CLIMATE CHANGE IMPLICATIONS

ANNEX C TO THE DROUGHT MITIGATION AND RESPONSE PLAN

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Prepared by
Colorado Water Conservation Board
Department of Natural Resources
in Cooperation with
The Department of Public Safety
Division of Homeland Security & Emergency Management
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1 INTRODUCTION

The hydrology and water resources of Colorado, and hence the economy of the state, are extremely sensitive to climate. Multifaceted stress on water supply such as irrigation, municipal demands, mandated biological flows, and the increasing need for hydropower, coupled with climate variability and change, are increasing the importance of supply forecasting to both water managers and business markets. This section of the Colorado Drought Mitigation and Response Plan was motivated by the question "what could drought look like in the future." What follows is a high level analysis of possible implications of climate change for drought in Colorado.

The International Panel on Climate Change (IPCC 2007) has indicated that projected changes in mean flow or flow variability could cause physical infrastructure to be inadequate for intended purposes, or increase the risk of failure of the water resource system under extremes of drought. While such risks may be somewhat buffered in large water systems by robustness and resilience in the design of the system, smaller systems may be extremely vulnerable under climate scenarios.

A significant body of work exists considering the effect of climate change on water availability in the western United States (refer to bibliography). While there is a large amount of uncertainty regarding future climate scenarios and how these may translate to physical conditions, it is clear that current climate is not stationary and responsible planning efforts should take into account this uncertainty. Planning approaches that rely on stationary climate and notions of hydrologic history repeating itself are inherently flawed. Water managers need to understand how the nature of drought might vary in the future and incorporate that understanding into their planning processes.

Climate change has implications both in terms of inter-annual droughts and intra-annual runoff patterns. Intra-annual spring warming can shift peak runoff earlier in the year; important for Colorado, where hydrology is driven by snowmelt. Furthermore, many studies agree that higher temperatures could lead to an increased ratio of precipitation falling as rain versus snow as well as a higher snowline, which reduces the natural storage effect of Colorado's mountain snowpack (i.e., CWCB 2008, CWCB 2012, Knowles et al. 2006, Mote 2006, Saunders 2005, Udall 2007). Consequently, runoff could start earlier and end earlier. If this is the case, reservoirs would fill earlier, and what could not be stored in the spring and early summer would be spilled when agricultural demands are not as great as they are later in the summer. Decreased runoff in the summer would result in additional reservoir drawdown, and many studies agree that higher temperatures and lower precipitation during summer months would further increase agricultural demands, thus causing even more stress on reservoir storage (CWCB 2008, CWCB 2012). These factors could reduce the amount of water available for year-to-year carryover storage, thus increasing drought vulnerability.

The effects of climate change are not expected to be spatially consistent across the state. For example, there may be areas that receive additional moisture even in a "drier" climate.

The Colorado Water Conservation Board commissioned a synthesis report summarizing climate change science as it relates to Colorado's water supply (CWCB 2008). Some of their key findings are copied below. Regional studies suggest a reduction in total water supply in Colorado by the mid-21st century. Temperature increases and the resulting changes in evaporation and soil moisture will also add to a trend of decreasing runoff for most of Colorado's basins (CWCB 2008). However, when all of the available climate projections are considered, about one-third indicate no change or an increase in average streamflow in the Upper Colorado River Basin (i.e. at Lees Ferry Arizona). (Harding et al., 2012)

- In Colorado, temperatures increased about 2º F from 1977-2006. All regions examined within the state warmed during this time period, except the far southeast corner, in which there was a slight cooling trend.
- Climate models project Colorado will warm 2.5º F (+1.5º F to +3.5º F) by 2025, relative to the 1950-1999 baseline, and 4º F (+2.5º F to +5.5º F) by 2050. The 2050 projections show summers warming by 5º F (3º F to 7º F). These projections also suggest that typical summer monthly temperatures will be as warm as or warmer than the hottest 10% of summers that occurred between 1950 and 1999.
- Winter projections show fewer extreme cold months, more extreme warm months, and more strings of consecutive warm winters. Typical projected winter monthly temperature, although significantly warmer than current, are between the 10th and 90th percentiles of the historical record. Between today and 2050, typical January temperatures of the Eastern Plain of Colorado are expected to shift northward by ~150 miles. In all seasons, the climate of the mountains is projected to migrate upward in elevation, and the climate of the Desert Southwest to progress up into the valleys of the Western Slope.
- Projections show a precipitous decline in lower-elevation (below 8,200 ft) snowpack across the western part of the state by the mid-21st century. Modest declines are projected (10-20%) for Colorado's high-elevation snowpack (above 8,200 ft) within the same timeframe.
- Between 1978 and 2004, the spring pulse (the onset of streamflow from melting snow) in Colorado has shifted earlier by two weeks. Several studies suggest that shifts in timing of streamflows are related to warming spring temperatures. The timing of runoff is projected to shift earlier in the spring, and late-summer flows may be reduced. These changes are projected to occur regardless of changes in precipitation.
- Throughout the western part of the state, less frequent and less severe drought conditions have occurred during the 20th century than revealed in the paleoclimate records over the last 1,000 years. Precipitation variations are the main driver of drought in Colorado and low Lake Powell inflows, including the recent drought of 2000-2007, and these variations are consistent with the natural variability observed in long-term and paleoclimate records. However, warming temperatures may have increased the severity of droughts and exacerbated drought impacts.

The drought vulnerability assessment conducted for this project considers vulnerability to drought in a contemporary sense. However, the climate change implications noted above could exacerbate future drought vulnerability for a broad array of water users. Table 1.1 outlines the connection between climate change and water management issues. As can be seen from this table, impacts touch nearly every sector covered in the vulnerability assessment.

Table 1.1 Challenges Faced by Water Managers and Projected Changes

Issues	Observed and/or Projected Change
Water demands for agriculture and outdoor watering	Increasing temperatures raise evapotranspiration by plants, lower soil moisture, alter growing seasons, and thus increase water demand.
Water supply infrastructure	Changes in snowpack, streamflow timing, and hydrograph evolution may affect reservoir operations including flood control and storage. Changes in the timing and magnitude of runoff may affect functioning of diversion, storage, and conveyance structures.
Legal water systems	Earlier runoff may complicate prior appropriation systems and interstate water compacts, affecting which rights holders receive water and operations plans for reservoirs
Water quality	Although other factors have a large impact, "water quality is sensitive both to increased water temperatures and changes in patterns of precipitation" (CCSP SAP 4.3, p. 149). For example, changes in the timing and hydrograph may affect sediment load and pollution, impacting human health.
Energy demand and operating costs	Warmer air temperatures may place higher demands on hydropower reservoirs for peaking power. Warmer lake and stream temperatures may affect water use by cooling power plants and other industries.
Mountain habitats	Increasing temperature and soil moisture changes may shift mountain habitats toward higher elevation.
Interplay among forests, hydrology, wildfires, and pests	Changes in air, water, and soil temperatures may affect the relationships between forests, surface and groundwater, wildfire, and insect pests. Water-stressed trees, for example, may be more vulnerable to pests.
Riparian habitats and fisheries	Stream temperatures are expected to increase as the climate warms, which could have direct and indirect effects on aquatic ecosystems (CCSP SAP 43.), including the spread of instream non-native species and diseases to higher elevation and the potential for non-native plant species to invade riparian areas. Changes in streamflow intensity and timing may also affect riparian ecosystems.
Water – and snow – based recreation	Changes in reservoir storage affect lake and river recreation activities; changes in streamflow intensity and timing will continue to affect rafting directly and trout fishing indirectly. Changes in the character and timing of snowpack and the ratio of snowfall to rainfall will continue to influence winter recreational activities and tourism.
Groundwater resources	Changes in long-term precipitation and soil moisture can affect groundwater recharge rates; coupled with demand issues, this may mean greater pressure on groundwater resources.

Source: Reproduced from CWCB, 2008

2 Placing Historical Conditions in Context: Past and Future

As a component of the 2013 update to this Plan, projections of future streamflow were obtained for a number of locations in the Colorado, South Platte and Arkansas River basins from the Colorado River Water Availability Study (CRWAS) and the Joint Front Range Climate Change Vulnerability Study (Front Range Study, WRF, 2012). Reconstructions of prehistoric ("paleo") flows have been made for a large number of stream gauges in Colorado (NOAA, 2013). Sixteen locations were selected where both climate change projections and prehistoric reconstructions exist. These locations, and the sources of data for the comparisons, are shown in Table 2.1.

Table 2.1 Gauge Locations for Comparisons

BASIN	PALEO GAGE	PROJECTED GAGE	
		CRWAS	JFRCCVS
Upper Arkansas			
Arkansas	Arkansas River near Canon City (07096000)	-	UC_Ark_Salida 07091500
Colorado			
Animas	Animas River at Durango, CO (09361500)	ARDUR 9361500	-
Blue	Blue River above Green Mountain Reservoir (09053500)	BRBGM 9057500	UC_GreenMountain 9057500
Colorado	Colorado River near Kremmling, CO (09058000)	CRKRE 9058000	-
Dolores	Dolores River near Cisco, UT (09180000)	DRGAT 09179500	-
Fraser	Fraser River at Granby (09034000)	-	UC_Fraser 09034000
Roaring Fork	Roaring Fork at Glenwood Springs, CO (09085000)	RFGWS 09085000	-
San Juan	San Juan River near Archuleta, NM (09355500)	SJRAR 09355500	-
White	White River near Watson, UT (09306500)	WRCUT 09306395	-
Yampa	Yampa River near Maybell, CO (09251000)	YRMBL 09251000	-
South Platte			
Big Thompson	Big Thompson River at Mouth of Canyon near Drake (06738000)	-	SP_BigThompson 6738000
Boulder Creek	Boulder Creek at Orodell	-	SP_BoulderCreek
Cache la Poudre	Cache la Poudre River at Mouth of Canyon (06752000)	-	SP_Poudre 06752000
South Platte	South Platte River at South Platte (06707500)	-	SP_SouthPlatte
South Platte	South Platte River below Cheesman Reservoir	-	SP_Cheesman
St. Vrain	St. Vrain Creek at Canyon Mouth near Lyons	-	SP_StVrain

At these locations, graphical comparisons of prehistoric, historical, and projected flows were developed that provide context within which to consider the 56-year period experienced from 1950 through 2005. Figure 2.1 shows the comparison for the Yampa River near Maybell. The 56-year running average of the paleo data is the solid blue line. The end of the solid blue line represents average conditions over the most recent 56 years. The dashed lines show the averages for each climate-impacted flow scenario. The highest and lowest 56-year average flows in the prehistoric data encompass most of the climate impacted flow averages, with the exceptions of the warm, wet scenarios for both 2040 and 2070.

Figure 2.2 shows the comparison for the Arkansas River at Salida. In contrast to the Yampa, the prehistoric flows show much less variability, and all but one of the projected scenarios fall outside the maximum and minimum flows of the prehistoric reconstruction. Also in contrast to the Yampa, six of the eight projected scenarios fall below the historical average flow (indicated by the end of the blue trace). This difference is indicative of a trend that is generally apparent in the CRWAS and Front Range Study results, where projections of future flows tend to be wetter in the northernmost portions of the State, and tend to be drier in the more southerly portions of the State.

