting that this change could be considered a statistically significant long-term increasing trend, if we had no other information to suggest that flows have exhibited multi-decadal natural variability associated with precipitation fluctuations for a much longer period of time.

In addition to seasonal variability, the Gila River exhibits extensive interannual and decadal variability. The time series of the entire observed record of flow at the Gila gage, with annual values calculated over Water Years (Oct-Sept), is shown in the top panel of Figure 3. As indicated in Figure 2, the second half of the data record has a considerably higher average flow than the first half. Notable decade-scale low-flow periods include the 1950s-1960s, and the years around the turn of the 21st Century. The interannual and decadal fluctuations are most evident in terms of high flow years (the peaks in the time series in the top panel of Figure 3). These are higher during decades of high flow, e.g. the cluster of years with annual flow exceeding 250 kaf in the 1980s and 1990s. Low flow years exhibit little trend: low flow years in the annual average time series tend to reach a minimum value of about 50 kaf/yr throughout the data record.

Most of the interannual and decadal variability in flow at the Gila gage is contained within the winter and spring months. The peaks in annual flow (high flow years) correspond to peaks in Dec-Jun flow, shown in the middle panel of Fig. 3. The spring seasonal maximum in streamflow occurs despite the observation that local precipitation peaks in the summer, not the winter, in southwestern New Mexico (Gutzler 2012).

In Sections 3 and 4, we will develop projections for future flows at the Gila gage that focus on Dec-Jun condtions, and emphasize changes in median flows. The statistics of median flows are less affected by relatively infrequent very high-flow years, and represent a more stable metric of average flow than the mean. Median observed flow at the Gila gage for 1951-2012, averaged from December through June, is 56 kaf/yr.

Summer season flows (bottom panel) are much smaller than cold season flows in all but a few years, consistent with the average hydrographs in Fig. 2. Recent years have exhibited higher summer flow variability, and several of the major peaks in summer flow (1988, 2006) follow low flow seasons in the Dec-Jun time series (Gutzler 2000).

A considerable fraction of interannual variance in streamflow is associated with shifts in the winter large-scale atmospheric storm track, forced by fluctuations of equatorial Pacific Ocean temperature (Molles and Dahm 1990; Seager et al. 2005). Winters in which equatorial Pacific Ocean temperature is anomalously warm (El Niño) tend to feature a southward-displaced storm track, yielding higher than average snowpack and high March-April streamflow when the snow melts. Winters in which equatorial Pacific temperature is cold (La Niña) tend to lead to negative snowpack and streamflow anomalies.

Recent research indicates that ocean temperature anomalies in both the Pacific (Gershunov and Barnett 1998; Gutzler et al. 2002) and the Atlantic (McCabe et al. 2004) are largely responsible for the pronounced decadal fluctuations of cold season precipitation variability observed in data from southwestern North America. The Pacific was cold and the Atlantic was warm during the 1950s and 1960s, leading to drought conditions across the southern United States; Pacific Ocean temperatures flipped in the 1970s and the Southwest was relatively very wet for several decades thereafter. The Pacific Decadal Oscillation appears to have flipped again around the turn of the 21st Century, leading to a return of lower cold season precipitation conditions that continue to the present day (Fig. 3, top and middle panels).

The high amplitude of variability observed in the instrumental record of precipitation and streamflow is almost certainly just the most recent expression of natural interannual/ decadal variability in southwestern climate. Recent reconstructions of streamflow on the Gila River just downstream from the Gila gage (Figure 4) generated by the Treeflow project (Meko et al. 2010; Woodhouse et al. 2012) suggest decadal variations on the order of ±30%, between low flows of ~250 kaf/yr in decadally-filtered data to high flow conditions of nearly 500 kaf/yr (Figure 4, bottom panel). On a percentage basis, this level of natural decadal variability is somewhat higher than the larger southwestern rivers discussed in the Review Paper, which tend to exhibit decadal fluctuations on the order of ±20%.

Within the Spring season the timing of flow at the Gila gage has changed over the historical period of record. The Center of Timing (CT) based on daily flows represents the day at which half the total flow during a specific period of time passes a measurement point (Stewart et al. 2004). We have calculated the CT of Gila gage flow for each Water Year for the December-June period (Figure 5). Considering just the December-June peak flow period, instead of the entire Water Year as is customarily done in other studies, removes the effect of strong or weak monsoon flows on the calculation so that the CT more clearly represents variability in snowmelt season streamflow timing at the Gila gage. The CT exhibits considerable year-to-year variability, but the 11-year running average in Figure 5 shows that CT at the Gila gage now occurs around day 153 of the Water Year, in the first week of March. This is two weeks earlier than the 11-year running average value of CT at the beginning of the data record in the 1930s.

The causes of the increase in flow and shift toward earlier CT at the Gila gage can be understood by examining the observed climatic variability of temperature and precipitation in southwestern New Mexico (Figure 6). The time series in Fig. 6 are derived from monthly data averaged over New Mexico Climate Division 4, the Southwestern Mountains division. This region extends across a much larger area than the drainage basin of the Gila River. However on monthly and longer time scales the spatial scale of weather is large, so Climate Division 4 represents a reasonable index for climatic conditions that affect Gila River streamflow, which we will exploit in Section 4 of this paper to develop a simple statistical model of projected upper Gila River streamflow.

As shown above, snowfed rivers such as the Gila exhibit highest flows, and highest interannual fluctuations in flow, that are closely tied to the winter precipitation that accumulates as snowpack and melts in the Spring season. We focus here on the temperature and precipitation records most relevant to variability and change in streamflow during the peak flow season from December-June. Our analysis of covariability in the historical record shows that the monthly periods that correlate best with peak flow season streamflow are January-April for temperature and November-April for precipitation, although the lag correlations between precipitation and streamflow, or temperature and streamflow, are not too sensitive to this specific choice of cold season months.

Temperature in Jan-Apr in Climate Division 4 has risen by more than 2°F since the 1930s, the start of the modern era of climate divisional data (Figure 6, top panel). Essentially all of the increase in temperature has come after 1970. Decade-average temperatures, shown as the thick red line, have been climbing rather steadily since the 1970s, punctuated by considerable interannual variability that is smoothed out by the 11-year running average. This increase is projected to continue in the coming decades, and is the principal cause of projected declines in average streamflow in the Gila River. However the average annual flow at the Gila gage generally *increased* during the late 20th Century period of warming, relative to the 1951-1980 average.

Precipitation during the cold season exhibits no significant long-term trend since the 1930s (Figure 6, bottom panel). The decades of the 1950s and 1960s were, on average, relatively dry, followed by wet decades in the 1980s and 1990s, and a subsequent decline since then. Interannual variability of precipitation is large relative to any long-term tendency in this record.

As shown in the bottom panel of Figure 7, the observed record (1932-2012) of cold season precipitation in NM4 (summed from November through April each Water Year) is correlated at a level of $r = 0.83$ with subsequent spring season flow at the Gila gage (summed from December through June). Thus about 68% (r^2) of interannual snowmelt-season streamflow variance is accounted for by Nov-Apr precipitation in NM4 during the instrumental period of record. This high r^2 value is easily statistically significant at the 5% level (assuming one degree of freedom per year), providing empirical justification for the use of NM4 precipitation as a proxy for precipitation falling within the (much smaller) upper Gila watershed contained within NM4.

The top panel of Figure 7 shows NM4 temperature in the late winter/early spring (Jan-Apr) plotted against Dec-Jun Gila gage streamflow. This correlation is negative as expected but much weaker ($r = -0.20$) than the corresponding precipitation correlation in the bottom panel. Nevertheless the negative relationship between streamflow and temperature, i.e. warm Jan-Apr temperature associated with diminished Dec-Jun streamflow, is statistically significant at the 5% level and it will be exploited in Section 4 where a regression model of streamflow is developed and assessed.

The increasing importance of warming temperature on streamflow can already be detected in observed data, by examining the declining interannual variance of Dec-Jun Gila gage streamflow accounted for by cold season precipitation. For the 1951-1980 period, Nov-Apr precipitation accounted for 75.4% of the interannual variance of Dec-Jun streamflow, with a regression coefficient of 42,375 ac-ft of total flow per inch of precipitation in NM4. That is, during this period each additional inch of precipitation over the Nov-Apr period yielded 42,375 ac-ft of Dec-Jun flow at the Gila gage. During the subsequent 30-year averaging period, 1981-2010, Nov-Apr precipitation accounted for just 66.2% of Dec-Jun streamflow variance, as temperature variability accounted for a larger fraction of streamflow variability. The 1981-2010 regression coefficient was 30,755 ac-ft of of Dec-Jun flow per inch of NM4 precipitation. As temperature increases, the streamflow yield in the Dec-Jun high flow season decreases, consistent with expectations for a warming climate. Winters with high precipitation still generate relatively high flows in the Gila River, but the flow yield per unit of precipitation is decreasing.

3. Dynamical Projection of Streamflow in the upper Gila River

The Review Paper summarized the results of many published projections of future streamflow, principally focusing on projected flows on the mainstem Colorado and Rio Grande rivers. While these projections are relevant to projected flows on the Gila River, the only published results for the upper Gila itself (of which we are aware) were generated and disseminated recently by the U.S. Bureau of Reclamation (Reclamation 2011a,b). These reports describe the results of a new suite of streamflow projections for the 21st Century for basins across the western United States, using an extensive suite of global model projections collectively denoted CMIP3 (Meehl et al. 2007). These are the same global climate model simulations that were used for the IPCC (2007) assessment of climate change. The CMIP3 archive includes many different global model projections, using a wide range of 21st Century greenhouse gas scenarios. For the Reclamation (2011a,b) projections, these climate model simulation were used as input to the VIC hydrologic model (Liang et al. 1994) to generate streamflow projections in western basins.

The procedure for generating these dynamical simulations is summarized very briefly here, with full details given in the BoR reports (Reclamation 2011a,b). The CMIP3 coarse resolution global climate models, based on dynamical representation of atmospheric and oceanic climate variables, simulate the effects of changing "boundary conditions" (greenhouse gas concentration, solar fluctuations, volcanic eruptions) on winds, temperature, precipitation, storm systems, snowpack, ocean currents, and other standard climate variables. Over the North American continent, these climate model results were downscaled to much finer resolution using a statistical technique (Wood et al. 2004). The downscaled climate variables were then expressed on a higher resolution grid suitable for driving a land surface/streamflow model (the Variable Infiltration Capacity or VIC model). The runoff simulated by VIC, averaged over multiple simulations driven by different climate models, represents the dynamical simulation analyzed here.

Uncertainty in these simulations derives from several sources. First, we depend on the climate models to represent faithfully the response of large-scale climate variables to the imposed forcing. The biggest forcing represented by the CMIP3 models comes from projected increases in atmospheric greenhouse gas concentration. Uncertainty in the coarse resolution climate model output can be shown explicitly by the variation in results generated by different models driven by the same climate forcing (Reclamation 2011a,b). In addition, there is considerable uncertainty in the future greenhouse gas forcing, which depends on economic and political choices made by countries around the world over the coming decades. We have chosen a midrange scenario of greenhouse gas forcing (A1B) to be consistent with the temperature and precipitation projections developed by Gutzler and Robbins (2011). Finally -- and very importantly for this study -- we depend on the models to simulate faithfully the natural (unforced) variability of climate and streamflow, as illustrated by the observed climate statistics described in the previous section. It is very difficult to quantify these individual sources of uncertainty using available data.

For this assessment we have analyzed the output of simulations of flow at the location of the Gila gage (Reclamation 2011b), available online at `http://gis.usbr.gov/streamflow_projections/`. The simulations extend backward in time to include the latter half of the 20th Century, so it is possible to directly compare more than a half century of model-simulated results since 1951 with the record of observed flows described in the previous section. We have used 39 separate simulations based on the A1B scenario of radiative forcing as the basis for analysis. The A1B scenario represents a "mid range" estimate of future greenhouse gas concentrations, although the differences in greenhouse gas forcing among plausible scenarios developed by the IPCC are not really large until the second half of the 21st Century. Seager et al. (2008) and Gutzler and Robbins (2011) used the suite of global climate models forced by this particular scenario in their studies of climate change across the Southwest.

Average hydrographs of monthly flow at the Gila gage, derived from historical observed data in the top panel, and from the average of 39 A1B-forced simulations as carried out by Reclamation (2011b) in the bottom panel, are shown in Figure 8. The top panel is based on the same daily streamflow data used to generate Figure 2. For this plot, we have summed the daily flow values into monthly averages and generated mean values (not median values as was shown in Fig. 2, so that the monthly values sum to the corresponding Water Year annual mean value) for two successive 30-year averaging periods. The 1951-1980 climatological average includes the major drought of the 1950s. The following 30-year period, 1981-2010, is the current "official" 30-year climatological averaging period. The current average shows higher flows at the Gila gage in the winter months (December-March) and again in summer (particularly August), compared to the earlier 1951-1980 period.

Median annual average flow observed at the Gila gage in the period 1951-80 was 110 cfs. The following 30 years, 1981-2010, were on average considerably wetter: average annual flow at the Gila gage increased to 182 cfs. Thus median annual flows during the 1981-2010 averaging period were 65% higher than during the 1951-1980 period, a huge multidecadal decadal fluctuation representing the transition from a very dry period to a very wet pluvial period.

The average of 39 BoR streamflow simulations is shown in the bottom panel of Figure 8 with the daily values averaged into monthly means. Hydrographs for successive 30-year periods for both retrospective and future projected climate conditions are shown. The retrospective simulations, shown using the same line color conventions as for the observed data, show that the VIC-based simulations capture the shape of seasonal hydrograph reasonably well but tend to overestimate flows relative to observations. The annual average (Water Year mean) flow rate simulated at the Gila gage is 199 cfs for 1951-1980 and 193 cfs for 1981-2010. Thus the dynamical simulations of Gila flow tend to show a decrease between the two most recent independent 30-year averaging period, whereas actual observations for the same periods shows an increase in flow at the Gila gage.

A complete diagnosis of the reasons for the general high bias of simulated streamflow is beyond the scope of this study, but an imperfect match with observations at a specific point is not surprising considering the uncertainties associated with model resolution, etc. (Reclamation 2011b). These uncertainties are extremely difficult to quantify using the output available. Given the systematic bias between model output and pointwise observations, it is customary to consider percentage changes in the model-simulated streamflows rather than try to use the direct output from a dynamical model to make quantitative projections of changes in streamflow.

Time series of annual flows for each of the 39 simulations considered are shown in Figure 9. The various simulations clearly exhibit intermittent high flow years which continue to skew mean flows. The time series of median values of all 39 simulations each year, shown as a thick black line in both panels, trends slowly but steadily downward through the 21st Century. (We revert back to median streamflow values in Fig. 9 to minimize the effects of one or two outlier annual values on each 39-model Water Year average; a time series of mean values would also trend downward but would contain much more interannual variability.)

Although precipitation variability accounts for most of the variance of streamflow in the historical record (Figure 7), precipitation change is <u>not</u> the principal cause of long-term projected streamflow change as shown in Figures 8 and 9. This is shown by considering the projected changes in snowpack and precipitation downscaled from global model projections to the upper Gila watershed (Figure 10). There is very little projected precipitation change except for the summer, when downscaled precipitation decreases somewhat (bottom panel). However snowpack changes in the cold season are extreme (top panel) despite the absence of simultaneous precipitation change. Snowpack is nearly eliminated in the Gila watershed due to the projected temperature increase (shown in the top panel of Fig. 11), a result that has been highlighted in previous studies of regional climate change in the southwestern U.S. (Diffenbaugh et al. 2005; NM OSE 2006).

The decrease in snowpack acts to reduce the snowmelt runoff peak that is projected to occur in coming decades (Fig. 8), to the point at which the peak in streamflow associated with snowmelt runoff is effectively spread out between January and March by the late 21st Century (red curve in the bottom panel of Fig. 8). The decline in snowpack shifts the Center of Timing toward earlier dates, as is already seen in observations (Fig. 5). Warmer temperatures over a longer snow-free season increase evapotranspiration rates, resulting in reduced streamflow year-round (Hurd and Coonrod 2008, 2012).

In the current climate a downward trend in streamflow driven by warmer temperatures has been masked by the increase in precipitation that occurred in the late 20th Century (Fig. 6). However if the wet decades were the late 20th Century represent an episodic decadal fluctuation of precipitation -- and the recent run of very dry years early in the 21st Century (Fig. 11) suggests that the wet period may be over -- then we can expect the temperature-driven streamflow changes illustrated in the streamflow projections (Figs. 8 and 12) to become more evident in the near future. This is the scenario outlined by Seager et al. (2008), which they described as an "imminent transition" toward long-term aridity across Southwestern North America.

Summer precipitation projections tend to be uncertain in both CMIP3 (Gutzler and Robbins 2011) and CMIP5 (Cook and Seager 2013) climate model simulations. As Figure 10 suggests, some climate models simulate decreased monsoon precipitation in a projected warmer climate. Here again, observations from the late 20th Century show higher streamflow, associated higher precipitation, in a warmer climate. The Reclamation simulations in the bottom panel of Figure 8 yield little change in summer streamflow, the result of a small net average change among different climate models that simulate a wide range of higher or lower summer streamflow.

Decadal variability represents a large source of uncertainty in these model simulations. Considerable progress has been made in the simulation of interannual ocean-atmosphere variability in coupled models, especially the El Niño-Southern Oscillation (ENSO) cycle, and the CMIP3 climate models used in the Reclamation simulations generally do a credible job simulating the evolution and large-scale climatic effects of ENSO (IPCC 2007).

However decadal variability, such as may be associated with the Pacific Decadal Oscillation or Atlantic Multidecadal Variability (McCabe et al. 2004), is more problematic. Atmospheric models that are provided with the correct ocean temperature fluctuations can reasonably simulate long-term drought and pluvial episodes (e.g. Hoerling and Kumar 2003; Seager et al. 2005; Schubert et al. 2009) but getting coupled ocean-atmosphere models to generate sufficient decadal variability on their own is more challenging. Gutzler et al. (2012) showed that even newer and more sophisticated coupled models from the new CMIP5 archive (Taylor et al. 2012), successor to the CMIP3 models used in the Reclamation streamflow simulations, generate annual precipitation variability across the Southwest that contains significantly less year-to-year persistence than observed precipitation. In other words, decadal variability associated with unforced ocean-atmosphere interactions is probably underestimated in the model simulations analyzed here.

With this in mind, we emphasize again that the dynamical simulations shown in Figure 8 yield the wrong answer for late 20th Century variability. The observed seasonal hydrographs for the Gila gage (top panel) show *increasing* flows between 1951-80 and 1981-2010. The corresponding Reclamation dynamical simulations (bottom panel) show *decreasing* flows between the same periods. The difference is caused by the failure of the models to correctly capture the increase in precipitation observed between the "drought epoch" (1951-1980) and the following "pluvial epoch" (1981-2010), which leads to higher flows in the upper Gila River in response to the generally heavier precipitation amounts. On the other hand, the models do respond to increasing greenhouse gases in the late 20th Century by increasing the temperature, as observed. The higher temperatures lead to decreases in simulated snowpack and increases in simulated evaporation, hence declining flows.

How should we assess future projections in streamflow, considering that the simulated streamflow over the past 60 years is changing with the wrong sign relative to observations? There are two distinct possible interpretations. First, the simulated future projections could be considered unreliable, given that the models generate the wrong answer (decreasing flow) for retrospective streamflow trend over the half-century period of time when we know the right answer (increasing flow). Alternatively, the simulated future trends could represent a reasonable long-term answer, keeping in mind that the long-term trend is subject to considerable uncertainty on decadal time scales.

The alternative possibility amounts to concluding that the retrospective simulation of a decrease in flow over the latter half of the 20th Century represents the "right answer" to the response of the Gila River to higher temperatures, but the simulated decrease was overwhelmed by a natural, decadal transition in precipitation from drought to pluvial climatic conditions during that time. *If* this is the proper interpretation; and *if* the wetter conditions observed in the late 20th Century represent the wet phase of an episodic, decadal fluctuation in precipitation that will naturally revert back toward drier conditions; and *if* the temperature increases over the next few decades to the point at which the long-term temperature effect overwhelms the decadal variability of precipitation variability; then the projection of decreased streamflow in the coming decades may in fact be a reasonable basis for water allocation, despite the failure of the dynamical simulations to correctly reproduce late 20th Century changes in streamflow in the upper Gila River.