Figure 2.1 Flow Comparison, Yampa River near Maybell

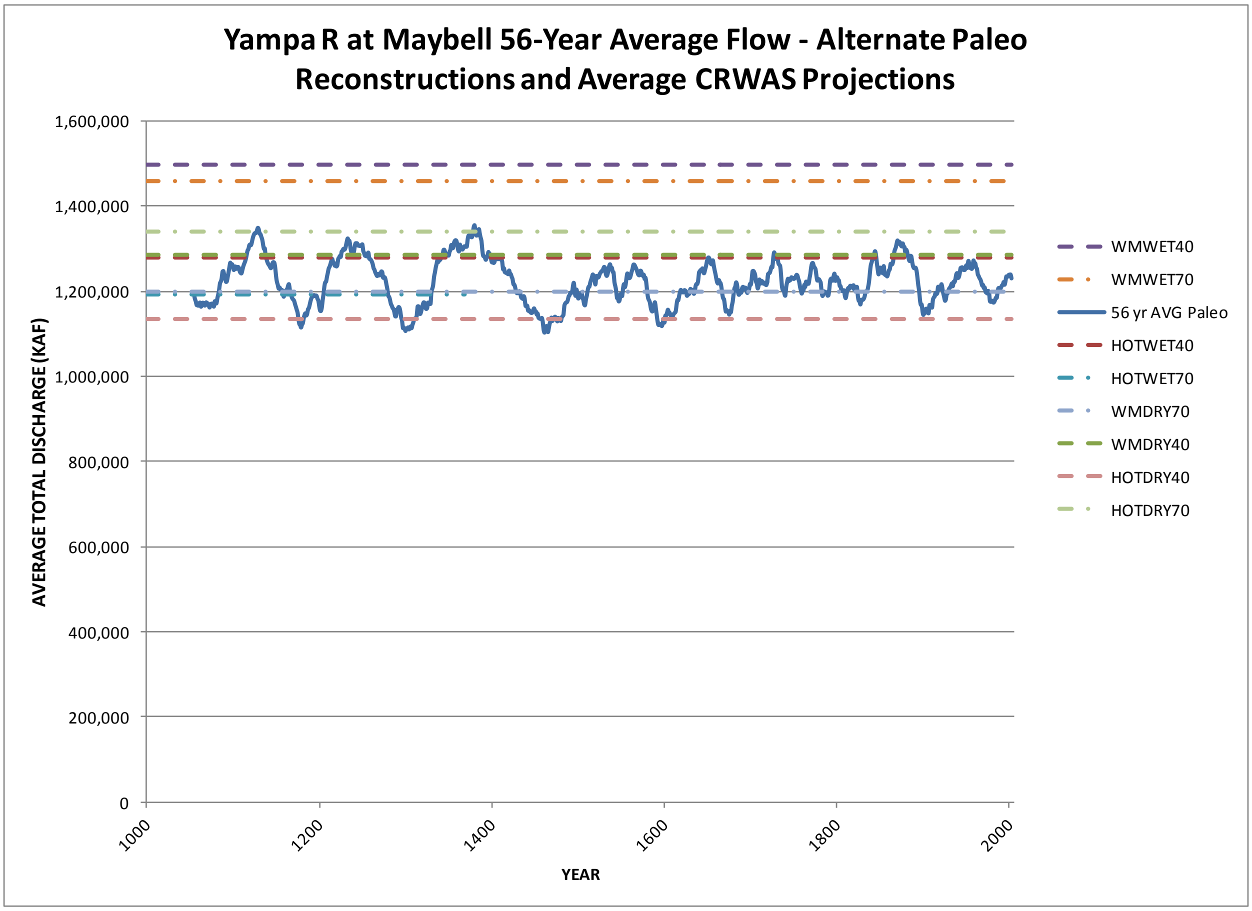
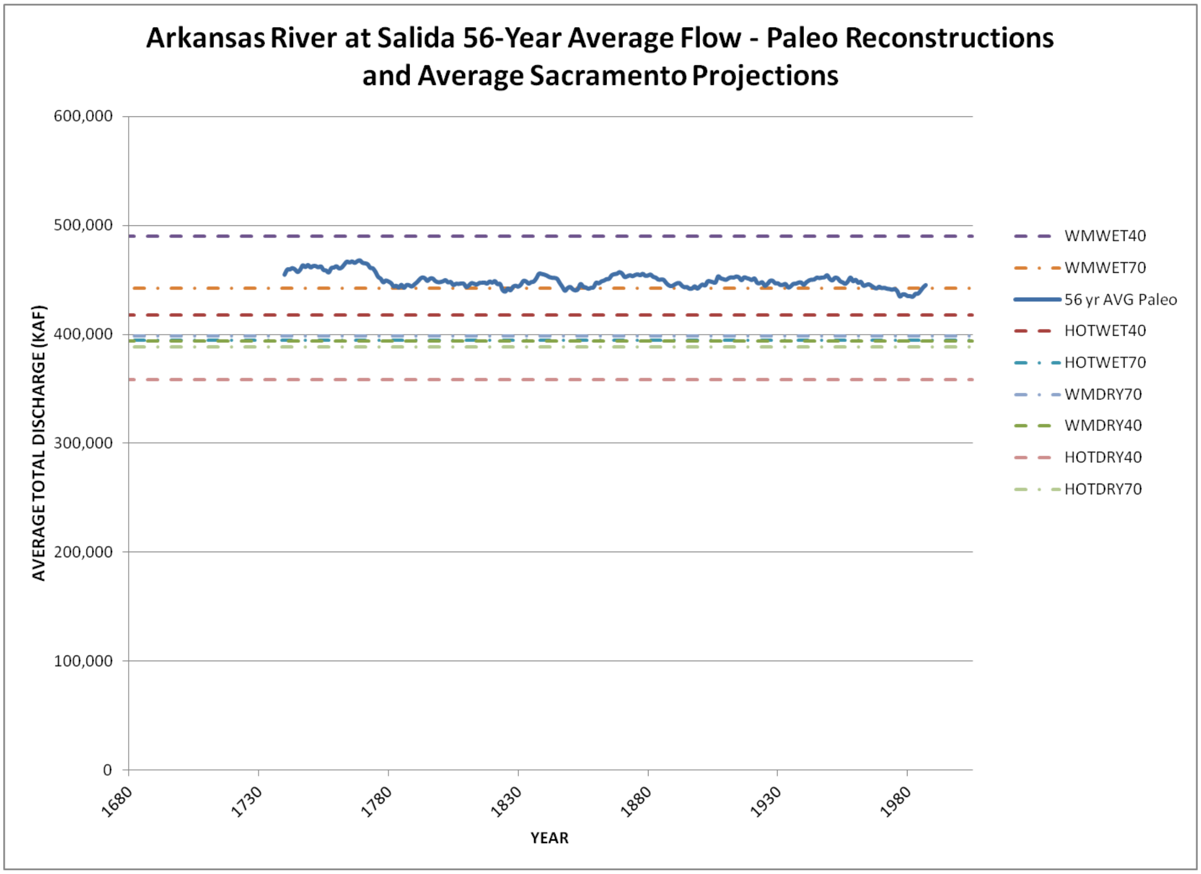


Figure 2.2 Flow Comparison, Arkansas River at Salida



Comparisons for all sixteen locations can be found in Appendix 1 to this Annex. The comparisons can be used to better understand the degree to which projected, climate-impacted streamflows differ from historical and prehistoric conditions. Because there is greater scientific confidence in the quantification of prehistoric flows than in the quantification of projected flows, there is a better scientific basis to support adaptation measures based on the variability of prehistoric flows. In the case of the Yampa, a system that performs acceptably over the range of prehistoric flows can be expected (within the limits of our current state of knowledge) to be reasonably well-adapted to future climate. In contrast, on the Arkansas, most of the projections fall outside the range of the prehistoric flows, and therefore decisions regarding adaptation must primarily consider the projections of future flow in order to develop management strategies that will meet future needs.

It is important to keep in mind that these comparisons use 56-year average flows. Annual droughts and multi-year dry spells will be superimposed on the average flows, so the curves and projections do not represent the most severe conditions that may face a system.

3 OTHER CLIMATE CHANGE FINDINGS IN COLORADO

3.1 Colorado River Water Availability Study Phase I

The Colorado River Water Availability Study (CRWAS Phase I), sponsored by the Colorado Water Conservation Board, investigated water availability on the Colorado River under a range of climate change scenarios. The Study Area for this work was the Colorado River Basin within the State of Colorado.[1] The methods are discussed in more detail in the following section. The discussion below outlines the primary findings of this study based on climate projections for 2040.

3.1.1 Colorado River Water Availability Study Findings

Compared to current conditions, CRWAS Phase I findings show that projected future climate conditions may lead to the following changes to hydrologic conditions in the Colorado River basin within western Colorado.

3.1.1.1 Temperature

- At northern climate stations (e.g., Grand Lake, Yampa, and Hayden), temperature increase is less than for the Study Area average.
- Every climate projection shows an increase in average annual and monthly temperature
- Study Area average annual increases range from 1.8°F to 5.2°F

3.1.1.2 Precipitation

- Generally increases in the winter months and decreases in the summer months
- Average winter increases are larger in the northern portion of the Study Area, and smaller in the southwestern portion of the Study Area
- Increase in temperatures causes a shift from snow to rain in the early and late winter months
- Study Area winter average changes by 102% to 116% of historical
- Study Area April through October average changes by 82% to 105% of historical

3.1.1.3 Crop Irrigation Requirement (based on acreage and crop types identified in a 1993 acreage inventory)

- Increases for each of the climate projections throughout the Study Area
- Increases are primarily due to higher temperature and lower irrigation-season precipitation, which increase:
  - the number of days in the growing season for perennial crops, and
  - the crop demand for irrigation water
- Peak CIR continues to occur in the same month as it has historically

[1] The CRWAS also evaluated the impact of climate change on streamflows at Lee's Ferry on the Colorado River.

- Study Area average annual CIR increases by 1.9 to 7.4 inches for individual climate scenarios
- Study Area average annual growing season increases by 8 to 32 days

3.1.1.3.1 *Crop Irrigation Requirement for Study Basins*

- Every Study Basin shows an increase for all climate scenarios
- The White River basin shows the largest percentage increase
- The Yampa River basin shows the smallest percentage increase

3.1.1.4 Natural Flow

3.1.1.4.1 *Historical Hydrology*

- The longest (historical) wet spells range from 4 to 16 years in length, with only 4% longer than 7 years
- Historical dry spells range from 3 to 11 years in length with 95% being 5 or 6 years long
- Moving from north to south, historical dry spells generally become shorter and historical wet spells generally become longer
- The alternative historical flow analysis indicates that the return intervals for dry spells generally become shorter moving from north to south, meaning that droughts are more frequent in southern Colorado

3.1.1.4.2 *Extended Historical Hydrology*

- The return interval of historical wet and dry spells vary widely from location to location
- Return intervals are shorter for locations that have shorter historical spells and longer for locations that have longer historical spells
- At 90% of the sites, the return interval of the historical dry spell ranges from about 8 to about 200 years, and the return interval of the historical wet spell ranges from about 13 to about 100 years

3.1.1.4.3 *In very general terms, locations with shorter historical spells should expect longer spells and vice versa*

3.1.1.4.4 Climate-Adjusted Hydrology

- At over 80% of the sites, the majority of climate cases suggest a decrease in annual flow
- Annual flow is more likely to increase in parts of the Yampa River basin and in some higher elevation watersheds
- Annual flow is more likely to decrease in southwestern watersheds and at lower elevations
- At 75% of locations, all climate cases showed a shift toward earlier runoff, and at all locations, some climate cases showed a shift toward earlier runoff
- Higher peak flows may be beneficial for riparian health; however, lower flows in late summer and fall may impact other non-consumptive needs

- At three locations, all climate cases showed increases in average annual flows. At the remaining 224 locations, the climate cases contained the historical average annual flow
- Runoff shifts earlier by an average of 8 days

3.1.1.4.5 *Modeled Streamflow*

- Flows are generally higher than historical in May and June and lower in July through March
- Flows are generally lower than historical in three of the five climate projections, but generally higher than historical in two projections
- The historical annual low-flow values generally fall within the range of projected low-flow values

3.1.1.4.6 *Water Available to Meet Future Demands*

- Upstream locations on main rivers and smaller tributaries generally have less flow available to meet future demands as a percent of modeled streamflow than gages farther downstream that include more tributary inflow
- Most locations show less water availability for three of the five climate projections. However, for one of the projections, the locations selected to display CRWAS Phase I results show more water available
- The climate projections generally indicate more water availability in April and May, corresponding to the shift in the natural flow hydrographs
- The historical annual minimum water availability values generally fall within the range of projected minimum water availability values for 2040 throughout the Study Area

3.1.1.4.7 *Modeled Reservoir Storage*

- Earlier peak runoff, reduced flows during the peak irrigation season, and increased crop demands result in more use of reservoirs (more reservoir fluctuation)
- Reservoirs are generally drawn down to lower levels, and generally fill to historical levels

3.1.1.4.8 *Modeled Consumptive Use*

- Average annual consumptive use in the Yampa, White, Upper Colorado, and Gunnison basins is greater for every climate projection. Average annual consumptive use in the San Juan basin is less for every climate projection
- Total consumptive use for the Study Area is greater than for historical climate conditions for most climate projections
- Although modeled consumptive use generally increases, not all crop demands are met in any basin. Similar to historical conditions, there continue to be water shortages on tributaries and in the late irrigation season for the projected conditions
- Projected consumptive use increases in most months in every basin except the San Juan. Projected consumptive use in the San Juan generally increases in spring months only

Phase I of the CRWAS considered five climate change scenarios, all treated as if they were equally probable. Temperature and precipitation changes from Global Climate Models (GCMs) were translated to natural flows using the Variable Infiltration Capacity (VIC) model. The historical hydrology used for comparison is the observed flow over the 56-year period from 1950-2005. Additionally, historical streamflow records were extended using previously published tree ring records dating back more than 1,200 years. The 56-year historical hydrology was re-sequenced into 100 equally likely 56-year traces based on the probabilities of transitioning between wet and dry years that were derived from the paleohydrology record. These traces are called the alternate historical hydrology traces in this report. The discussion in the following section outlines the technical approach of the CRWAS in more detail. The results of the CRWAS include information about how projected future climate might affect drought duration, drought intensity and drought frequency.

The CRWAS analyzed drought frequency and intensity compared to the longest drought observed throughout the 56-year period of record. Modeled natural flow results from each of the five equally likely climate change scenarios and the historical hydrology were each re-sequenced to produce a record 5,600 years long, equivalent to 100 equally likely 56-year hydrology traces. Drought durations and intensities (the degree to which flows are reduced during the drought) were calculated for each of the 100 traces. Drought conditions were defined as any time flow drops below the historical mean flow.

All of the droughts identified for each of the six scenarios (five climate change scenarios and the alternate historical hydrology) were used to calculate the return interval and the intensity of a dry or wet spell that has the same length as the longest spell experienced during the historical period. This approach answers the question: What is the likelihood that a spell of a particular length will begin next year (now, or in 2040 or 2070)?

3.1.1.5 Colorado River Water Availability Study Technical Approach Summary

- Historical Hydrology includes hydrology observed for period 1950-2005.
- Paleohydrology is based on an extended record dating to AD 762 (more than 1,200 years ago)
  - Provides estimated streamflow duration/frequency/intensity for years prior to gaged data.
  - Estimated using statistical models applied to tree ring data.
  - Paleohydrology flow magnitudes are derived from the historical flow record (1950-2005).
  - Flow sequences are derived from paleohydrology flow record to provide more robust variety of year to year flow sequences than historical record.
  - Re-sequencing – Future sequences of wet and dry years cannot be predicted; therefore, a 5,600-year hydrologic trace was developed.
    - This is statistically equivalent to the 100 56-year traces used for modeling in CRWAS.
    - Each 56-year period in the 5,600-year trace is equally probable.
- Climate-Adjusted Hydrology is based on five climate projections selected in consultation with the State's Climate Change Technical Advisory Group.

- Five climate projections were chosen for each of the 2040 and 2070 planning horizons.
- Each of the selected climate projections is treated as being equally probable; but differs from the others.
- Projections are "downscaled" to the Colorado River basin and temperature and precipitation changes were translated into effects on hydrology using the VIC hydrologic model. Flow sequences (dry/wet spells) were derived from those used in the paleohydrology flow record because it has been shown in the literature that GCM's alone do not simulate flow sequences reliably.

Selected results from CRWAS are displayed in Table 3.1 through Table 3.4 and Figure 3.1 through Figure 3.6. Results for 42 sub-basins and selected weather stations and reservoirs may be found in Appendix C of the CRWAS final report (CWCB 2012a).

Table 3.1 through Table 3.4 present the characteristics of spells for the observed period, the Extended Historical Hydrology (EHH, labeled as Alternative Historical) and the Climate-Adjusted Hydrology (CAH) (CWCB, 2012a, Appendix C).

The observed spells are characterized in the top panel of the table. For example, for the Colorado River near Cameo (Table 3.1), the observed drought (during the period 1950 through 2005) was six years in length and, for those six years, the flow was, on average, 19 percent below the long-term mean flow. Similarly, the observed surplus was five years in length and flows were 46 percent greater than the mean during that period.

The statistics of the EHH (developed by re-sequencing) are shown in the first row of the bottom panel (Alternative Historical). The results in Table 3.1 show that droughts of six years in length returned every 31 years and surpluses of five years in length returned every 19 years. The average drought intensity for six-year droughts was -24 percent, somewhat greater than the historical intensity (-19 percent). The average intensity of surplus spells of five years in length was 27 percent, less than the historical intensity (46 percent).