It is my professional opinion that the alternative hypothesis sketched above is correct, and that it is likely that the long-term effects of increasing temperature on snowpack and streamflow will become comparable to the decadal variability driven largely by natural precipitation fluctuations by the middle of the 21st century. This opinion is supported by historical observations of precipitation (Figs. 6 and 11), suggesting that late 20th Century wet conditions were part of a multi-decadal fluctuation that may already have reverted back toward dry conditions, and by the steadier, ongoing increase in temperature (Figs. 6, 11) and streamflow timing (Fig. 5) that are entirely consistent with long-term projections of a 21st Century warming trend.

Hurd and Coonrod (2008, 2012) showed that streamflows in the middle Rio Grande (northeast of the upper Gila basin) are projected to decrease significantly by the late 21st Century *regardless* of precipitation projections. Even a model simulation that includes higher precipitation amounts in the late 21st Century yielded smaller Rio Grande streamflow in the Hurd and Coonrod study, because the projected increases in evapotranspiration (associated with higher temperature) cause the water budget (Precipitation minus Evapotranspiration) to trend downward even if precipitation trends upward, as occurs in some individual climate model simulations.

If we assume that the effect of increasing temperature to produce diminished streamflow is at least qualitatively reasonable, we can use the dynamical simulations to try to project percentage change in streamflow in coming decades. Median annual streamflow at the Gila gage in the period 2021-2050 in 39 BoR simulations is 157 cfs, whereas median annual flow in the same simulations in the period 1951-2012 is 170 cfs, a decrease of 13 cfs/year (about 8% lower in 2021-2050). Here we use a record longer than the official 30 year averaging period to establish current climatic conditions, in order to include both dry and wet historical periods in our definition of current climate.

The Reclamation A1B-forced dynamical simulations indicate a decrease in annual median flow at the Gila gage of 13 cfs, or about 8%, between the periods 1951-2012 and 2021-2050.

4. Statistical Projection of Streamflow in the upper Gila River

Statistical models of streamflow examine the climatic factors that modulate streamflow in the current climate, as demonstrated by observed data, and use the observed relationships between climate and streamflow to estimate future flows based on projected climatic conditions.

The relationship between interannual fluctuations of cold season precipitation (or snowpack) and spring streamflow in southwestern rivers is strong and unassailable -- this relationship forms the basis for operational seasonal forecasts of streamflow issued early each calendar year, near the end of the snow accumulation season. Jones (2007) showed that 80% of the interannual variance of the spring season flow in the late 20th Century in the upper San Juan river could be accounted for by the annual 1 April measurement of snow water equivalent at a single SNOTEL site near the river's headwaters. Similarly, Salgado and Gutzler (2013) showed that just under 60% of late 20th Century spring season flow in the upper Pecos River could be accounted for by winter precipitation averaged over New Mexico Climate Division 2, which includes the Pecos headwaters in northern New Mexico. Figure 7 illustrates an analogous relationship between interannual fluctuations of observed winter precipitation and spring streamflow in the upper Gila River, with 68% of interannual Dec-Jun streamflow variance at the Gila gage accounted for by Nov-Apr precipitation averaged over the NM4 Climate Division.

These statistical models of interannual streamflow fluctuations work for the current climate because year-to-year variations of winter precipitation represent the major climatic factor modulating streamflow. Statistical projections derived from the statistics of current climate models are potentially applicable to future climatic conditions only as long as the mean and variability of climate remain similar to present-day statistics (Milly et al. 2008). However, if the climate warms to the point at which temperature, rather than precipitation, becomes a primary control on streamflow changes, then a precipitation-dominated statistical model would no longer be applicable. As discussed at the end of Section 2, a precipitation-only regression model already exhibits evidence of a changing climate: Nov-Apr precipitation accounted for a decreasing fraction of Dec-Jun streamflow variance in 1980-2010 relative to 1951-1980, and the yield of streamflow per unit of Nov-Apr precipitation declined substantially in the later period. As climate continues to change, a regression model derived from observed statistics becomes increasingly problematic.

The potential non-applicability of statistical models as discussed above has been discussed at length by Milly et al. (2008), whose paper has the evocative title "Stationarity is Dead." Hoerling and Eischeid (2007) used the 20th Century relationship between Palmer Drought Severity Index (PDSI) and Colorado River streamflow to estimate future flows at Lees Ferry based on PDSI values derived from temperature and precipitation projected by a climate model. They projected a 45% reduction in Colorado River flows using this statistical model by 2035-2060 relative to the 1990-2005 average, a dramatic decline that is roughly double the reduction in flow generated directly by the dynamical model projections cited earlier. The difference has been attributed to the increasing role of temperature in projected PDSI values, which may lead to overestimates of the reduction in actual surface drying due to the way in which surface moisture is parameterized in the PDSI calculation (Sheffield et al. 2012). Given this uncertainty I would assess the Hoerling and Eischeid (2007) streamflow projection with skepticism and consider it to represent an overestimate of likely streamflow reduction in the Colorado River.

Although temperatures are already increasing significantly in southwestern New Mexico (Figure 6), projected temperature does not completely leave its envelope of historical variability until the mid-21st Century (Gutzler and Robbins 2011; Gutzler 2012). Furthermore precipitation trends in observations or projections are relatively small compared to the magnitude of 20th Century climate variability (Gutzler and Robbins 2011; bottom panel of Fig. 11). Development of statistical models to project streamflow in the upper Gila River for the next several decades, while temperatures are still within historical bounds, therefore seems justifiable.

We have adapted the regressions described in Fig. 7, shown as curves fit to the scatter plots of temperature or precipitation vs. streamflow, and have thereby generated a multivariable regression model that relates annual values of Nov-Apr precipitation (denoted P_{NovApr}, units = inches) and Jan-Apr temperature (denoted T_{JanApr}, units = °F) in New Mexico Climate Division 4, to corresponding annual values of Dec-Jun average streamflow at the Gila gage (denoted Q_{DecJun}, units = kaf).

Observed values of these variables for the period 1951-2012 (as in the previous section, we wish to include both dry and wet decadal periods) were used to create the regression model, which is:

$$Q_{DecJun} = 9.29P_{NovApr} + 2.59(P_{NovApr})^2 - 5.38T_{JanApr} + 208.6 \qquad [1]$$

The linear precipitation term (the first term on the right hand side of the equation) accounts for the most variance. The quadratic precipitation term that follows is needed to make the model fit low-precipitation years, during which base flow in the drainage basin continues even when precipitation is quite low. The bottom panel in Figure 7 shows clearly that the relationship between precipitation and streamflow is not linear at both the high- and low ends of the range of seasonal precipitation values.

The third term, a negative linear term involving Jan-Apr temperature, plays a small role in modulating streamflow in the historical record but becomes increasingly important as temperatures rise. Although interannual fluctuations of temperature are not highly correlated with streamflow in the historical record (Figure 7, top panel), there is a cluster of data points in the bottom-right corner of the plot describing years where T_{JanApr} is warm (between 40°F and 42°F) and Q_{DecJun} is very low (<50 kaf). These data points in the historical record of temperature are a harbinger of the projected warmer climate shown in the top panel of Fig. 11. The inclusion of this temperature-related term in the statistical model captures the effects of these historical years in depressing streamflow when applied to projected future years in the climate record.

For projections of temperature and precipitation, we use a time series that incorporates projected climate model-based trends combined with observed interannual variability developed by Gutzler and Robbins (2011, hereafter denoted GR2011). The 21st Century trends in temperature and precipitation used for the GR2011 projections use the same set of CMIP3 global climate models, forced by the A1B scenario of radiative forcing, that was used to drive the VIC hydrological model to make the Reclamation projections described in the previous section. Interannual variability is reproduced from exactly 100 years earlier in the 20th Century. This procedure ensures that the statistics of projected interannual and decadal variability are "realistic", in the sense that the variability is exactly reproduced from the observational record. For southwestern New Mexico, this means that the historic drought of the 1950s is reproduced (exactly, in terms of variability about the projected long-term trend) in the decade of the 2050s.

Temperature in Jan-Apr increases at a rate of 7.6°F/century in the GR2011 projection (Figure 11, top panel). The 7.6°F/century warming trend brings temperature outside the envelope of historical 20th Century variability by the second half of the 21st Century. The corresponding precipitation projection for NM4 in Nov-Apr (bottom panel of Figure 11) exhibits a downward trend of -1.2 inches/century. As was the case for temperature, 20th Century variability is reproduced by construction for this projection. For example, the increase in precipitation over the decade of the 1970s is reproduced in the decade of the 2070s, with the time series in the 2070s shifted downward by approximately 1 inch due to the long-term trend derived from the CMIP3 projection. In contrast to the temperature projection, the model-projected trend in precipitation is not large enough in the 21st Century for precipitation values to depart from historical variability. Thus, while the projected long-term trend of -1.2 in/century is a substantial reduction, the overall sense of 21st Century climate illustrated in these projections is a combination of much warmer temperatures and continued interannual and decadal variability of precipitation, with a secondary effect associated with the relatively modest downward precipitation trend.

Applying the regression model from equation [1] to the GR2011 projection of temperature and precipitation yields a statistical estimate of future flows (for Dec-Jun) as shown in Figure 12. The portion of the time series between 1951 and 2012, shown as a green line, is the actual Dec-Jun flow reproduced from the middle panel of Figure 3. The black crosses in the figure represent the streamflow as predicted from the regression equation. With an r-squared value of 0.69, the time series of crosses is highly correlated with the actual observations but the regression values do not exactly reproduce the observations.

Flows derived from regression model using the GR2011 projected values of temperature and precipitation for 2013-2100 are continued as the black line in Figure 12. It is important to keep in mind that the interannual variability of the GR2011 projection is synthetic, so individual, specific high flow and low flow years are not meaningful; it is the statistics of interannual variability that are the projection is designed to capture. The overall trend of projected flows is seen to decrease in Figure 12 through the 21st Century, although individual high and low flow years are present throughout the projected time series.