The statistics for the CAH are in the ten rows below the statistics for the EHH in the lower panel. The first five rows are the results for the projections for 2040 while the next five rows are the results for the projections for 2070. Because the CAH and the EHH are based on the same year sequences, it is best to compare those two results rather than trying to compare the CAH to the historical observed event. On that basis, in Table 3.1, the 2040 time frame cases A, B and C show more frequent six-year droughts than is the case in the EHH; cases D and E show droughts that are less frequent. For 2070, cases F and G show six-year droughts that are substantially more frequent than the EHH, cases H and I show 6-year droughts that are approximately as frequent as in the EHH, and case J shows droughts that are substantially less frequent. For the 2040 time frame, cases A, B and C show five-year surpluses that are less frequent than was the case in the EHH, case D shows 5-year surpluses that are approximately as frequent as the EHH, and case E shows 5-year surpluses that are substantially more frequent than the EHH. For the 2070 time frame, cases F, G and H show five-year surpluses that are less frequent than was the case in the EHH, case I shows

5-year surpluses that are approximately the same frequency as in the EHH, and case J shows more frequent surpluses than in the EHH. Deficit intensities vary from case to case, but not by a large amount except for cases E and J; surplus intensities vary over a wider range.

When a spell of a length equal to or exceeding the historical spell is not encountered in a particular climate case, this is designated by a double dash in the return interval and intensity fields. For example, in Table 3.2, Yampa River near Maybell, a drought of six years in length was not encountered in climate case J for 2070.

Table 3.1 Colorado River near Cameo

	Observed Spells			
	Length of Spell (years)		Intensity of Spell (% of mean)	
	Drought	Surplus	Drought	Surplus
	6	**5**	**-19%**	**46%**

Alternative Hydrology Spells				
	Return Interval of historic spell length (years)		Average Annual Deficit/Surplus (% of mean)	
Case	Drought	Surplus	Drought	Surplus
Alternative Historical	31	19	-24%	27%
2040 Climate A	6	933	-30%	23%
2040 Climate B	27	47	-29%	19%
2040 Climate C	22	49	-28%	18%
2040 Climate D	53	20	-25%	29%
2040 Climate E	800	6	-19%	36%
2070 Climate F	6	5600	-31%	24%
2070 Climate G	12	267	-31%	18%
2070 Climate H	27	66	-32%	17%
2070 Climate I	30	22	-23%	27%
2070 Climate J	127	13	-19%	38%

Table 3.2 Yampa River near Maybell

	Observed Spells			
	Length of Spell (years)		Intensity of Spell (% of mean)	
	Drought	Surplus	Drought	Surplus
	6	**5**	**-26%**	**48%**

Alternative Hydrology Spells				
	Return Interval of historic spell length (years)		Average Annual Deficit/Surplus (% of mean)	
Case	**Drought**	**Surplus**	**Drought**	**Surplus**
Alternative Historical	31	14	-28%	31%
2040 Climate A	15	79	-30%	28%
2040 Climate B	56	21	-29%	34%
2040 Climate C	56	21	-28%	35%
2040 Climate D	--	6	--	51%
2040 Climate E	800	8	-21%	46%
2070 Climate F	24	51	-34%	29%
2070 Climate G	62	17	-29%	43%
2070 Climate H	66	15	-28%	41%
2070 Climate I	1120	8	-23%	44%
2070 Climate J	--	2	--	78%

Table 3.3 Gunnison River near Grand Junction

	Observed Spells			
	Length of Spell (years)		Intensity of Spell (% of mean)	
	Drought	Surplus	Drought	Surplus
	5	6	-33%	50%

Alternative Hydrology Spells				
	Return Interval of historic spell length (years)		Average Annual Deficit/Surplus (% of mean)	
Case	Drought	Surplus	Drought	Surplus
Alternative Historical	17	20	-30%	30%
2040 Climate A	5	2800	-40%	26%
2040 Climate B	13	187	-35%	32%
2040 Climate C	12	187	-36%	29%
2040 Climate D	18	35	-31%	36%
2040 Climate E	30	15	-22%	48%
2070 Climate F	4	--	-40%	--
2070 Climate G	8	311	-39%	15%
2070 Climate H	13	187	-38%	28%
2070 Climate I	13	187	-33%	37%
2070 Climate J	19	48	-28%	47%

Table 3.4 San Juan River near Carracas

	Observed Spells			
	Length of Spell (years)		Intensity of Spell (% of mean)	
	Drought	Surplus	Drought	Surplus
	4	6	-35%	47%

Alternative Hydrology Spells				
	Return Interval of historic spell length (years)		Average Annual Deficit/Surplus (% of mean)	
Case	Drought	Surplus	Drought	Surplus
Alternative Historical	17	34	-36%	35%
2040 Climate A	2	--	-40%	--
2040 Climate B	6	207	-38%	31%
2040 Climate C	11	86	-37%	45%
2040 Climate D	14	57	-33%	52%
2040 Climate E	61	16	-34%	54%
2070 Climate F	3	--	-44%	--
2070 Climate G	3	--	-46%	--
2070 Climate H	9	509	-44%	45%
2070 Climate I	6	200	-38%	33%
2070 Climate J	18	64	-39%	57%

The CRWAS also provided information that helps frame projected low-flow conditions in the context of conditions over the 56-year historical baseline. Figure 3.1 illustrates the effect of projected future climate conditions on mean flows and on low-flow events.

Figure 3.1 Low Flow Comparison Chart, Colorado River near Cameo

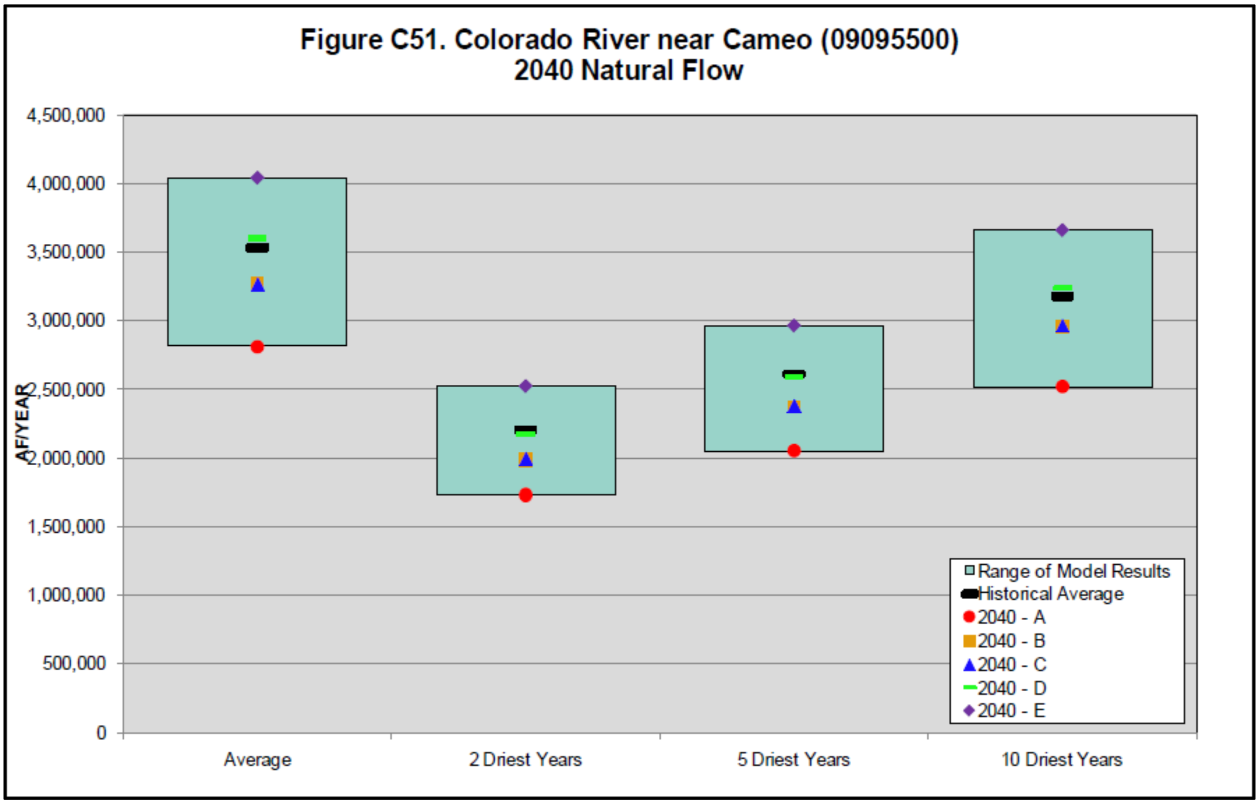


Figure 3.1 provides a direct comparison of projected conditions to conditions at Cameo during the 56-year historical baseline. From left to right, the chart represents four statistics of annual flow: average annual flow over the 56-year study period, the lowest consecutive 2-year average flow in the 56-year study period, the lowest consecutive 5-year average flow in the 56-year study period and the lowest consecutive 10-year average flow in the 56-year study period (CWCB 2012a). For each statistic, several pieces of information are shown. The red filled diamond represents the value of the statistic from the historical record during the study period. The estimated values of the statistics for the five different projections of future climate are represented by dashes. The wide cyan-colored bars show the overall range of the projected future values of the statistic.

Depending on the selected projections, average flows and low flows for durations of 2, 5, and 10 years may be greater or lesser than the corresponding condition during the 56-year historical baseline. As noted above, wetter scenarios will tend to exhibit droughts that are shorter and less intense that those experienced during the 56-year baseline period. Conversely, drier scenarios will tend to exhibit droughts that are longer and more intense than those experienced during the 56-year baseline period. Figure 3.2 through Figure 3.4 show the same information for the Yampa River near Maybell, the Gunnison River near Grand Junction, and the San Juan River near Carracas.

Figure 3.2 Low Flow Comparison Chart, Yampa River near Maybell

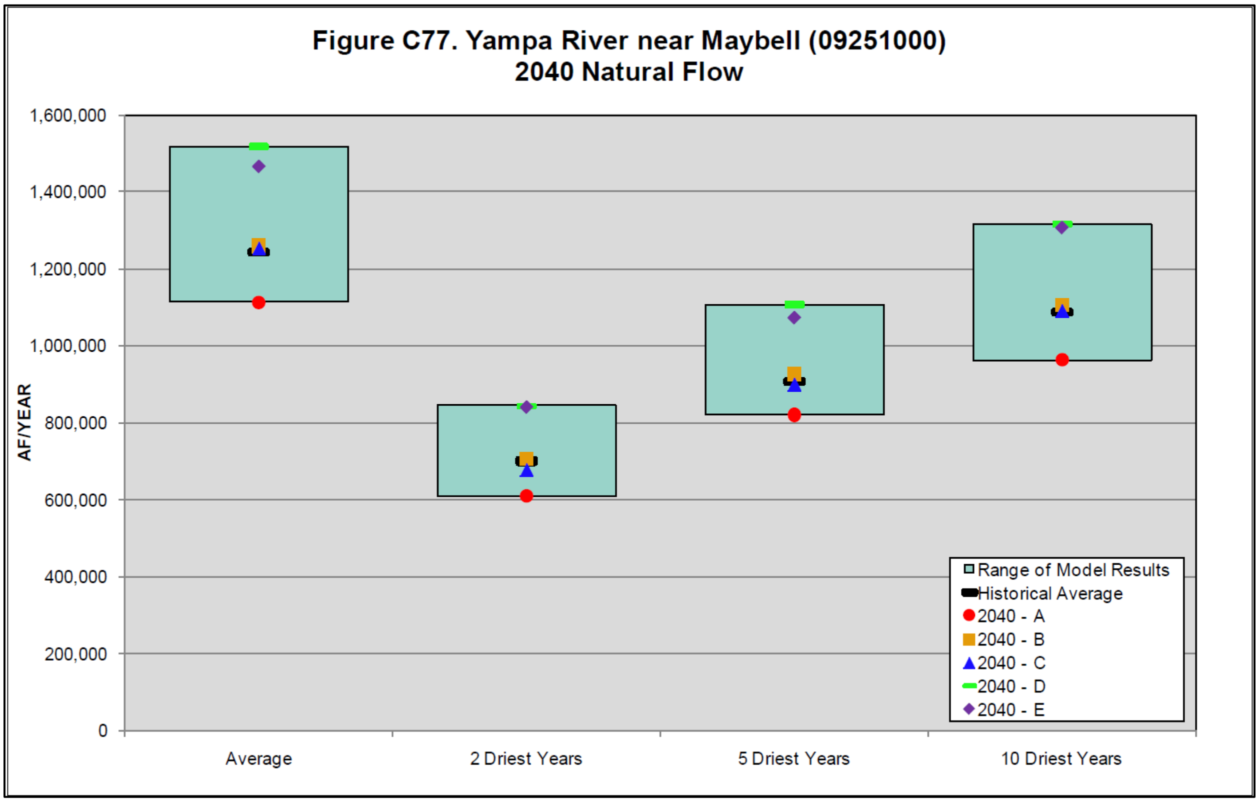


Figure 3.3 Low Flow Comparison Chart, Gunnison River near Grand Junction

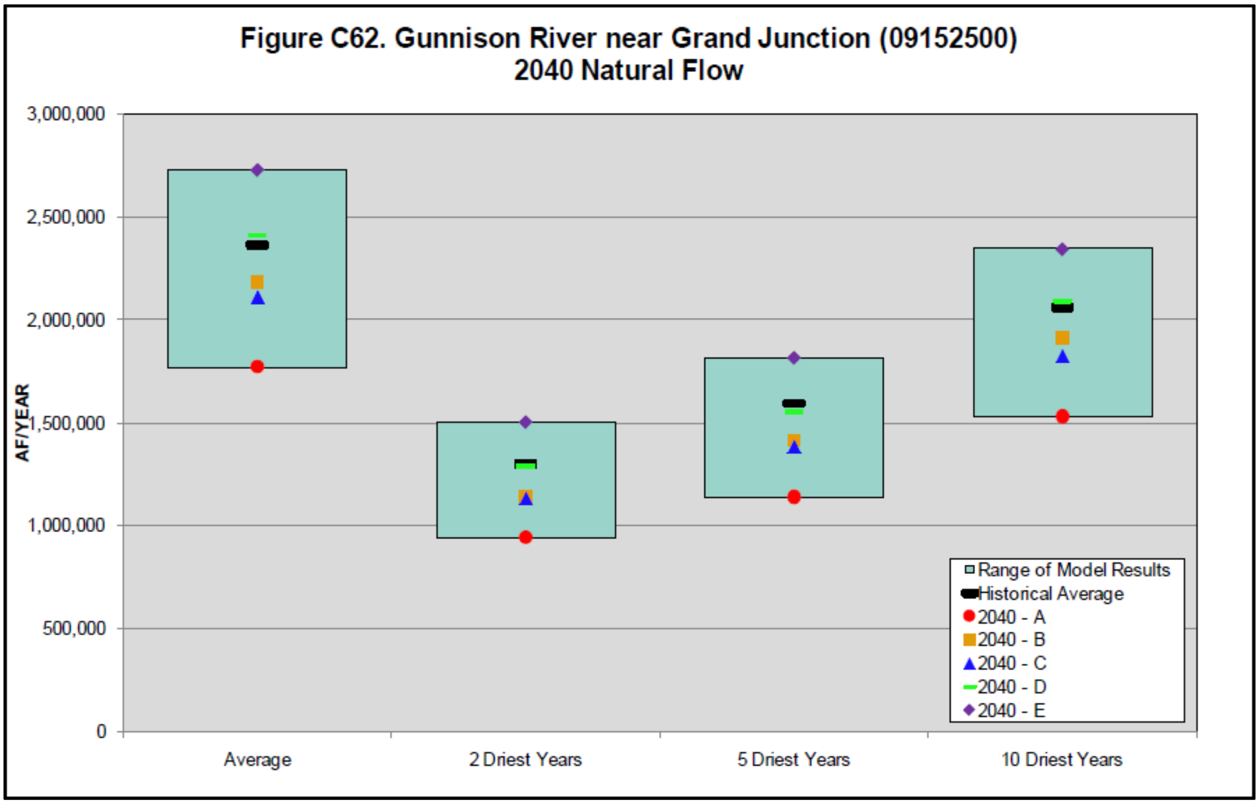


Figure 3.4 Low Flow Comparison Chart, San Juan River near Carracas

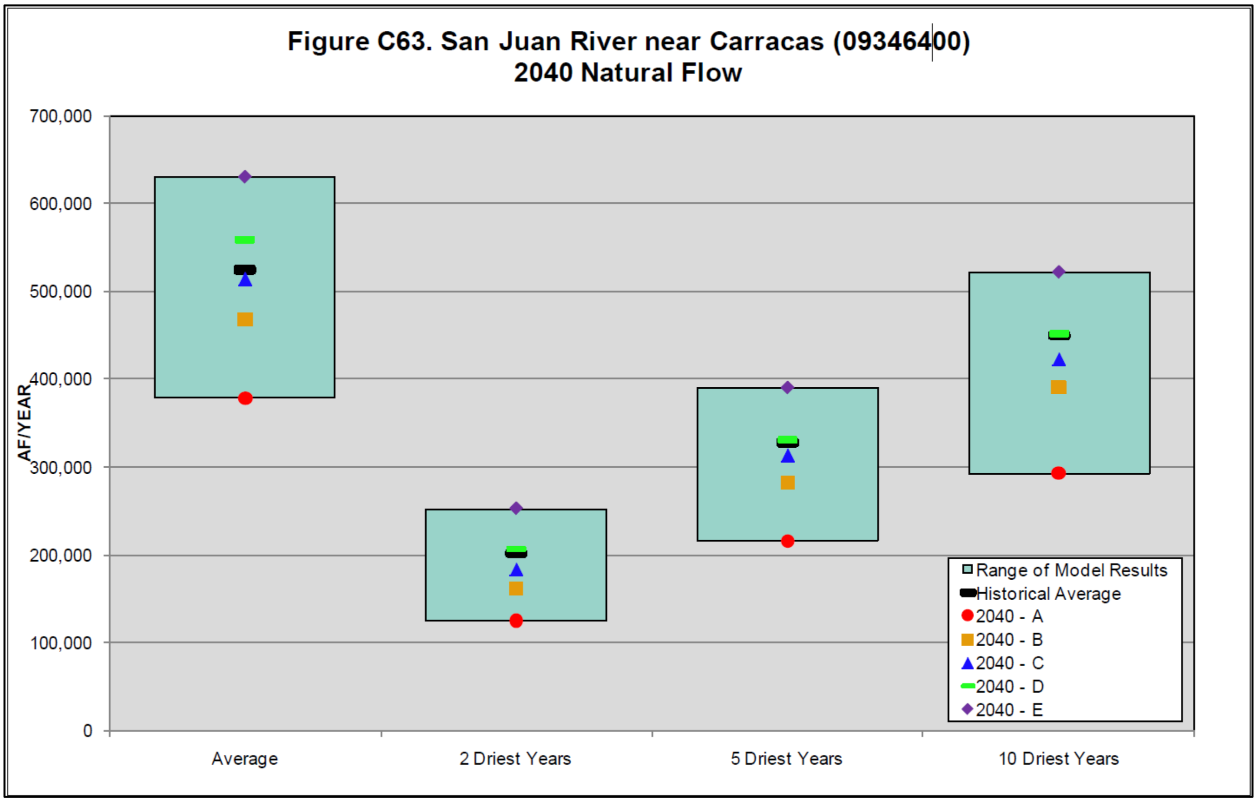


Figure 3.1 through Figure 3.4 reflect the spatial pattern of the impact of projected climate on streamflow in Colorado: in the selected projections, natural flow increases (or decreases less) more often in more northerly parts of the state (and at higher elevations) while the converse is true in more southerly areas (and at lower elevations).

Figure 3.5 illustrates the impact of projected climate conditions on crop irrigation requirement or consumptive irrigation requirement (CIR), the amount of water (expressed as depth, in inches) necessary to supplement precipitation in order to fully supply a crop's water needs. This is also commonly referred to as the irrigation water requirement (IWR). Figure 3.5 shows that because temperature increases in all projections, CIR increases even if the projections indicate an increase in precipitation.

Figure 3.5 Average Monthly CIR Comparison

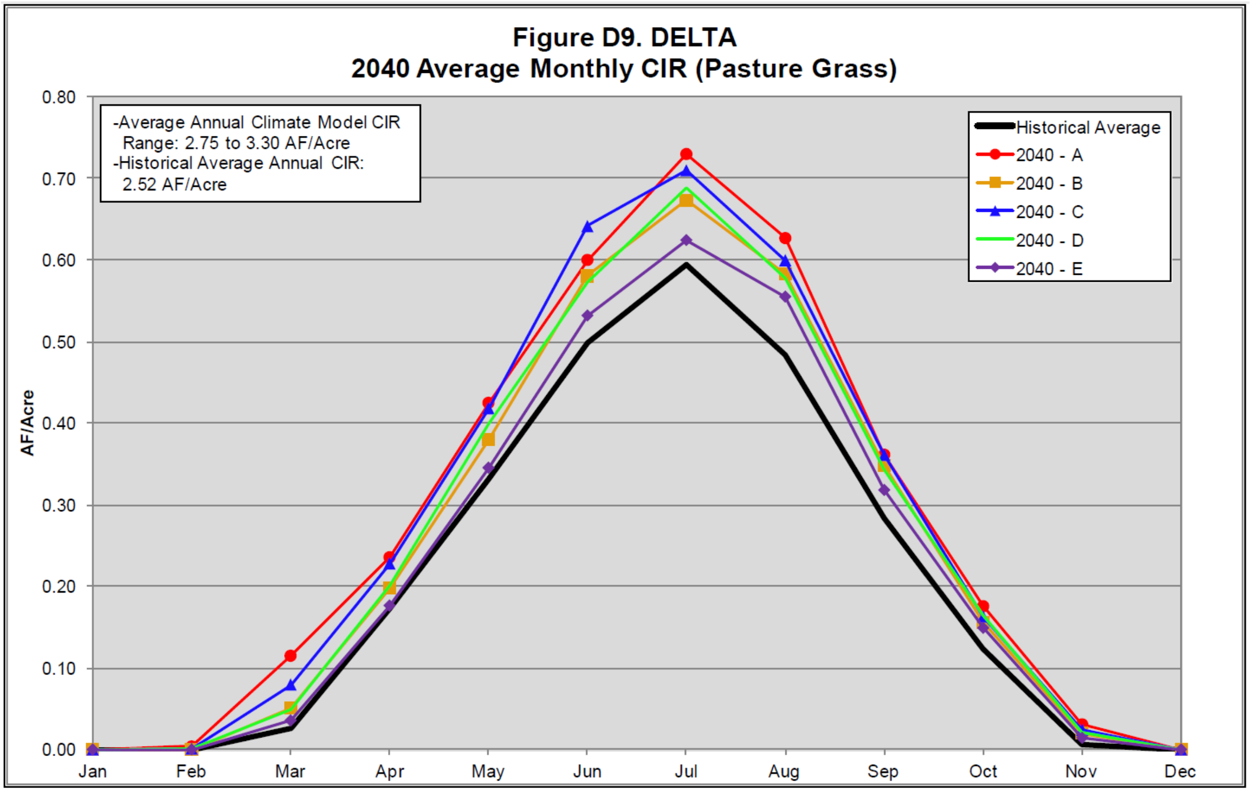
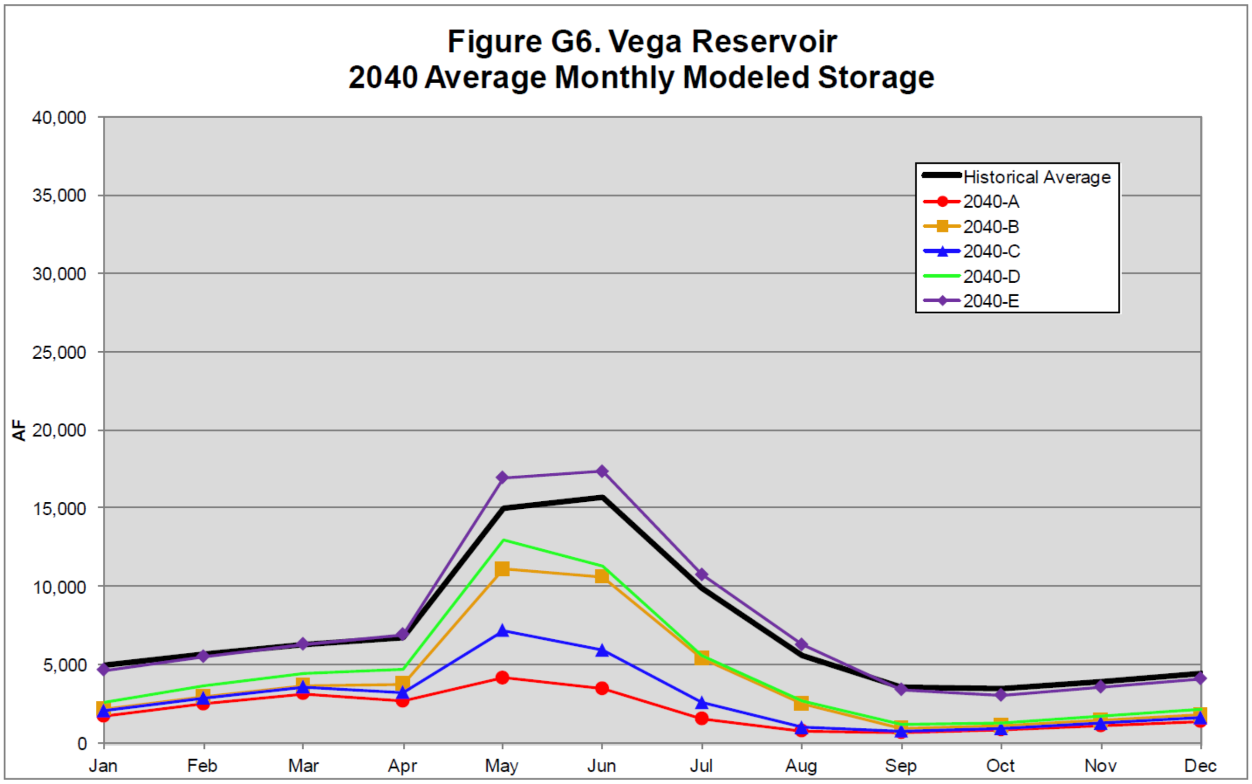


Figure 3.6 brings together the effects of climate on natural flow and agricultural water demand. It shows average monthly modeled Vega Reservoir content over the 1950 through 2005 study period for historical climate conditions, and for each of the 2040 climate projections. These results, which are from StateMod modeling done as part of the CRWAS, reflect the operation of Vega reservoir in the context of the climate-impacted natural flows, climate-impacted water demands, and the water rights and operating rules in the basin. Figure 3.6 illustrates the significance of changes in the monthly pattern of precipitation and increasing temperature – even the climate projections that result in natural flows similar to or greater than historical conditions show increased impacts on reservoir storage. This is due to increased agricultural water demand as is illustrated in Figure 3.5. Because average end-of-water-year storage is reduced in all climate projections, the amount of water available for year-to-year carryover storage is reduced, which will increase vulnerability to drought.

Figure 3.6 Vega Reservoir - 2040 Average Monthly Modeled Storage Contents



The CRWAS provides excellent information for the Colorado River. However, given the diversity of Colorado's river basins and the spatial differences noted just within the Colorado River, it is not appropriate to translate the results of the CRWAS to other basins.

3.2 Colorado River Water Availability Study Phase II

The CRWAS project was completed in 2012 and was later continued as CRWAS Phase II (CRWAS-II), to achieve the following climate and hydrology objectives:

- Update Phase I (CRWAS-I) to include projections in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive;
- Develop an improved method for creating climate scenarios;
- Extend the historical hydrology through 2012;
- Provide climate adjustments to natural flow and CIR for the entire state (not just the Colorado River Basin).

The CRWAS-II extension was completed in 2015, and the data was used to update the low flow comparison charts included in the 2013 Drought Mitigation and Response Plan (Annex C). This 2018 update to the Drought Mitigation and Response Plan includes low flow analysis charts for the major rivers throughout Colorado, including the Colorado River, Dolores River, Gunnison

River, Los Pinos River, San Juan River, White River, Yampa River, Arkansas River, North Platte River, South Platte River, and Rio Grande.

3.2.1 Climate Model Background

The CRWAS-I project was based on the latest climate data available at the time, the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive, which aligned with the IPCC Assessment Report 4 (AR4) (CWCB, 2012). When CRWAS was updated as a part of Phase II, the CMIP5 dataset was the latest available data, therefore CRWAS Phase II (CRWAS-II) incorporated model projections from both the CMIP3 and CMIP5 archives to draw the most robust understanding of future climate conditions. The following paragraphs present a brief introduction into high level differences between the CMIP3 and CMIP5 datasets.

The CMIP3 archive of twenty-first century projections contains 112 projections from 16 GCMs forced with three Special Report on Emission Scenarios (SRES) emissions pathways (A1B, A2, and B1). Each projection consists of a twentieth century simulation running through 1999 and a twenty-first century projection running from 2000 through 2099 (CWCB, 2015a). Additional information regarding the SRES emissions pathways can be found online at the IPCC website (http://sedac.ipcc-data.org/ddc/sres/index.html).

The CMIP5 archive consists of a number of model experiments involving more than 20 modeling groups and more than 50 models (Taylor et al., 2012). Long term simulations within the CMIP5 archive consist of a historical period from the mid-nineteenth century to 2005, and a simulation of future climate from 2006 to the end of the twenty-first century. The CMIP5 long-term projection ensemble consists of 234 runs of 37 climate models (CWCB, 2015a). The CMIP5 model runs are forced by representative concentration pathways (RCPs), which are used to represent different assumptions about the effect of past and future greenhouse gas emissions. There are four different RCPs used for the CMIP5 experiment: 2.6, 4.5, 6.0, and 8.5. Research currently makes no distinction between the CMIP3 and CMIP5 projections with respect to reliability or accuracy (Rupp et al., 2013).