Median values of annual Q_{DecJun} streamflow generated by this statistical model during the 1951-2012 observed period over which the model was developed was 65.5 kaf, with very large interannual variability superimposed on the mean. Median projected Q_{DecJun} flow for 2021-2050 is 60.7 kaf, a reduction relative to 1951-2012 of 7.4%.

As discussed above, a common limitation of statistical models applied to future climate is their applicability when climatic conditions change beyond the envelope of historical variability in observed data sets. Temperature in the Gila headwaters region is projected to emerge from its range of historical variability by the middle of the 21st century (Fig. 11), making the validity of statistical models to project future streamflows on the upper Gila problematic. In Fig. 12 the statistical model projects negative flow at the Gila gage with increasing frequency after 2050, when the temperature term in the regression model increases in magnitude and overwhelms the positive contributions to Q_{DecJun} represented by the other terms in the model.

The projected decrease of 7.4% in median Q_{DecJun} yielded by the statistical model for the 2021-2050 period is almost identical to the 8% decrease in projected in median annual flow for that period derived directly from the suite of Reclamation (2011a,b) dynamical models. While the near-match in these projections is somewhat fortuitous, the similarity in results from these two approaches reinforces our confidence that the projection is a reasonable one.

Based on the similarity of the results derived from dynamical models and statistical models, our confidence is increased in making an approximate projection of 8% reduction in upper Gila River flow by 2021-2050, relative to the observed median flow between 1951-2012.

5. Conclusions

The principal conclusions of this study are as follows:

1) **Our best estimate of the effect of projected climate change on average peak-season flow in the upper Gila River is a reduction of approximately 8% by 2021-2050, relative to a baseline period of 1951-2012.**

We assessed future flows at the Gila gage using two different techniques: first, an analysis of a multi-model ensemble of hydrologic model (VIC) simulations driven by an ensemble of global climate models, and second, an empirical model based on historical flows at the Gila gage and their correlation with winter-spring precipitationa and spring season temperature.

Each of these projection techniques is subject to considerable uncertainty, associated with the myriad approximations and uncertainties inherent in dynamical modeling of extremely complex physical systems on the one hand, and with the assumptions built into statistical extrapolation of observed climate variability and streamflow on the other hand. Our limited confidence in either approach is bolstered significantly by reaching similar conclusions using the two approaches.

2) **Pronounced multidecadal natural variability will continue to be superimposed on the projected decrease in streamflow.**

By 2021-2050 the projected 8% decline will still be considerably smaller than the ±30% variability in streamflow associated with multi-decadal shifts in storm tracks, that seems to have been responsible for the pronounced historical alternation between drought and pluvial episodes for centuries in the Gila River. The late 20th Century was very wet by historical standards, so one might expect a considerable decline in flows relative to the unrepresentative 1981-2010 climatological value to occur in coming decades even in the absence of forced climate change. The projected long-term, temperature-drived decline in streamflow is smaller than

This study has not attempted to determine whether interannual and decadal variability should be expected to change as the result of forced climate change in the 21st Century. The projections by Gutzler and Robbins (2011) of temperature and precipitation, used to generate the statistical projection of 2021-2050 flow at the Gila gage discussed here, deliberately and artificially kept the statistics of interannual variability fixed by superimposing 20th Century variability onto model-projected long term forced changes in climate. Absent better quantitative guidance from dynamical models, we think it is prudent to assume that historical interannual and decadal variability (such as illustrated in Fig. 4) will continue in the 21st Century.

A corollary note associated with the huge natural variability exhibited in southwestern river basins is that projected reductions in streamflow are highly sensitive to the baseline period from which the reduction is calculated. The 8% reduction quoted here is deliberately calculated relative to a long climatological baseline that includes the dry decades of the middle 20th Century. The projected reduction would be much greater if it were calculated relative to a shorter and wetter baseline period, such as the current official climate normal period of 1981-2010.

As noted in conclusion (1), there are multiple uncertainties inherent in climate projections are very difficult to quantify. In qualitative terms, current observational trends in temperature, streamflow timing and the declining ratio of winter precipitation/ streamflow yield, together with the consistency between dynamical and statistical projections, all support the conclusion that Dec-June streamflow in the upper Gila River is likely to decline somewhat over the first half of the 21st Century (and beyond), with a best estimate of about 8% relative to a baseline climatology of at least a half-century. This level of decline would still be considerably less than the natural multidecadal variability expressed in instrumental and long-term proxy records of streamflow. Thus for planning purposes, climate change needs to be considered together with natural variability. From this perspective the principal effect of climate change on total flow over the first half of the

21st Century will be to exacerbate low-flow drought conditions driven by episodic precipitation deficits during drought years.

3) **The timing of peak streamflow and the shape of the seasonal hydrograph are likely to change considerably over the next several decades.**

Peak season flows associated with snowmelt runoff are projected to be much reduced as snowpack is diminished in association with warmer temperatures. A much greater fraction of cold season precipitation will become runoff immediately instead of accumulating as winter snowpack, then melting in a well-defined snowmelt runoff event. Therefore, spring season peak flows resulting from snowmelt runoff become much diminished in projections of future streamflow in the upper Gila basin.

4) **Possible changes in the secondary streamflow peak in summer are difficult to assess.**

Summer season precipitation remains challenging for climate models to simulate. Projections of summer streamflow are correspondingly uncertain. The present analysis has therefore focused on flows associated with snowpack, which comprise the high-flow portion of the seasonal hydrograph at the Gila gage. Flows were assessed for the extended "peak flow" season of December-June, but actual changes in the summer monsoon could affect the quantitative projection of Gila River streamflow in ways that are not accounted for in this study.

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Fig 1

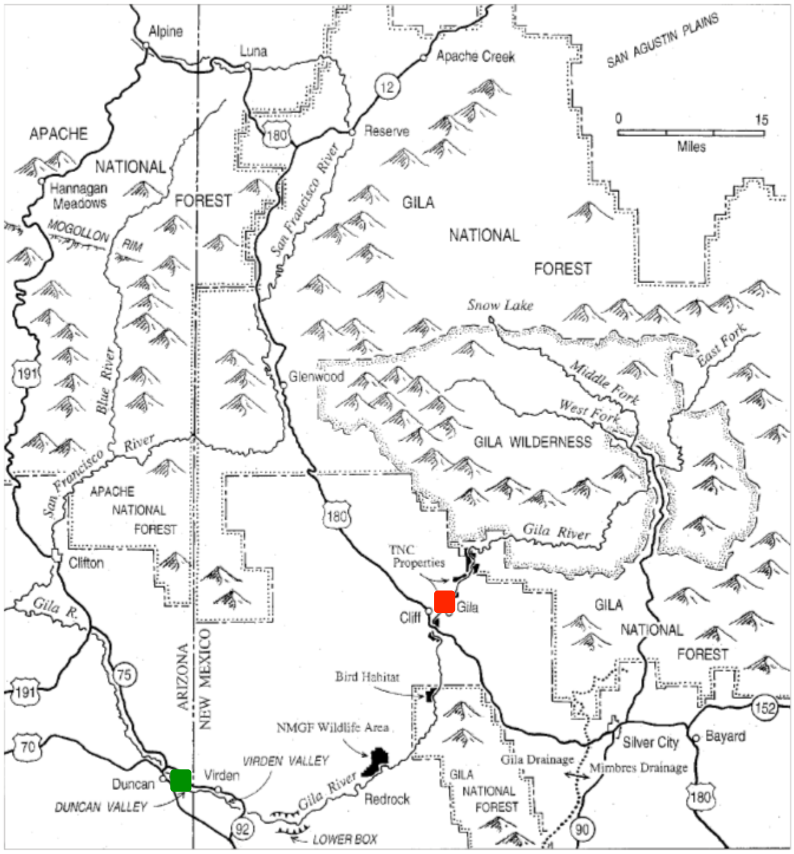


Figure 1. Map of the upper Gila basin, adapted with permission from "The Gila and San Francisco Rivers" by Jerold Widdison for the Utton Transboundary Resources Center. Red square indicates the location of the Gila gage (USGS gage 09430500), which is the principal analysis point for this study. The green square indicates the location of the Solomon gage (USGS gage 09448500) for which tree ring-based reconstructed flows are illustrated in Figure 4.

Fig 2

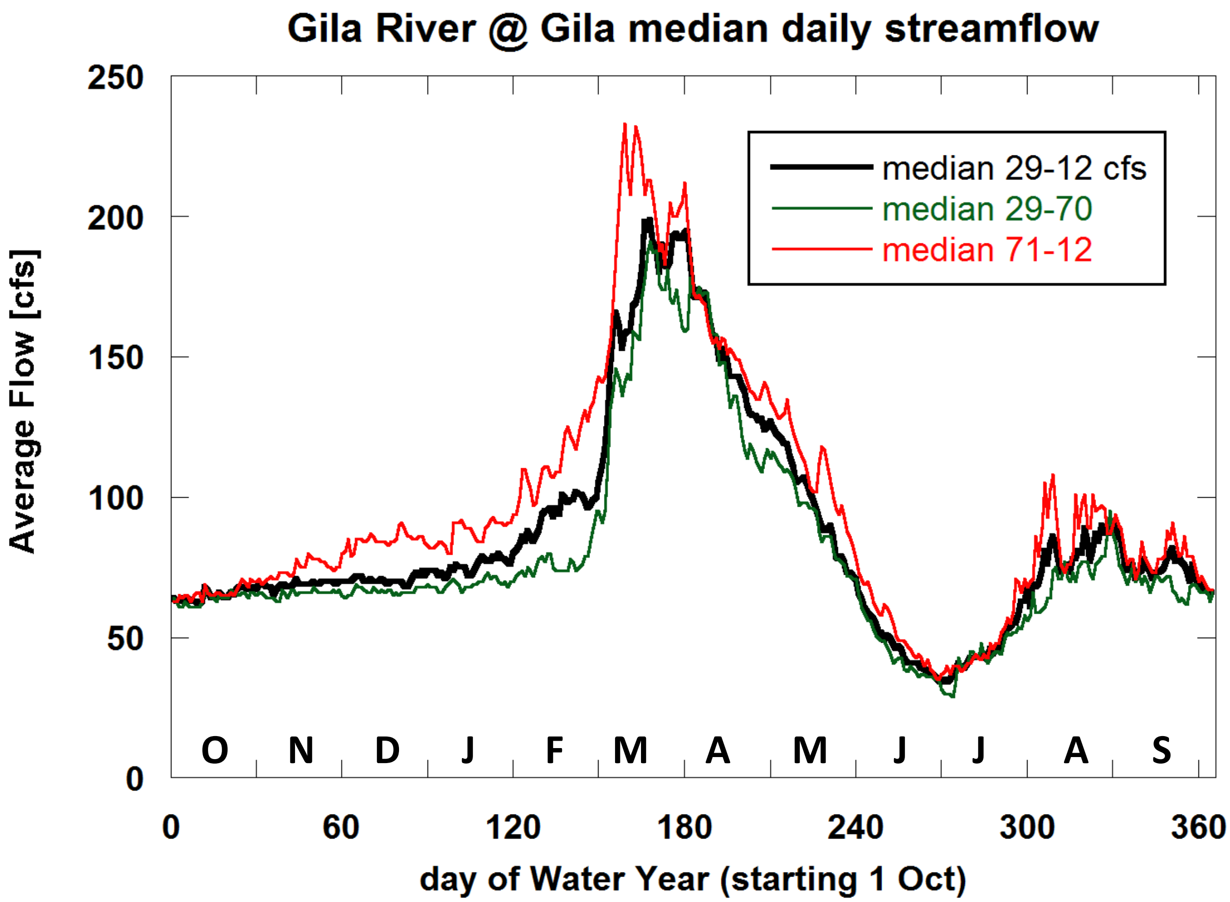


Figure 2. Hydrographs for streamflow at the Gila gage on the Gila River. The thick black line shows the median daily flow for each day of the Water Year (e.g. day 1 = Oct 1, day 365 = Sep 30) for the 82-year period Oct 1928 – Sep 2012 (WY 1929-2012). The thin green line shows the median flow based on just the first half of the period of record (WY 1929- 1970); the thin red line shows the median daily flow based on just the second half of the record (WY 1971-2012). Months of the year are indicated between tick marks on the x-axis.

Fig 3

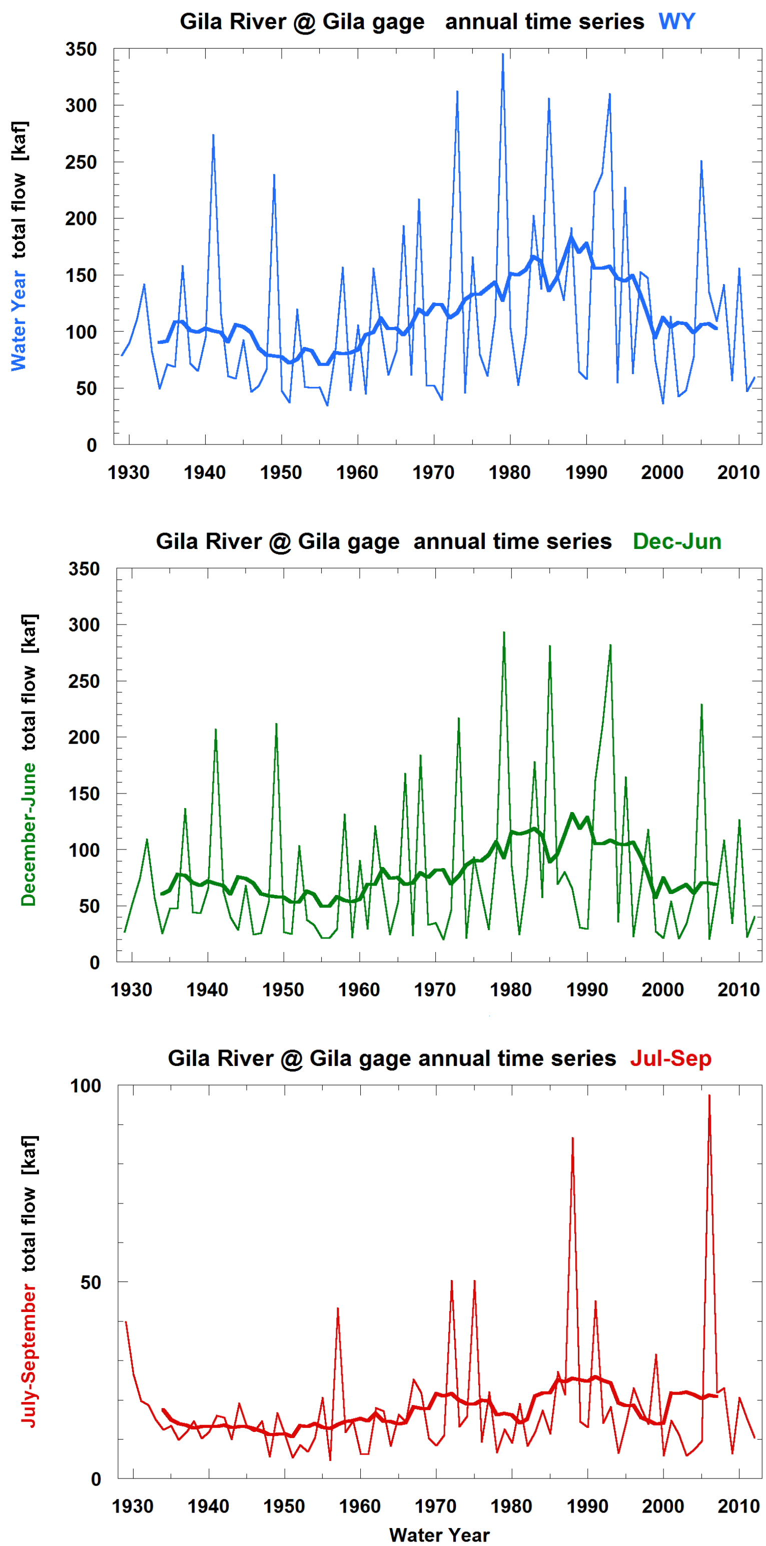


Figure 3. Annual time series of streamflow at the Gila gage, 1929-2012. Thin line in each panel represents annual data; thick line is an 11-year running average.
Top: Annual flow (kaf) for the entire Water Year (October-September).
Middle: 7-month average streamflow for December-June, the high-flow portion of the year.
Bottom: Monsoon season (July-September) flow (note much-expanded y-axis).

Fig 4

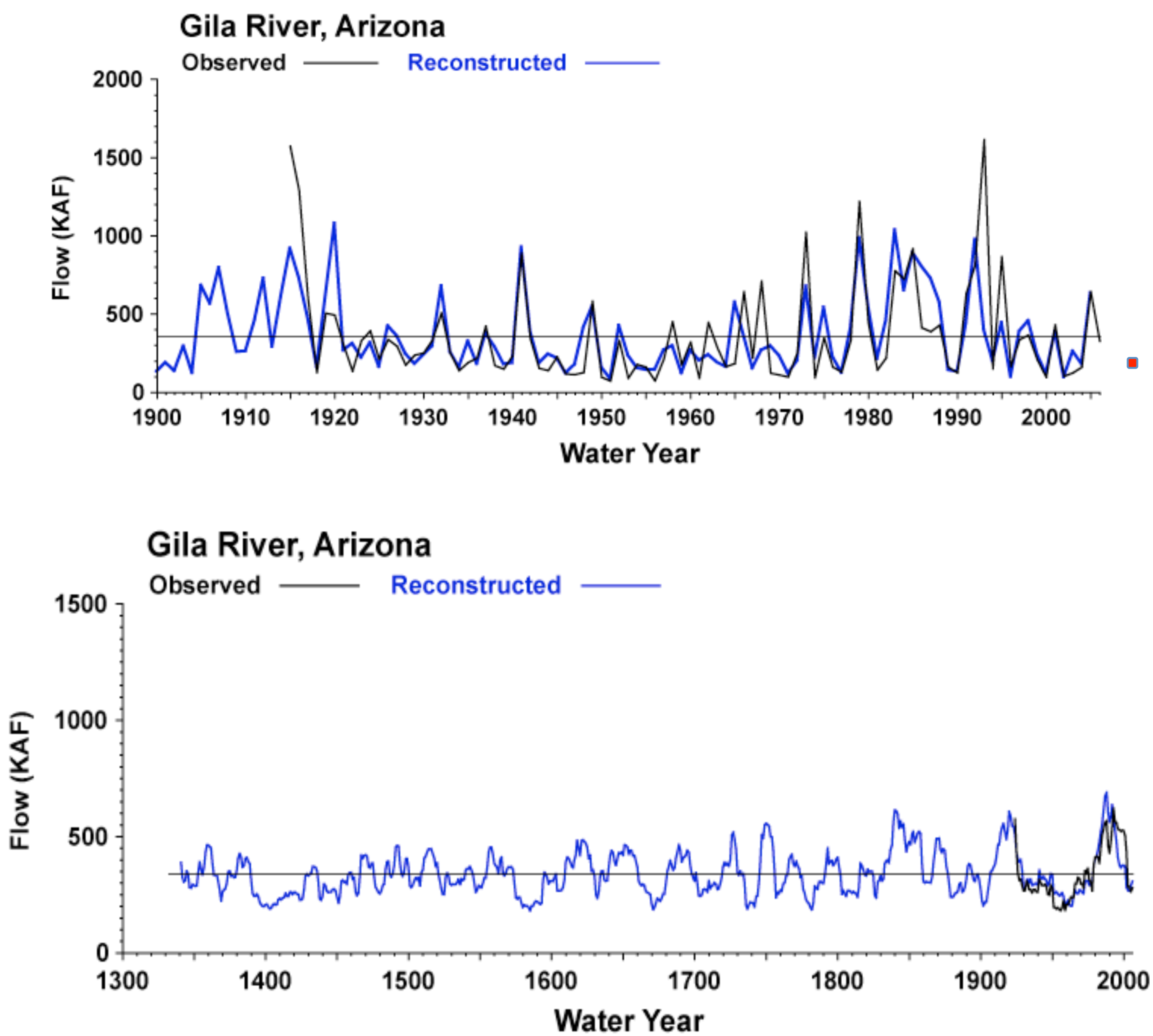


Figure 4. Time series of observed and reconstructed flow on the Gila River at the Solomon gage (USGS gage 09448500, shown as the green square in Figure 1). The black line in each panel shows annual flow derived from gage data, with a decadal smoother applied to emphasize long-period fluctuations. The blue line in each panel shows the reconstruction based on tree ring analysis using dendrochronology sites that demonstrate a strong correlation with Gila@Solomon flows. The calculated regression between tree ring records and Solomon gage flows during the instrumental data record is extended backward in time to generate the flow reconstruction. Data and graphics adapted from the treeflow.info website (Meko et al. 2010).