3.2.1.1 Climate Scenarios

Due to the large size of climate datasets (period of record, model runs, scenarios, future periods), climate change studies necessarily must consolidate results from hundreds of projections into a few meaningful scenarios that will be used for planning purposes. The CRWAS-I study approach selected individual climate projections that would capture most of the variability of future climate according to temperature and precipitation for two time periods (2040 and 2070). The five CRWAS planning scenarios are described in Table 3.5 below:

Table 3.5 Characteristics for CRWAS-I Future Climate Scenarios

Qualitative Scenario	Characteristic Temperature	Characteristic Precipitation
Hot and Dry	90th percentile	10th percentile
Hot and Wet	70th percentile	70th percentile
Warm and Dry	30th percentile	30th percentile
Warm and Wet	10th percentile	90th percentile
Median	50th percentile	50th percentile

In CRWAS-II, the methods for scenario selection were refined by selecting the future climate impacts from runoff and CIR, rather than temperature and precipitation. While changes in temperature and precipitation are a good representation of the environment, the more important element is how they affect water systems. Thus the change in supply (runoff) and demand (CIR) were used to determine future climate change impacts. Additional information regarding the change in methods can be found in the CRWAS Phase II Climate, Task 1 technical memorandum, *Approach for constructing climate scenarios* (CWCB, 2015b). For the CRWAS-II study, seven aggregated climate scenarios were selected from pooled model projections (Table 3.6), listed in ascending order of severity of impact on water supply systems. These seven climate scenarios each were comprised of a pool of ten projections taken from the combined ensemble of CMIP3 and CMIP5 climate projections for the 2050 time period. These scenarios did not distinguish between CMIP3 SRES scenarios or CMIP5 RCPs; instead, all model projections were included within the same sample space for aggregation into the seven climate scenarios. The designation "9010" is pronounced "ninety-ten" and represents the 90th percentile CIR and 10th percentile runoff. Other designations follow this convention.

Table 3.6 Characteristics for CRWAS-II Future Climate Scenarios

Designation	CIR Percentile	Runoff Percentile
Lower Left	100%	0%
9010	90%	10%
7525	75%	25%
Center	50%	50%
2575	25%	75%
1090	10%	90%
Upper Right	0%	100%

3.2.1.2 Change Factors

The CRWAS-I project was assessed using a baseline historical dataset (natural flow and CIR) from water years 1950 to 2005, which was extended through water year 2013 as a part of CRWAS-II. The CRWAS method for assessing future climate change impacts involves the use of change factors or ratios to determine adjustments to runoff and CIR. For instance, the annual average runoff change factor would be calculated as the annual average simulated future runoff divided by the annual average simulated historical runoff (Equation 1).

Equation 1:

$$Runoff\ change\ factor = \frac{annual\ average\ future\ runoff}{annual\ average\ historical\ runoff}$$

The change factors were calculated by month (one set of 12 change factors) using a 30-year window around the target future date. Thus the 2050 analysis used the average change factor for years 2035 to 2064, the 2040 analysis used the average change from 2025 to 2054, and the 2070 analysis used the average change factors from 2055 to 2084. These change factors were then applied back to the original historical dataset, to provide climate-adjusted hydrology (runoff and CIR) that could be used for a climate change impact analysis.

3.2.1.3 Historical Flows

Utilizing the change factor method is a fairly simple approach that minimizes model bias when completing a climate change impact analysis. However, it requires natural flow data, also referred to as unimpaired flow or full natural flow. Simply stated, this is the flow that would exist in the river without human impact. Natural flow is calculated by removing the unnatural, human-caused impacts to rivers such as reservoirs, diversions, augmentations, evaporation, etc. In Colorado, the stream simulation model StateMod has been developed to model historical and future river flows. The historical flows referred to within this analysis are natural flows calculated by StateMod modeling. This modeling has been completed for the Colorado River, South Platte River and North Platte River, but not for the Arkansas River and Rio Grande.

The natural flow records at the Colorado River sites were extended through 2014 as part of the CRWAS-II work, so the statistics of those flow records are slightly different than those of the CRWAS-I records.

In the place of natural flow for the Rio Grande, measured historical gage flows have been used from a site located near the headwaters of the watershed, where there is less human influence. The measured flow is assumed to be similar enough to the natural flow that it provides output which is useful for the purposes of this drought analysis.

The Arkansas River was analyzed in a unique manner, because none of the climate-adjusted gage (flow) stations closely reflected the natural flow of the river. In this instance, nine flow gages on the Arkansas River and tributaries to the Arkansas River were used to calculate flow-weighted adjustment factors for the Arkansas River. The nine gage stations used for the Arkansas River are provided in Table 3.7.

Since the sum of these nine Arkansas River stations did not reflect the total natural flow of the Arkansas River, the low flow statistics were analyzed using the climate-adjusted change factors for flow rather than the flow itself. A flow (runoff) change factor (see Equation 1) with a value less than 1 indicates a reduction in flow for the future (2050), while a change factor greater than 1 indicates an increase in flow for the future. The change factor for the Arkansas River analysis is a flow-weighted average, divided by the aggregate natural flow of the nine sites, thereby reflecting the future climate condition of the Arkansas River Basin.

Table 3.7 Arkansas River Gages

Station Name	StationID	River Basin	Historical Flow Period of Record
Arkansas River near Leadville	USGS 07081200	Arkansas	1/1950 –12/2013
Clear Creek above Clear Creek Reservoir	USGS 07086500	Arkansas	1/1950 –12/2013
Grape Creek near Westcliffe	USGS 07095000	Arkansas	1/1950 –12/2013
Fountain Creek near Fountain.	USGS 07106000	Arkansas	1/1950 –12/2013
St. Charles River at Vineland	USGS 07108900	Arkansas	1/1950 –12/2013
Huerfano River at Manzanares Xing near Redwing	USGS 07111000	Arkansas	1/1950 –12/2013
Cucharas River at Boyd Ranch near La Veta	USGS 07114000	Arkansas	1/1950 –12/2013
Apishapa River near Fowler	USGS 07119500	Arkansas	1/1950 –12/2013
Purgatoire River at Madrid	USGS 07124200	Arkansas	1/1950 –12/2013

3.2.1.4 Drought Analysis Results

The low flow analysis completed for the CRWAS-I study was updated using results from CRWAS-II. The analysis shows the climate-adjusted low flow conditions during the future period of 2050 (from CRWAS-II), combined with the climate-adjusted low flow conditions during the future periods of 2040 and 2070 (from CRWAS-I, if available), compared to the historical natural flow. Note that CRWAS-I results were not available for the rivers outside of the Colorado River Basin, including the North Platte River, South Platte River, Arkansas River and Rio Grande. Additionally, the historical flows for the Arkansas River and the Rio Grande represent measured gage flow rather than natural flow. A map of the stations is provided in Figure 3.7 and the station names and ID numbers are listed in Table 3.8.

Figure 3.7 Map of Low Flow Stations

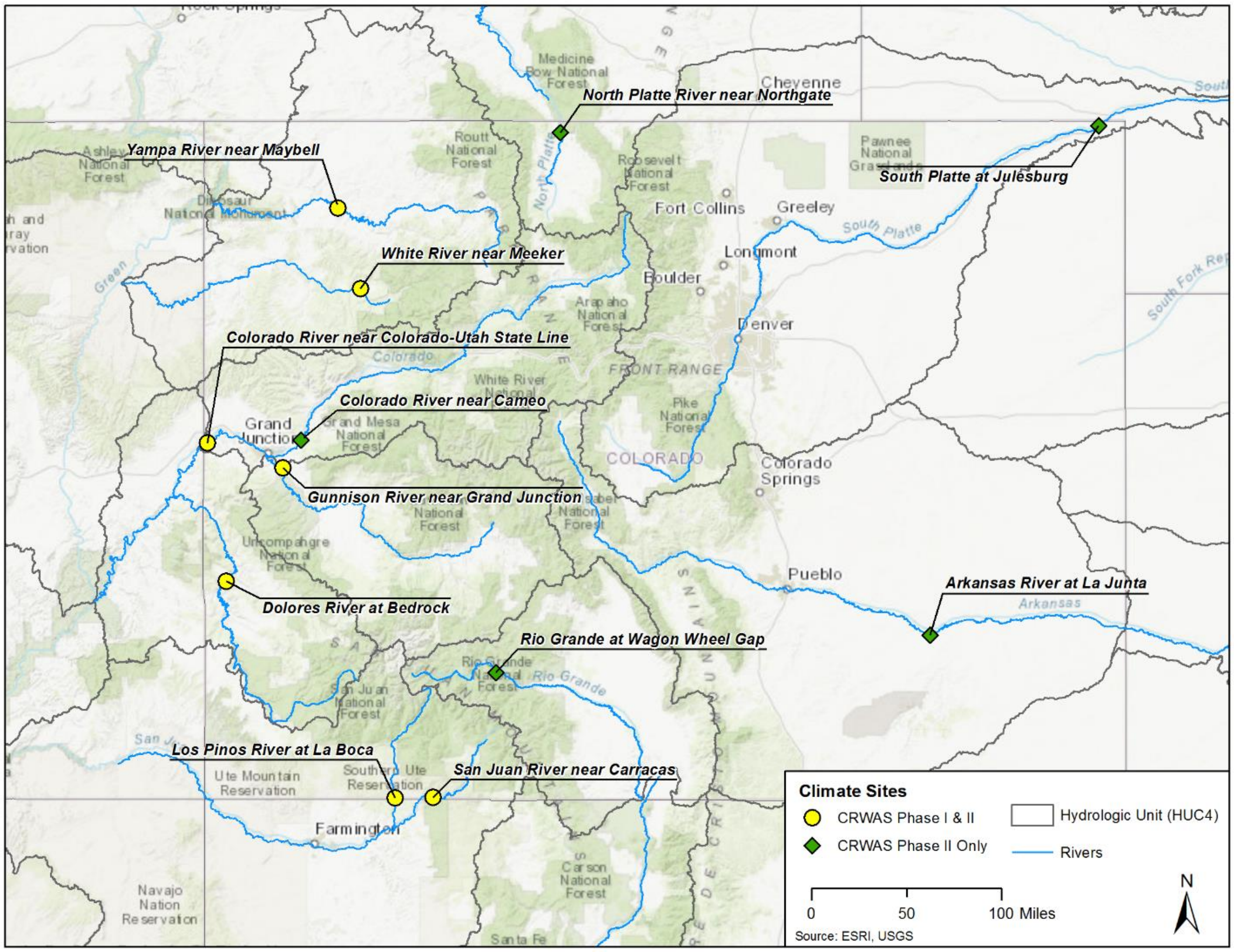


Table 3.8 CRWAS-II Stations

Station Name	StationID	River Basin	Historical Flow Period of Record
Colorado River near Cameo	USGS 09095500	Colorado	10/1949 – 9/2013
Colorado River near Colorado-Utah State Line	USGS 09163500	Colorado	10/1949 – 9/2013
Dolores River at Bedrock	USGS 09169500	Colorado	10/1949 – 9/2013
Gunnison River near Grand Junction	USGS 09152500	Colorado	10/1949 – 9/2013
Los Pinos River at La Boca	USGS 09354500	Colorado	10/1949 – 9/2013
San Juan River near Carracas	USGS 09346400	Colorado	10/1949 – 9/2013
White River near Meeker	USGS 09304500	Colorado	10/1949 – 9/2013
Yampa River near Maybell	USGS 09251000	Colorado	10/1949 – 9/2013
Arkansas River at La Junta	USGS 07123000	Arkansas	1/19450 – 9/2013
North Platte River near Northgate	USGS 06620000	North Platte	10/1956 – 9/2007
Rio Grande at Wagon Wheel Gap	USGS 08217500	Rio Grande	10/1950 – 9/2013
South Platte River at Julesburg	USGS 06764000	South Platte	10/1950 – 9/2012

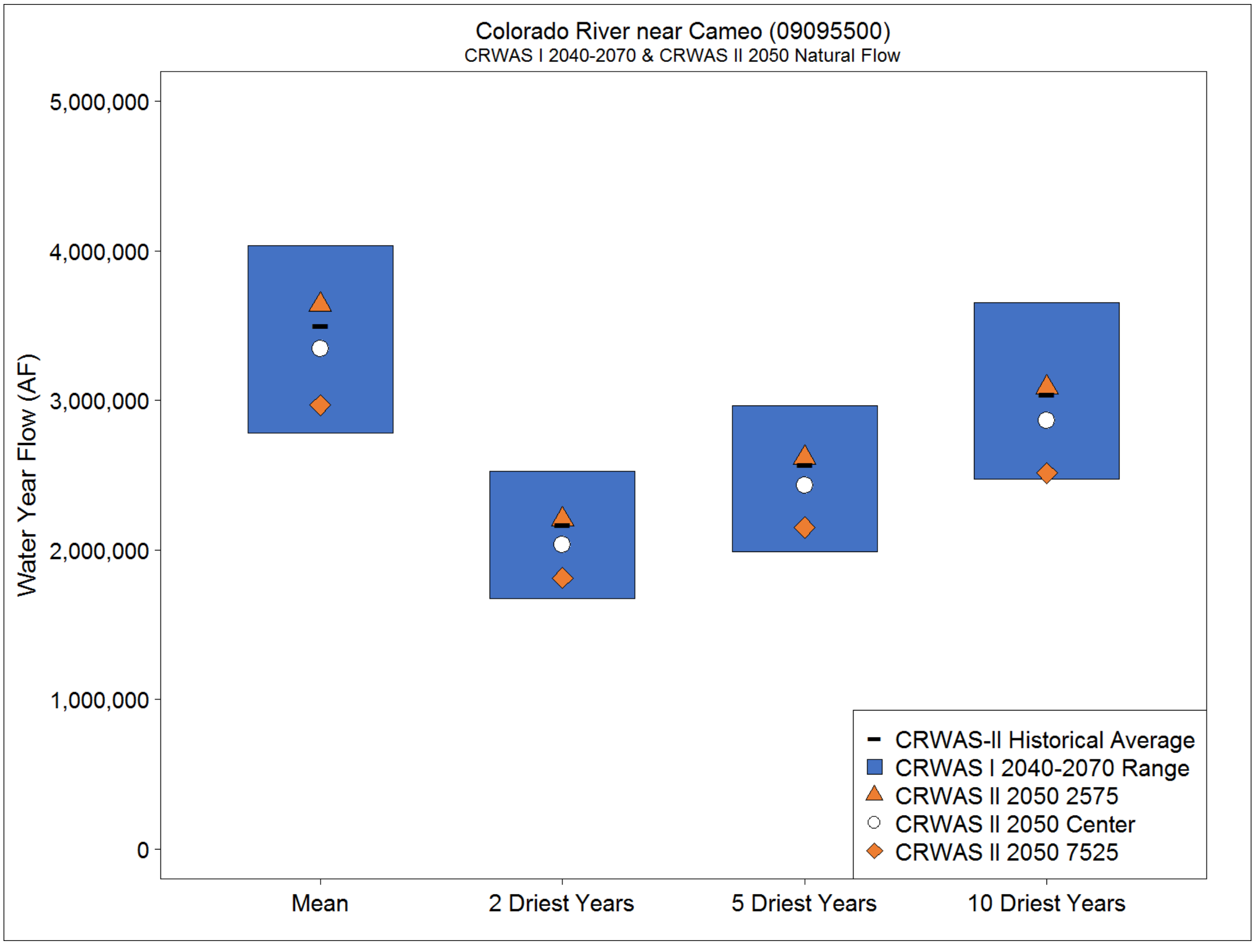
Each chart (Figure 3.8 to Figure 3.19) presents four statistics of annual flow, from left to right: average annual flow over the study period, the lowest consecutive 2-year average flow over the study period, the lowest consecutive 5-year average flow over the study period, and the lowest consecutive 10-year average flow over the study period. Due to the different data availability at the time of completion, the CRWAS-I analysis (2040 and 2070) uses a study period from 1950 to 2005, while the CRWAS II analysis (2050) uses a study period from 1950 to 2014. For each graph presented, several pieces of information are shown:

- The blue box represents the range of values from the CRWAS-I results for both the 2040 and 2070 analyses. The top of the box represents the maximum annual flow (in acre feet [AF]) and the bottom of the box represents the minimum annual flow (in AF).
- The orange-filled diamond represents the CRWAS-II year 2050, 7525 value (75th percentile CIR, 25th percentile runoff).
- The white-filled circle represents the CRWAS-II year 2050, 5050 or center value (50th percentile CIR, 50th percentile runoff).
- The orange-filled triangle represents the CRWAS-II year 2050, 2575 value (25th percentile CIR, 75th percentile runoff).
- The black horizontal line represents the average historical natural flow for the CRWAS-II record.

On average, the CRWAS-II results are slightly drier than the CRWAS-I results; the CRWAS-II results are skewed slightly to the bottom of the box representing the CRWAS-I results. The results for the Yampa River near Maybell (Figure 3.15) show that CRWAS-II flows are noticeably drier than CRWAS-I flows. The CRWAS-II model results follow the same relative order, where the 2575 scenario (25th percentile CIR, 75th percentile runoff) is the wettest, the Center scenario (50th percentile CIR, 50th percentile runoff) is in the middle and the 7525 scenario (75th percentile CIR, 25th percentile runoff) is the driest of the three aggregated scenarios. The historical flows are typically closest to the CRWAS-II 2575 scenario (orange triangle); however, this varies from site to site.

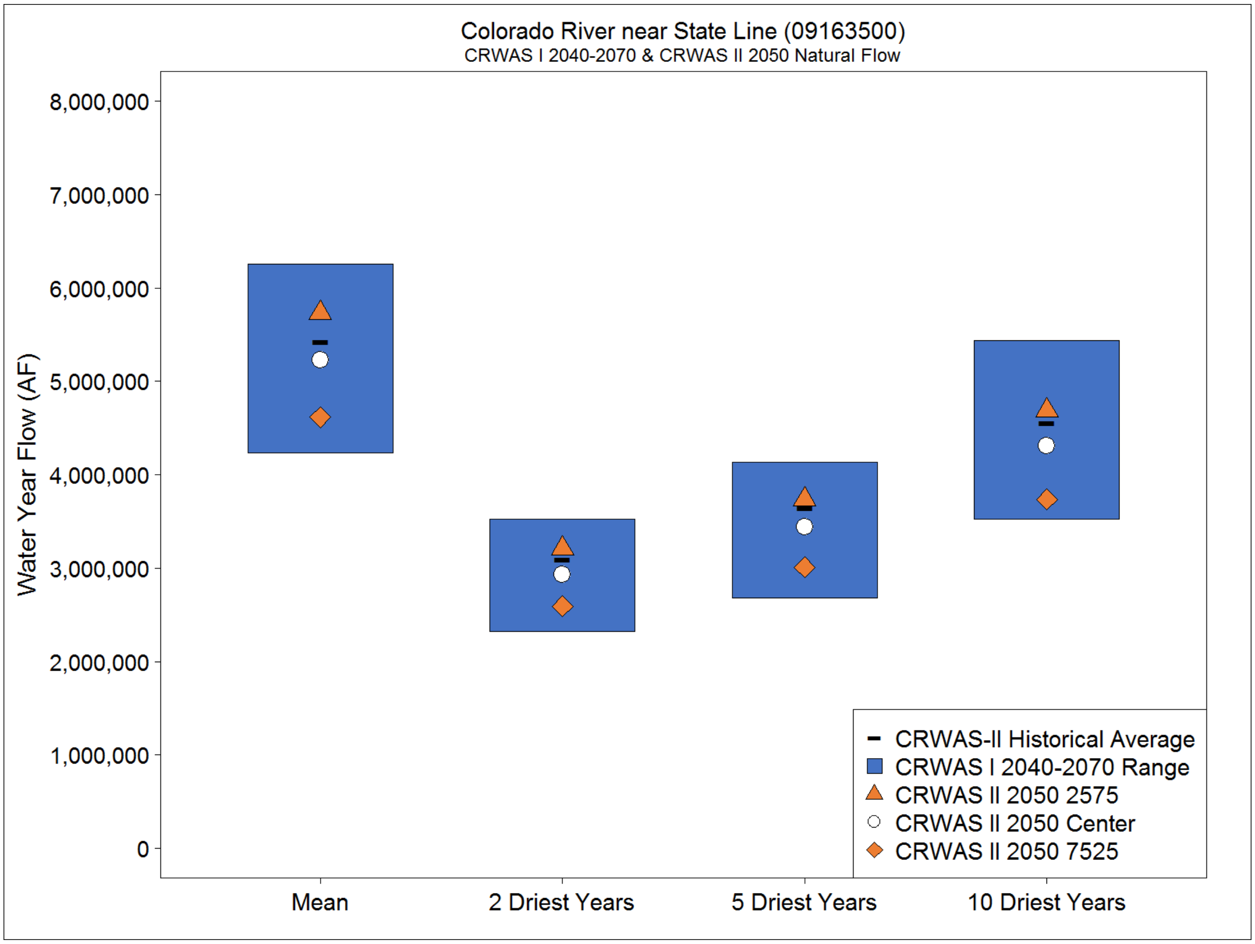
The future climate scenarios for the Colorado River near Cameo shows that the driest 2-year flow represents a 39% reduction from the average annual flow of approximately 3.3 million AF when comparing the CRWAS-II Center (2050) scenarios. The CRWAS-II Center scenario is within 5% of the historical average flow. The results are shown in Figure 3.8.

Figure 3.8 Low Flow Comparison Chart, Colorado River near Cameo



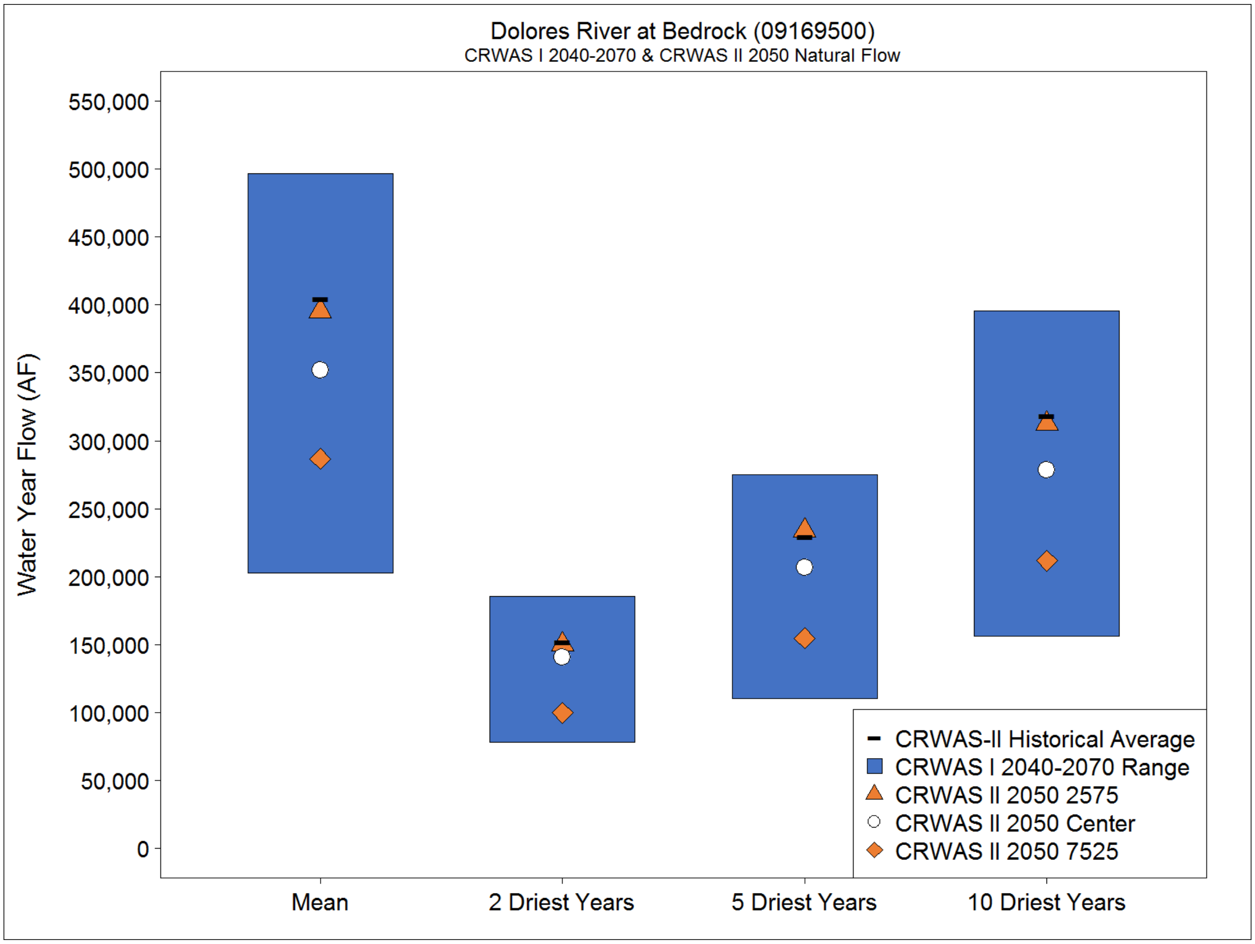
The future climate scenarios for the Colorado River near the Utah state line shows that the driest 2-year flow represents a 44% reduction from the average annual flow of approximately 5.2 million AF when comparing the CRWAS-II Center scenarios. The CRWAS-II Center scenario is within 5% of the historical average flow. The results are shown in Figure 3.9.

Figure 3.9 Low Flow Comparison Chart, Colorado River near State Line



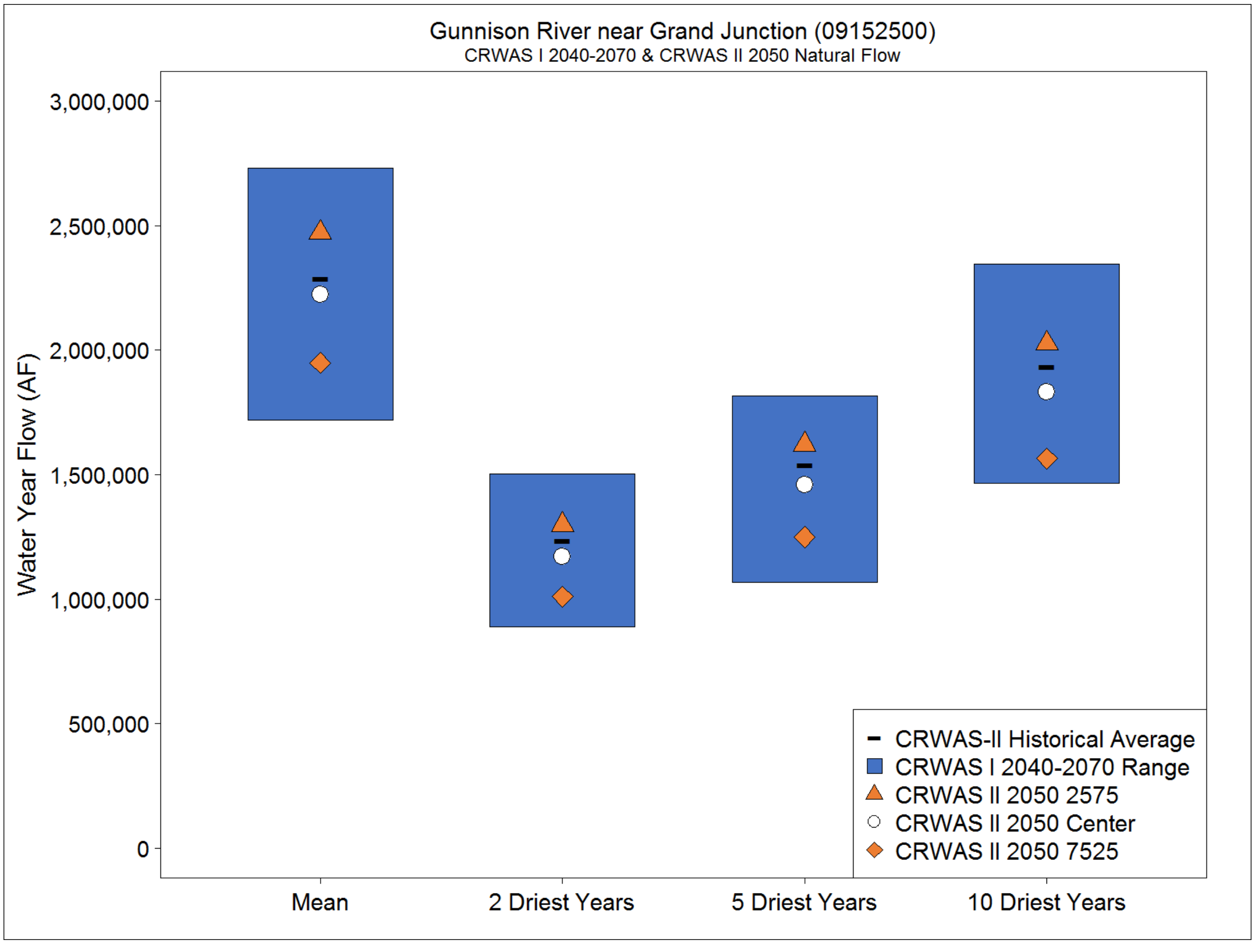
The future climate scenarios for the Dolores River at Bedrock show that the driest 2-year flow represents a 60% reduction from the average annual flow of approximately 350,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 13% drier than the average annual historical flow. The results are shown in Figure 3.10.