Fig 5

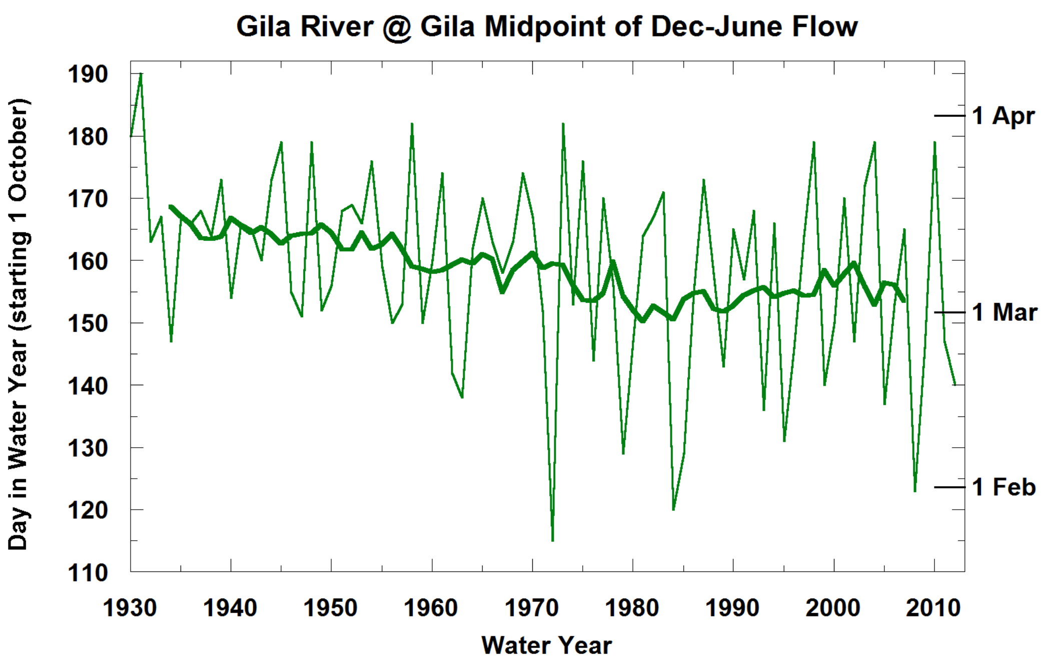


Figure 5. Center of timing of December-June streamflow at the Gila gage. The Center of Timing is the day at which half of the total flow between December and June each year has passed the gage. Days are measured relative to the start of each Water Year on October 1. The days corresponding to 1 February, 1 March and 1 April are labelled on the right-hand axis.

Fig 6

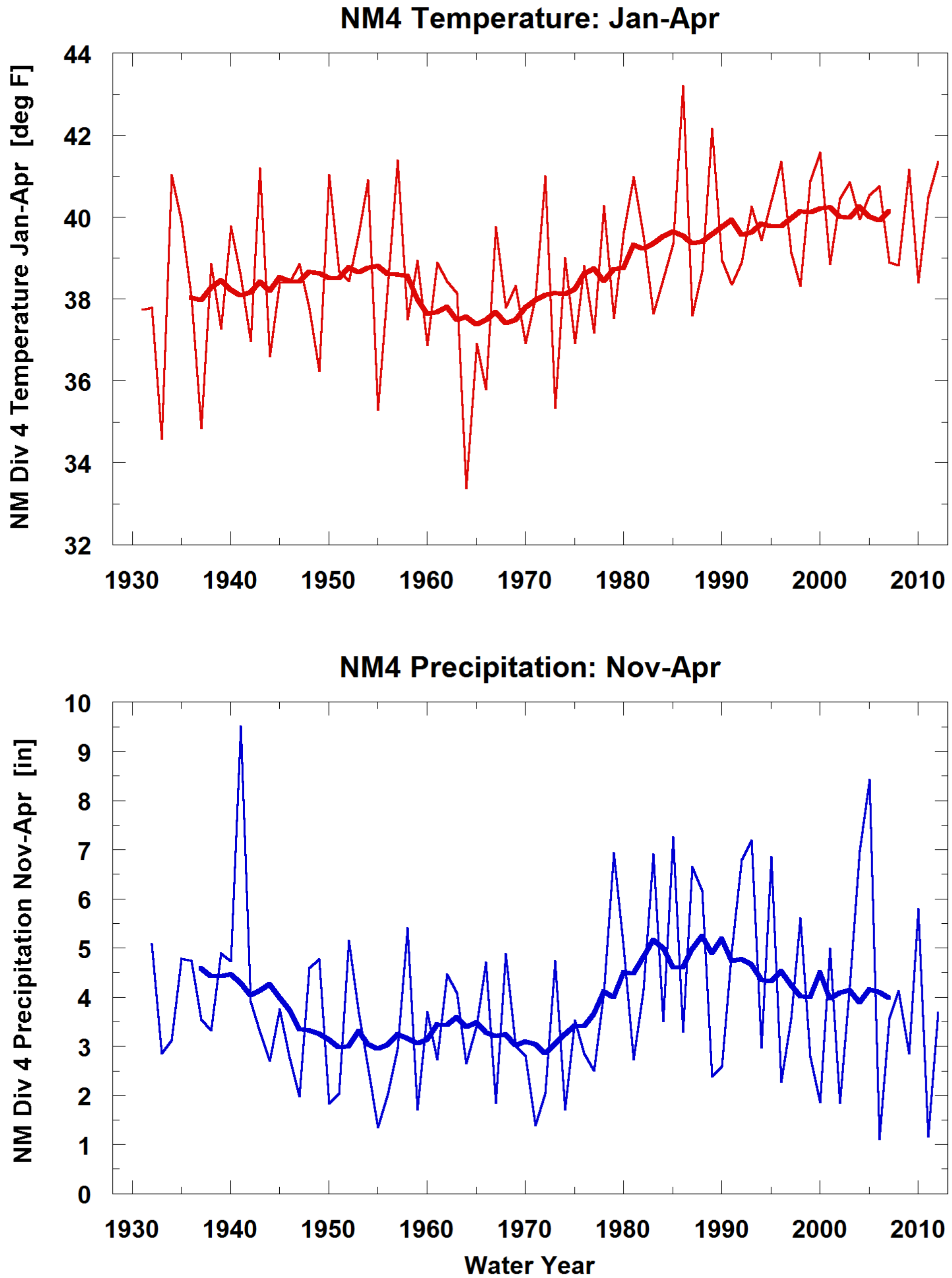
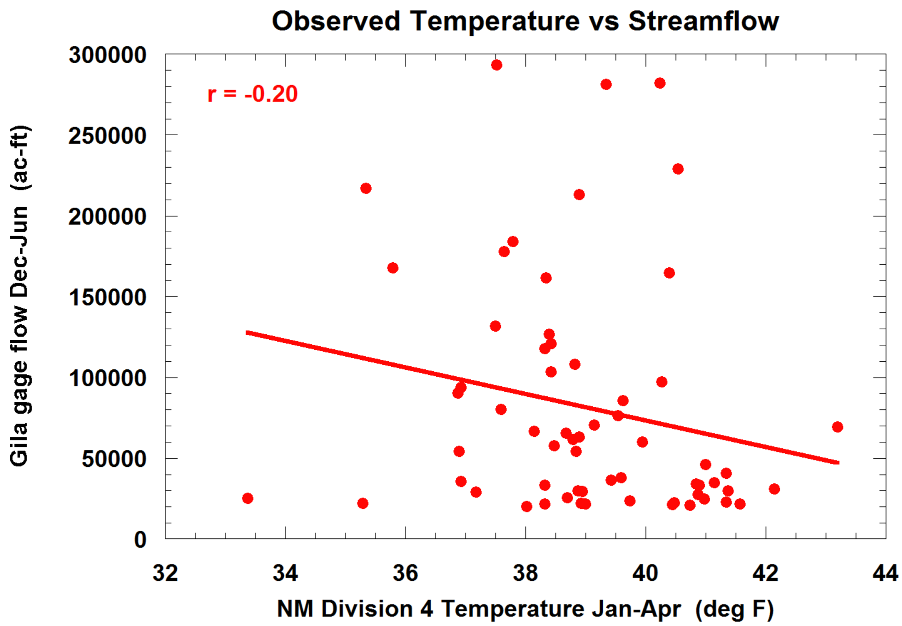


Figure 6. Time series of seasonal temperature (top) and precipitation (bottom) for New Mexico Climate Division 4, which includes the headwaters of the Gila River.
Top: temperature averaged over 4 months (Jan-Apr) from 1931-2012. Thin red line shows annual data; thick red line shows an 11-year running average through the annual data.
Bottom: precipitation averaged over 6 months (Nov-Apr each Water Year), with thin and thick lines similar to temperature panel.