Figure 3.10 Low Flow Comparison Chart, Dolores River at Bedrock



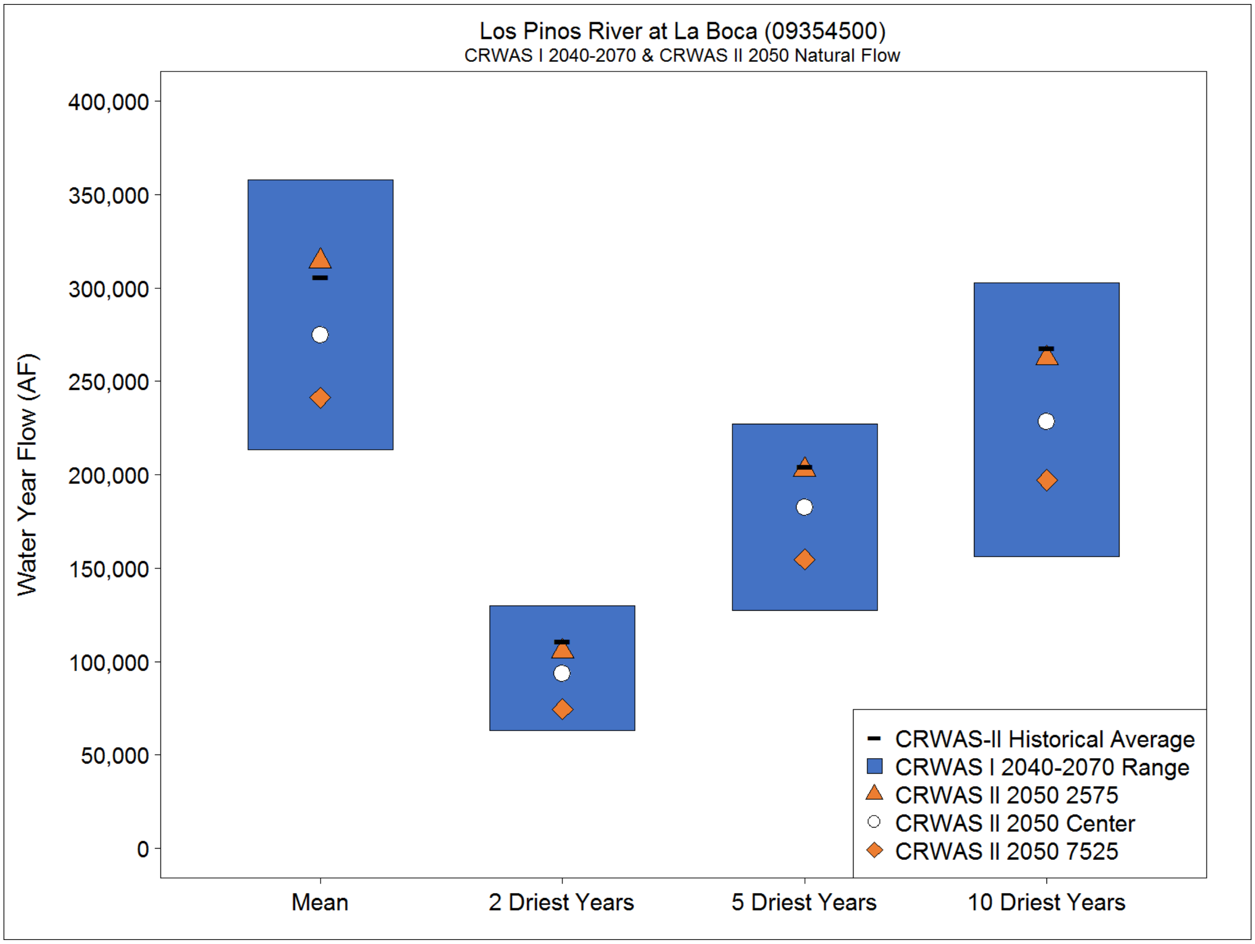
The future climate scenarios for the Gunnison River near Grand Junction show that the driest 2-year flow represents a 47% reduction from the average annual flow of approximately 2.2 million AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is within 5% of the average annual historical flow. The results are shown in Figure 3.11.

Figure 3.11 Low Flow Comparison Chart, Gunnison River near Grand Junction



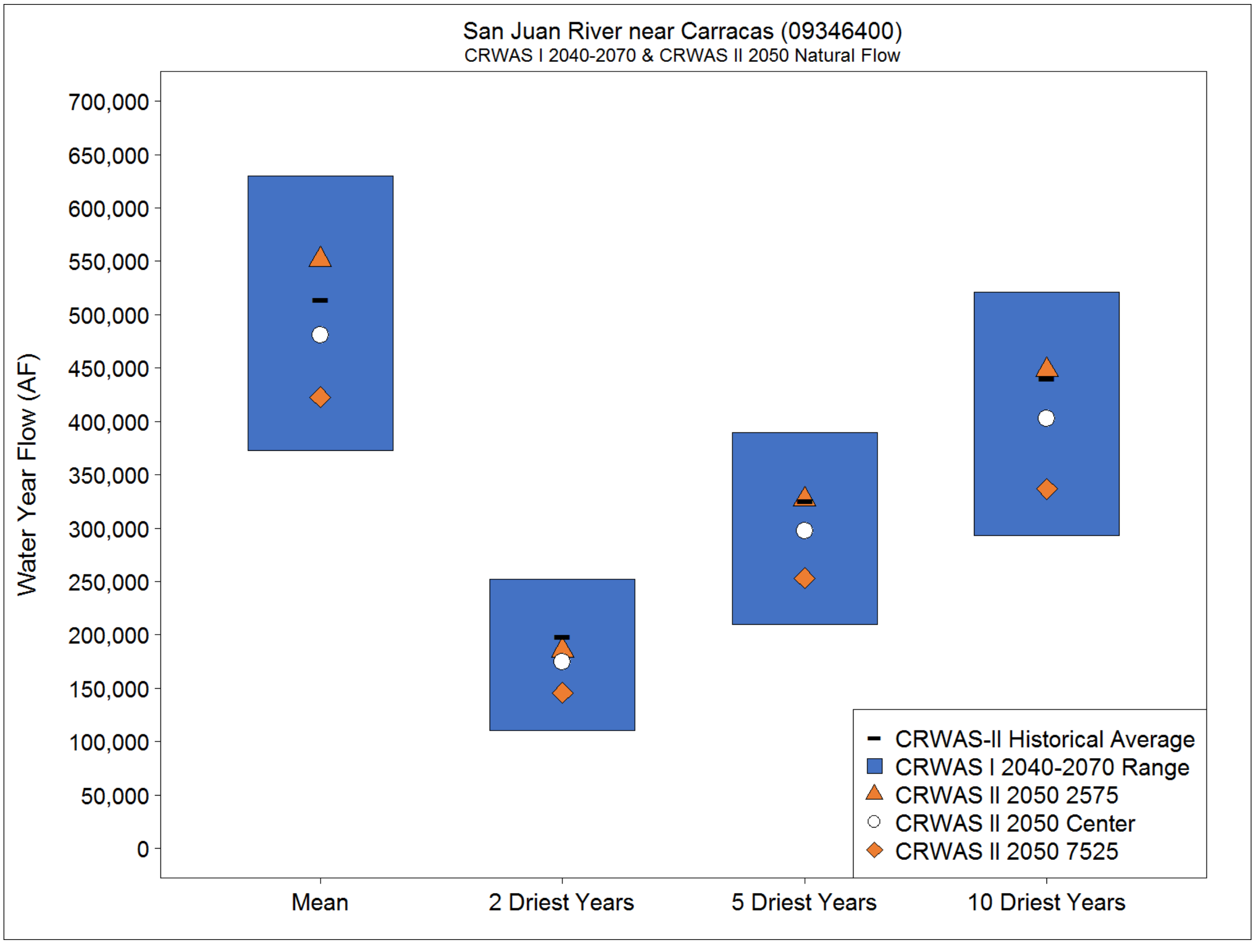
The future climate scenarios for the Los Pinos River at La Boca show that the driest 2-year flow represents a 66% reduction from the average annual flow of approximately 270,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 10% drier than the average annual historical flow. The results are shown in Figure 3.12.

Figure 3.12 Low Flow Comparison Chart, Los Pinos River at La Boca



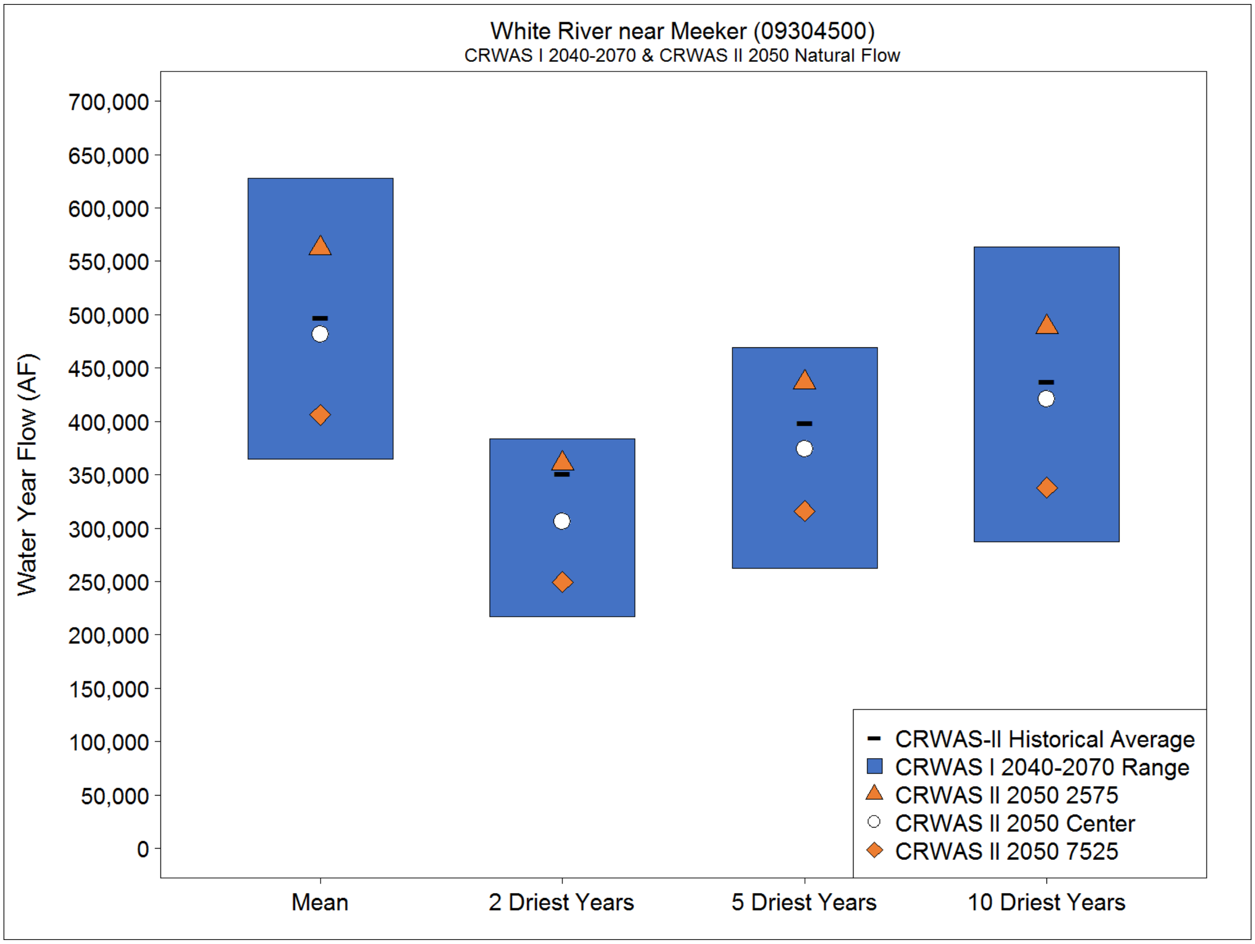
The future climate scenarios for the San Juan River near Carracas show that the driest 2-year flow represents an 64% reduction from the average annual flow of approximately 480,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 6% drier than the average annual historical flow. The results are shown in Figure 3.13.

Figure 3.13 Low Flow Comparison Chart, San Juan River near Carracas



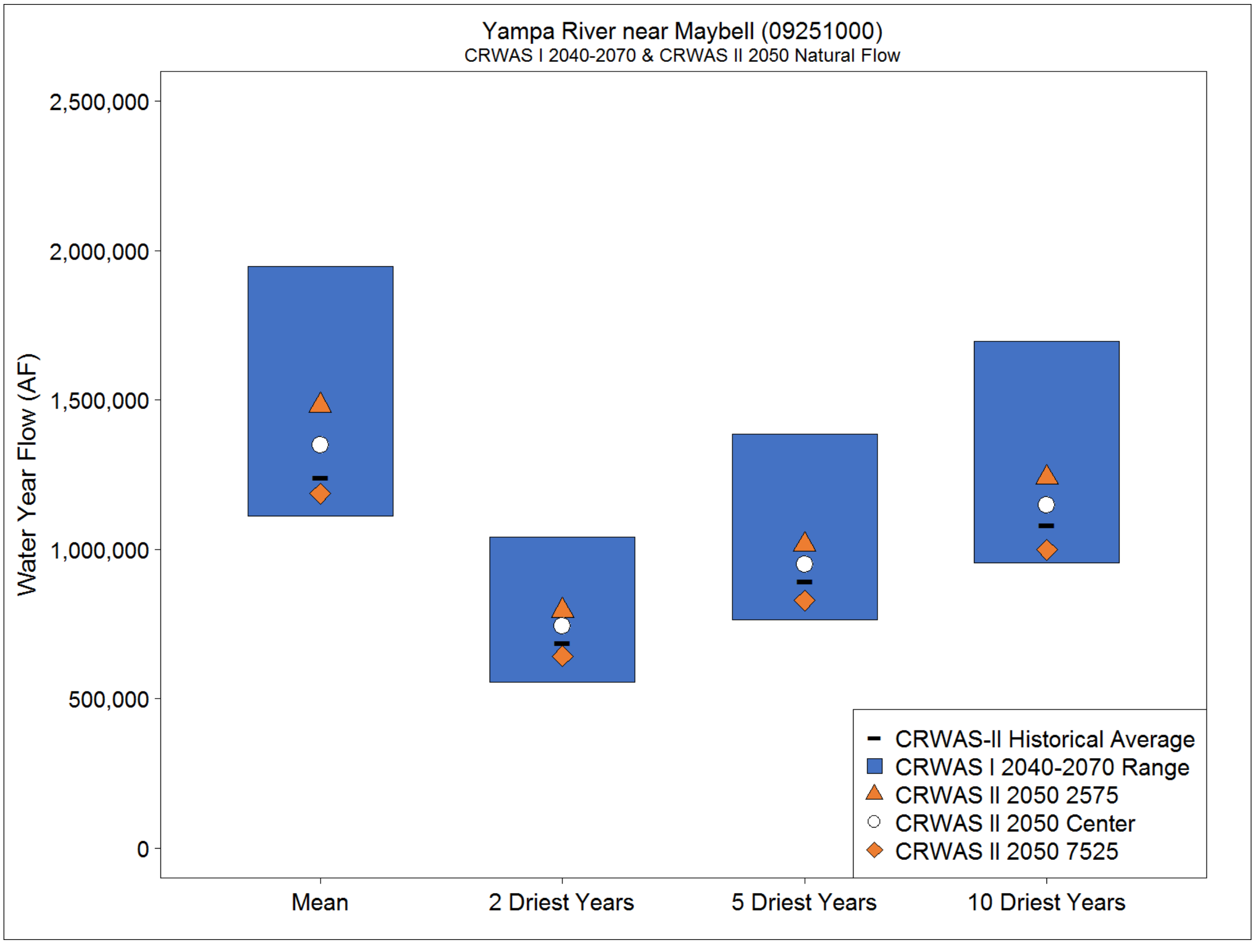
The future climate scenarios for the White River near Meeker show that the driest 2-year flow represents a 36% reduction from the average annual flow of approximately 480,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is within 5% of the average annual historical flow. The results are shown in Figure 3.14.