Fig 7



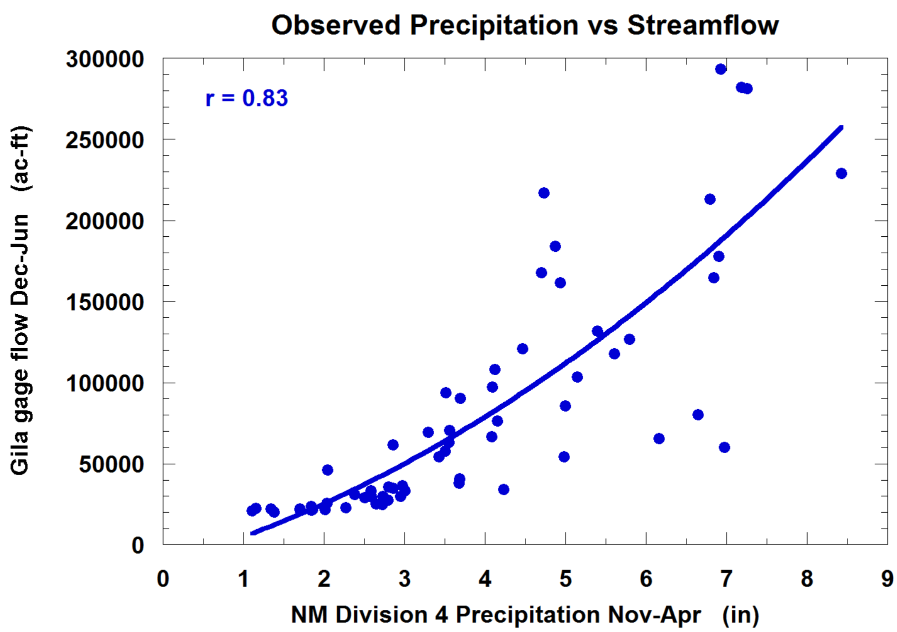
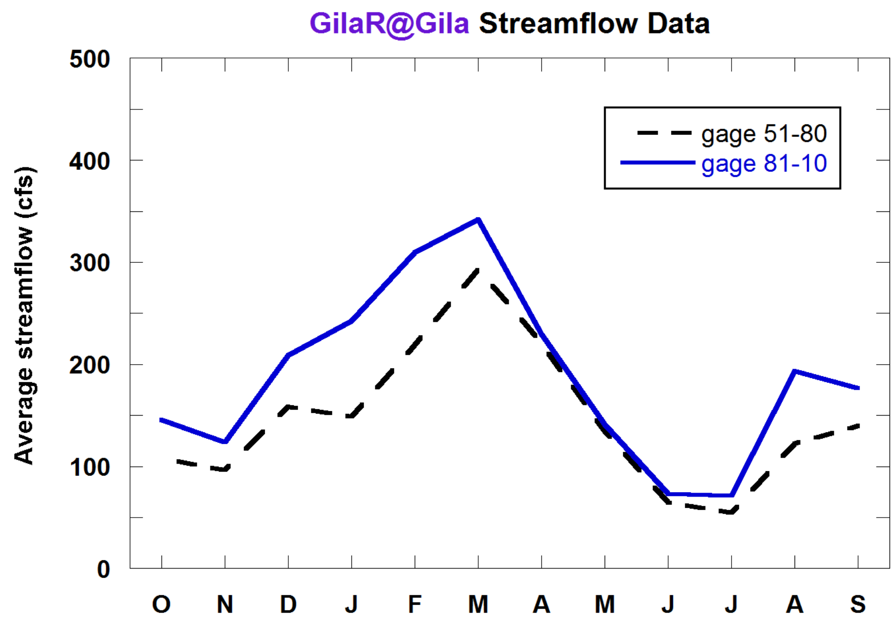


Figure 7. Scatter plots of observed temperature (top) and precipitation (bottom) in New Mexico Climate Division 4, plotted against observed peak season streamflow (Dec-Jun) at the Gila gage. **Top**: Temperature averaged over 4 months (Jan-Apr) vs. Dec-Jun flow. The line shows a best-fit linear regression. Correlation between the data and the regression line is -0.20.
Bottom: Precipitation averaged over 6 months (Nov-Apr each Water Year) vs. Dec-Jun flow. The line shows a best-fit quadratic regression. Correlation between the data and the regression curve is 0.83. See text for descriptions of these regressions, and the multvariate regression model that incorporates both temperature and precipitation.

Fig 8



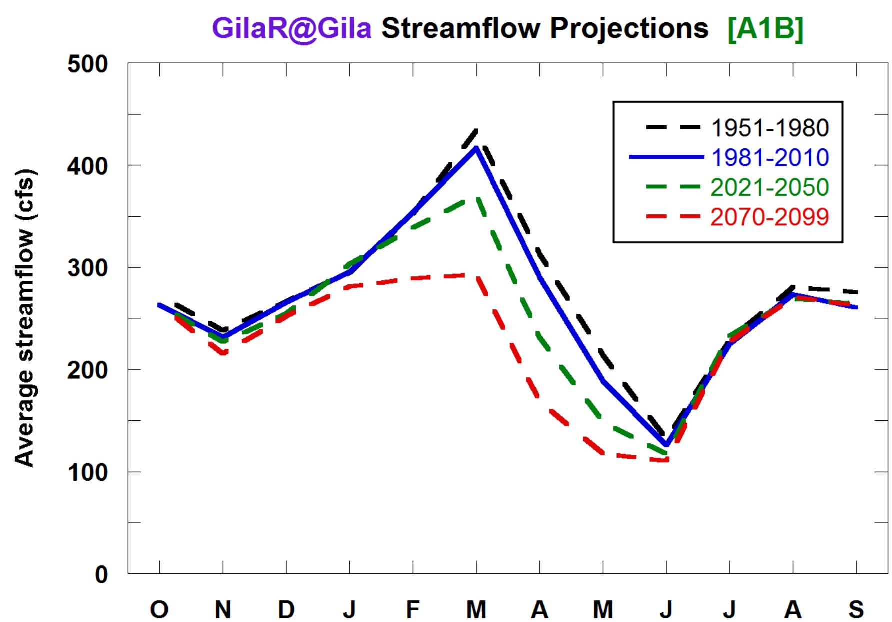


Figure 8. Seasonal hydrographs for successive 30 year periods at the Gila gage. **Top**: Observed monthly mean flows at the Gila gage. Dashed black line shows 1951-1980 mean; solid blue line shows 1981-2010 mean. **Bottom**: Streamflow values derived from the mean of 39 climate model driven simulations (Reclamation, 2011b). Black and blue lines correspond to the same periods as the observations in the top panel; green and red dashed lines represent 2021-2050 and 2070-2099 averages based on projected climate conditions.

Fig 9

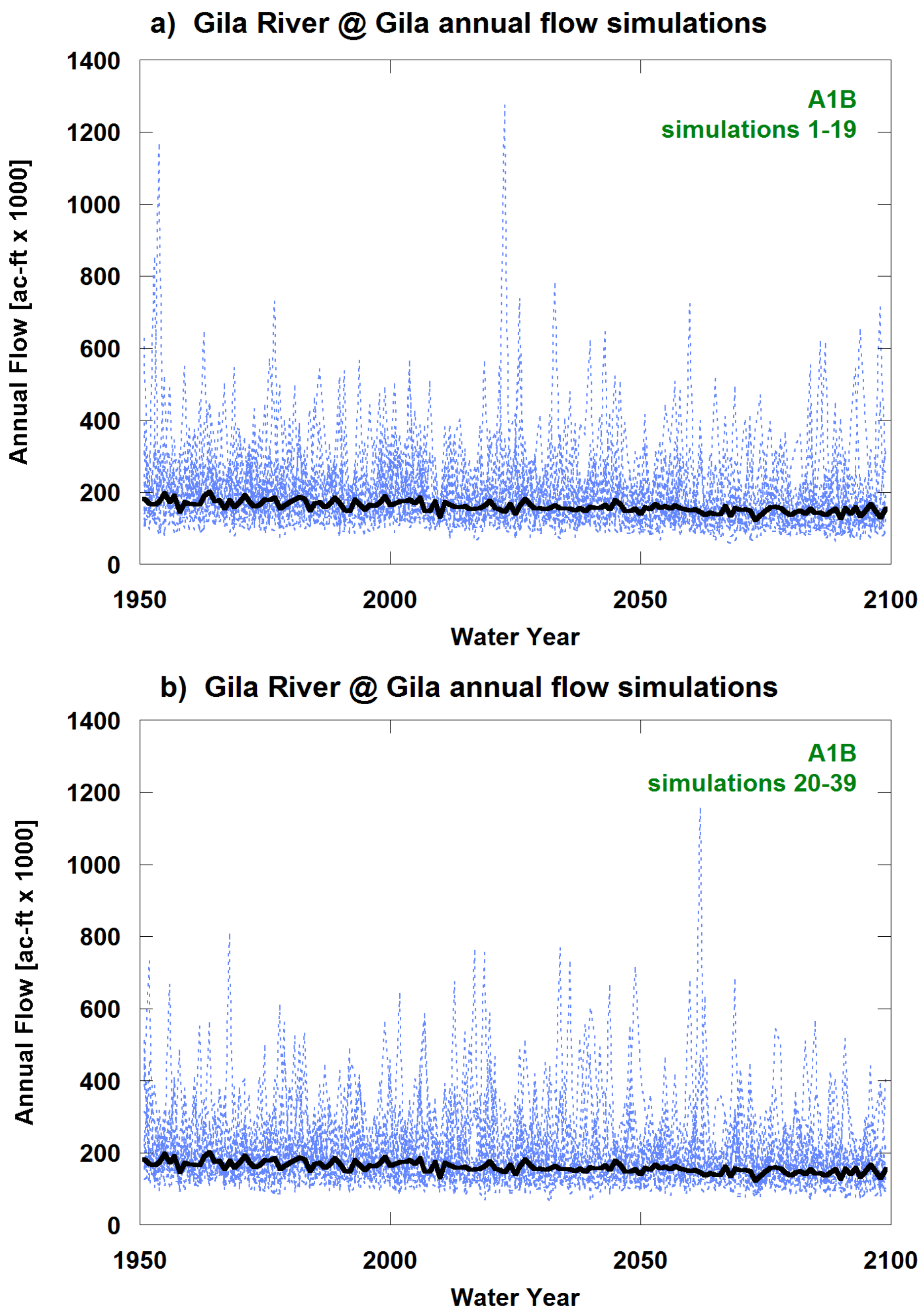


Figure 9. Time series of annual flow at the Gila gage in 39 simulations by the VIC land surface/runoff model (Reclamation, 2011). Each VIC simulation is driven by a different global climate model simulation. The radiative forcing for each of the 39 simulations is the A1B scenario as defined by the IPCC (2002). Dashed blue lines represent each simulation. For clarity, the 39 simulations are split into two groups: 19 simulations are shown in panel (a) and 20 simulations are shown in panel (b). The solid black line in each panel is the annual median value of all 39 simulations for each Water Year.

Fig 10

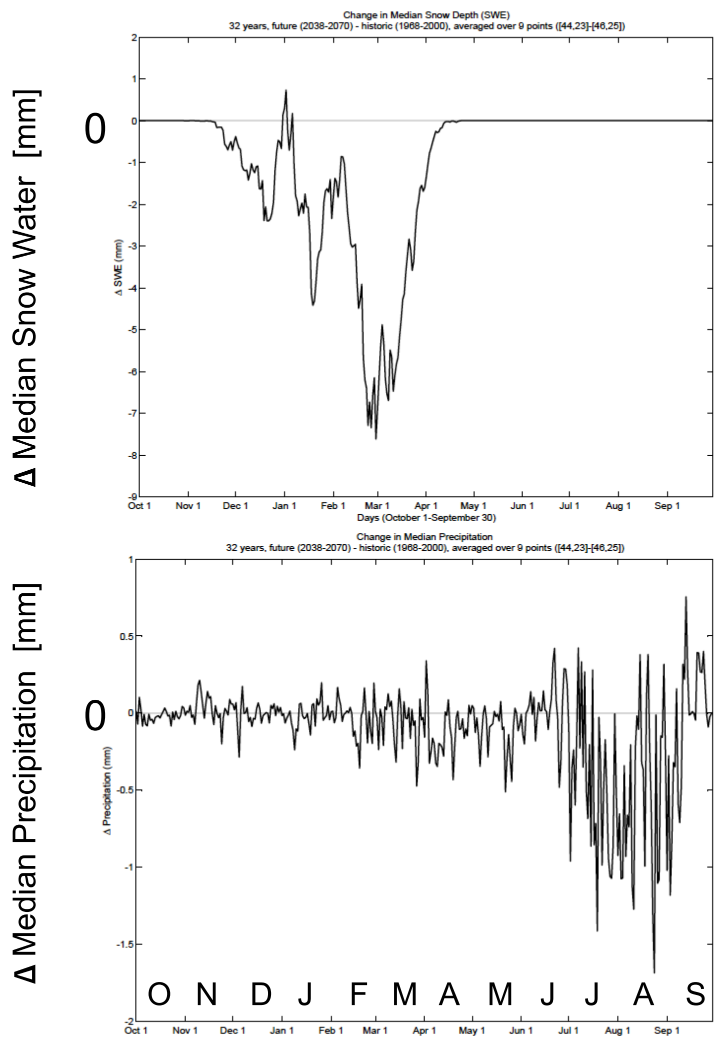


Figure 10. Change in median snow water (top panel) and precipitation (bottom panel), for each day of the water year, between a simulation of current climate (1968-2000) and a simulation using the same climate model for future climate (2038-2070). Calculations were made using output from the NARCCAP ensemble of downscaled climate models, including just the model gridpoints covering the upper Gila basin upstream of the location of the Gila gage.

Fig 11

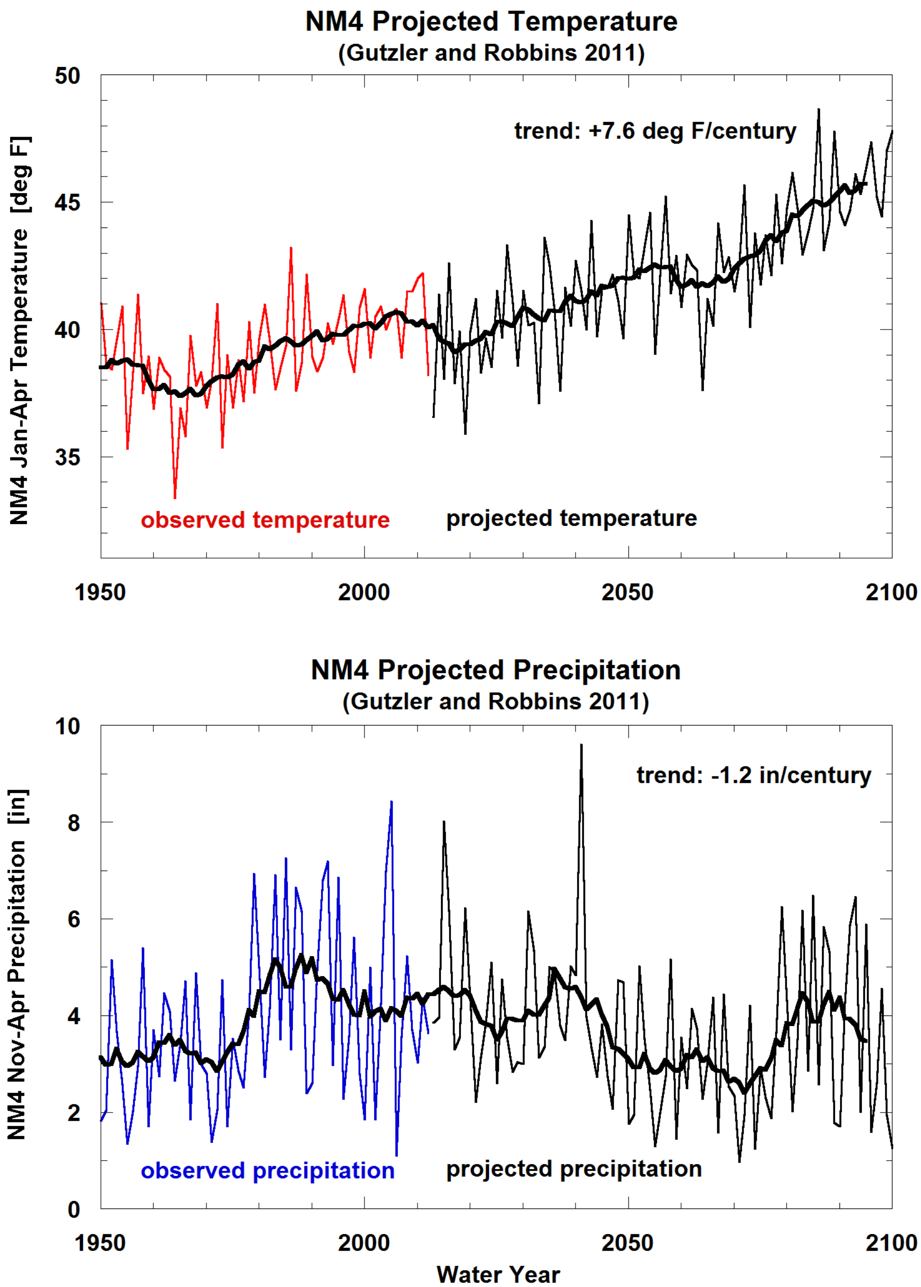


Figure 11. Projections of 21st Century temperature (top) and precipitation (bottom) in New Mexico Climate Division 4, generated by Gutzler and Robbins (2011). The initial segments of each time series, from 1951-2012, are observed data as shown in Figure 6. Projected monthly temperature and precipitation are derived by reproducing interannual variability from 20th Century observations in the 21st Century, then adding the linear trend for the 21st Century derived from the average of an ensemble of global climate models forced by the A1B radiative forcing scenario. Thick black lines in each panel indicate 11-year running averages.

Fig 12

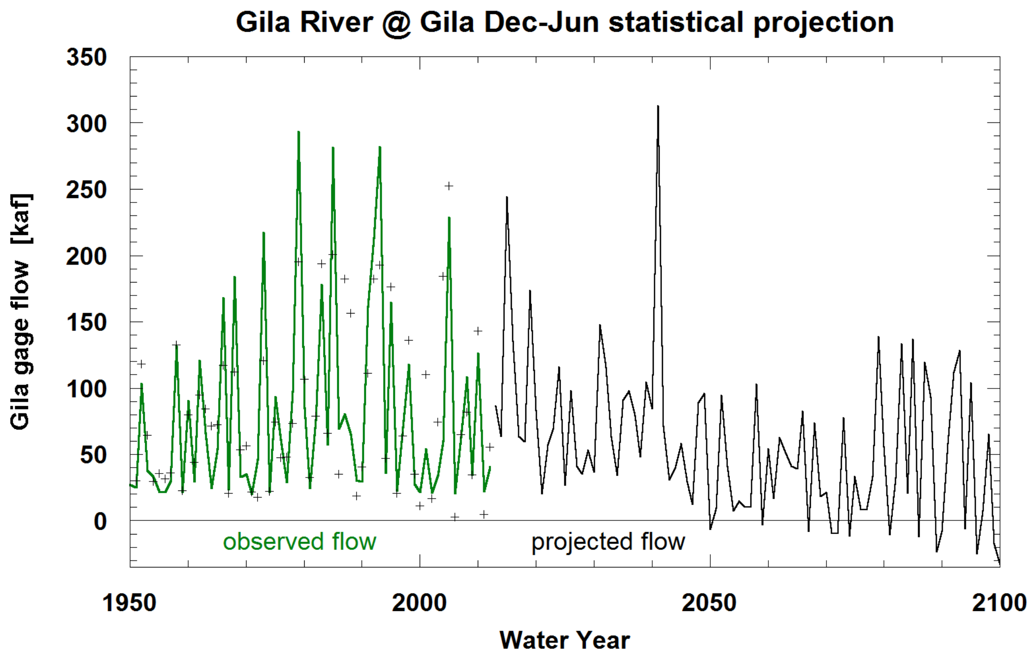


Figure 12. Time series of Dec-Jun flow at the Gila gage. The green line shows the observed time series from 1951-2012, reproduced from the middle panel of Figure 3. Black x's show the results of a regression model of Dec-Jun flow based on Nov-Apr precipitation and Dec-Apr temperature, as illustrated in the scatter plots presented in Figure 7. This model accounts for 69% of the observed variability of Dec-Jun streamflow at the Gila gage. The black line shows the continuation of the streamflow record into the future, using the same regression model for streamflow applied to projected NM4 precipitation and temperature as derived by Gutzler and Robbins (2011).

Note that in extreme dry or hot years the regression model can project unphysical negative flows. Negative flows are generated by the model with increasing frequency after 2050, as temperatures in NM4 warm up beyond the envelope of historical variability.