Figure 3.14 Low Flow Comparison Chart, White River near Meeker



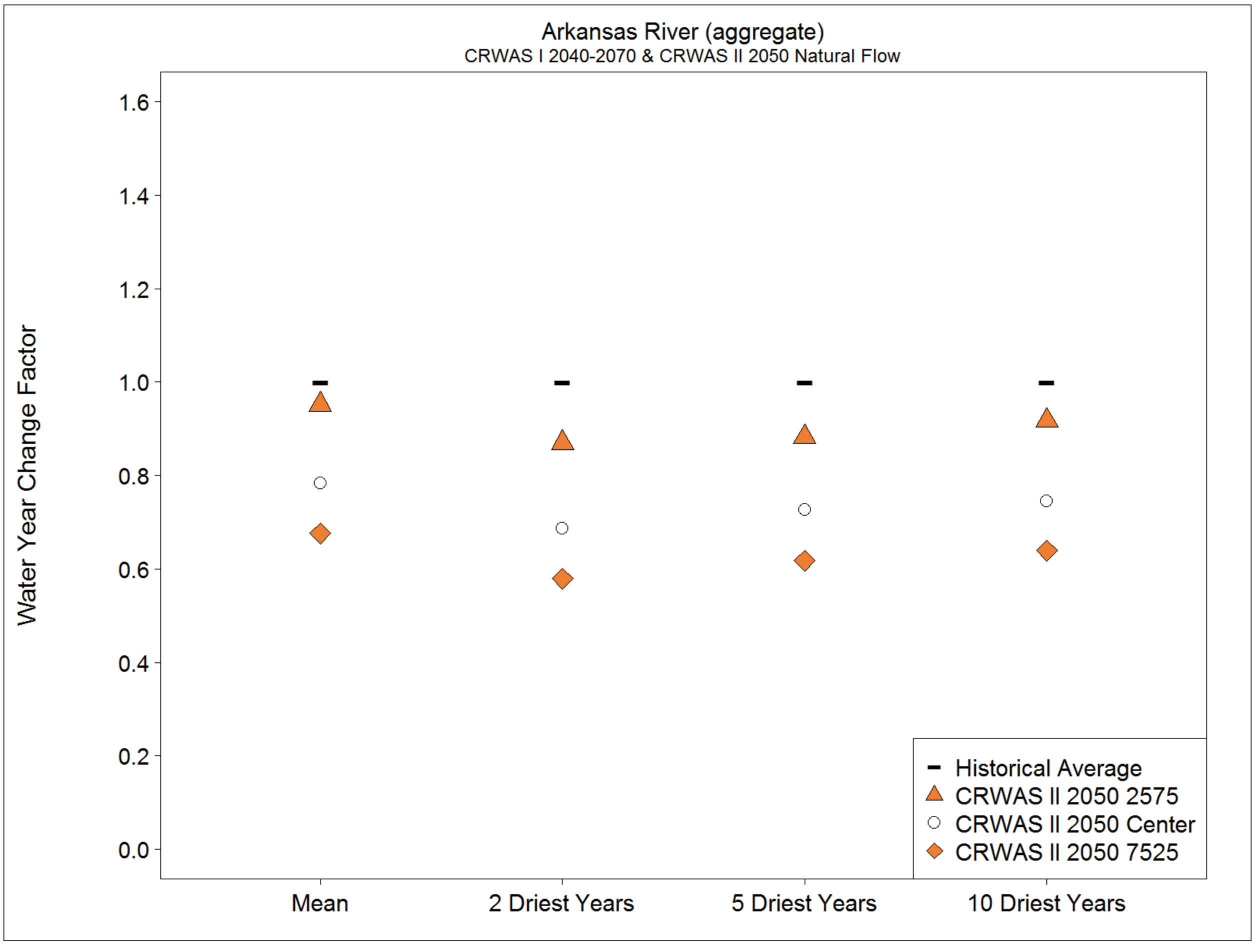
The future climate scenarios for the Yampa River near Maybell show that the driest 2-year flow represents a 45% reduction from the average annual flow of approximately 1.35 million AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 9% wetter than the average annual historical flow, reflecting the trend for northern Colorado that indicates there is a higher probability of increased precipitation in the future. The results are shown in Figure 3.15.

Figure 3.15 Low Flow Comparison Chart, Yampa River near Maybell



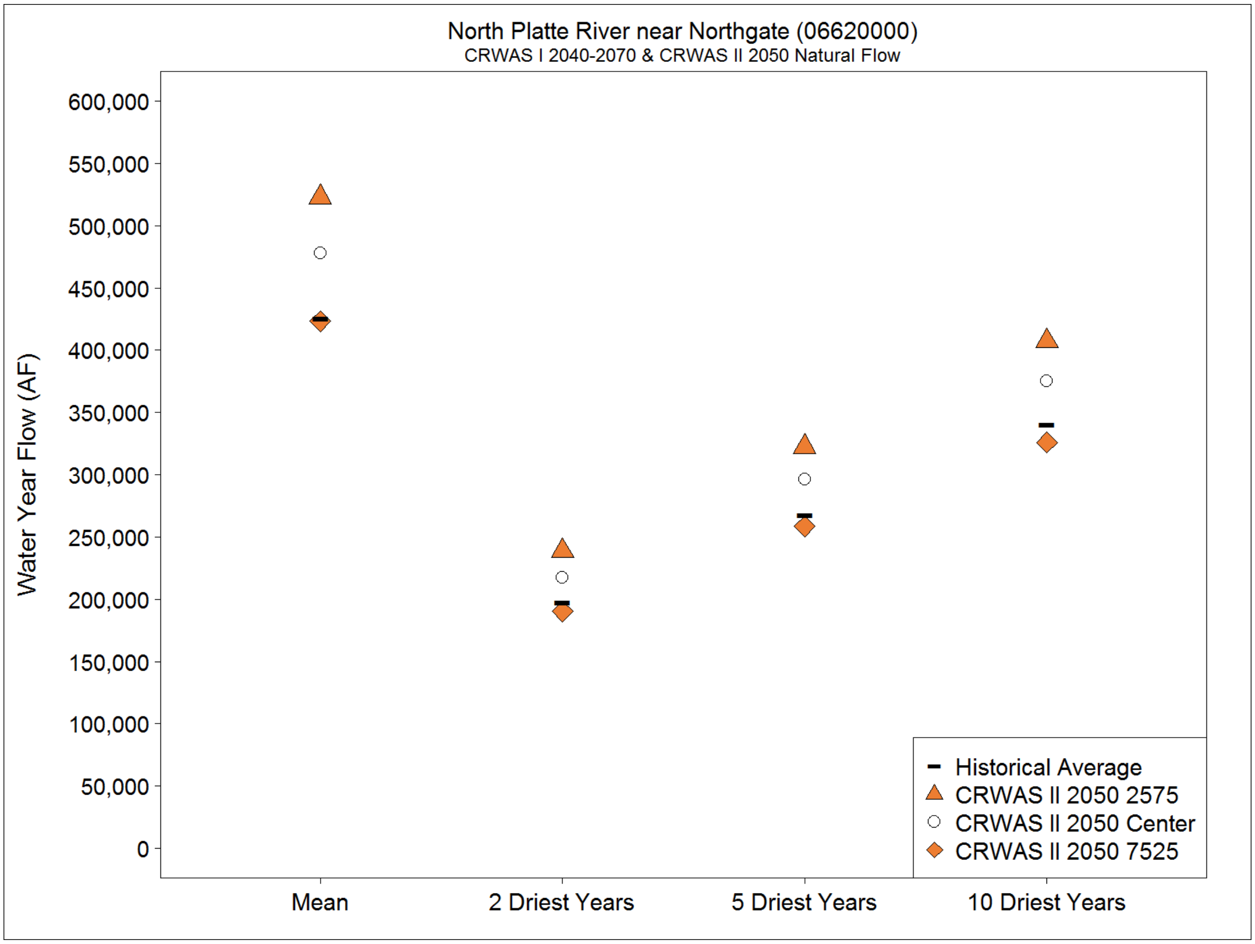
As discussed in Section 3.2, Historical Flow, there was no single gage station that represented the full natural flow of the Arkansas River. Thus, the low flow analysis was completed using an aggregate of nine Arkansas River gages. Figure 3.16 is unique in this way because it presents results using change factors (indicating future increases or decreases in flow) rather than the flow itself. The future climate scenarios for the Arkansas River at La Junta show that the change factors for the driest 2-year flow represents a 12% reduction from the change factor for average annual flow of approximately 0.78, for the CRWAS-II Center scenario. The change factor for the CRWAS-II Center scenario is 22% drier than the change factor for the average annual historical flow. The results are shown in Figure 3.16.

Figure 3.16 Low Flow Comparison Chart, Arkansas River at La Junta



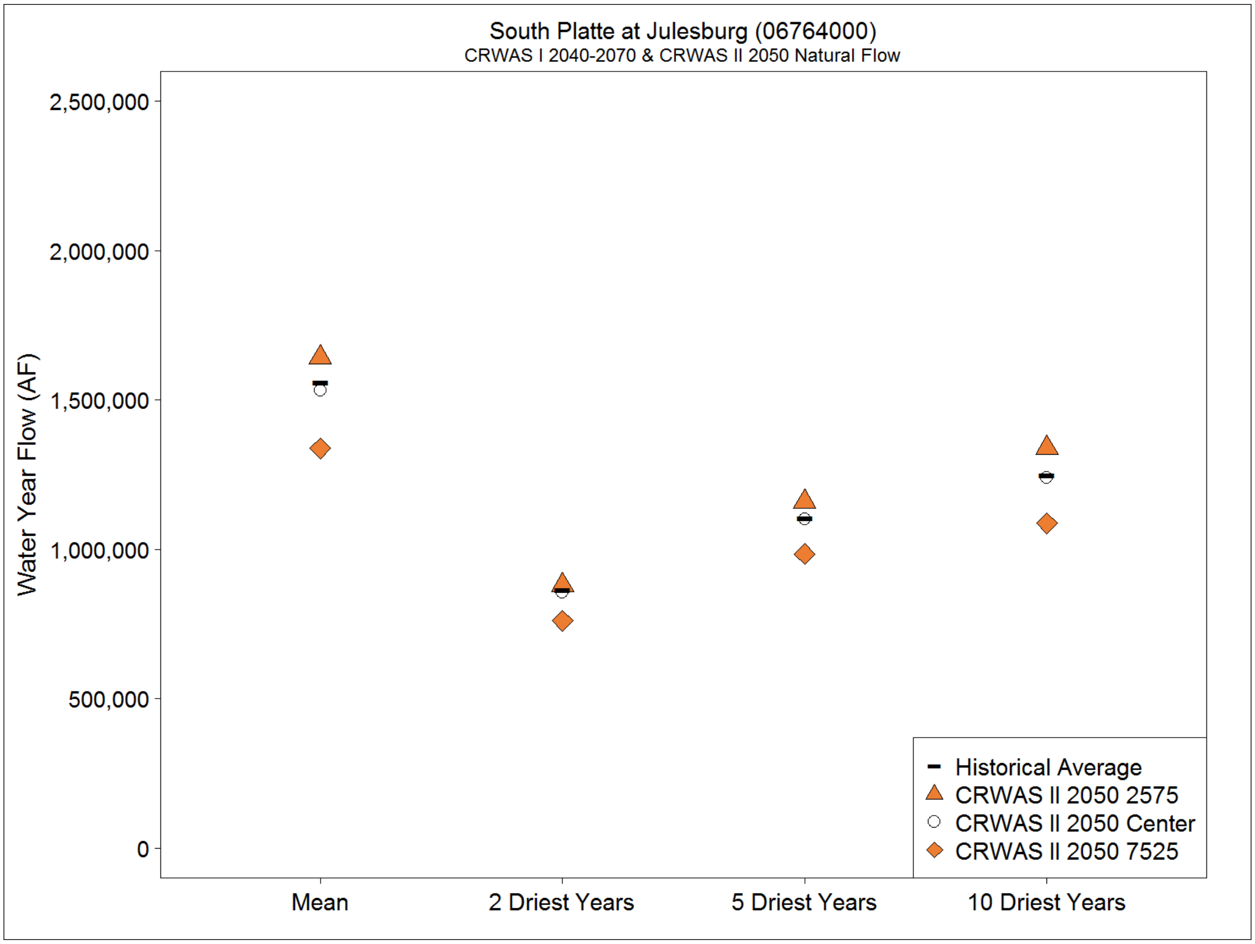
The future climate scenarios for the North Platte River near Northgate show that the driest 2-year flow represents a 54% reduction from the average annual flow of approximately 480,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 12% wetter than the average annual historical flow, reflecting the trend for northern Colorado that indicates there is a higher probability of increased precipitation in the future. The results are shown in Figure 3.17.

Figure 3.17 Low Flow Comparison Chart, North Platte River near Northgate



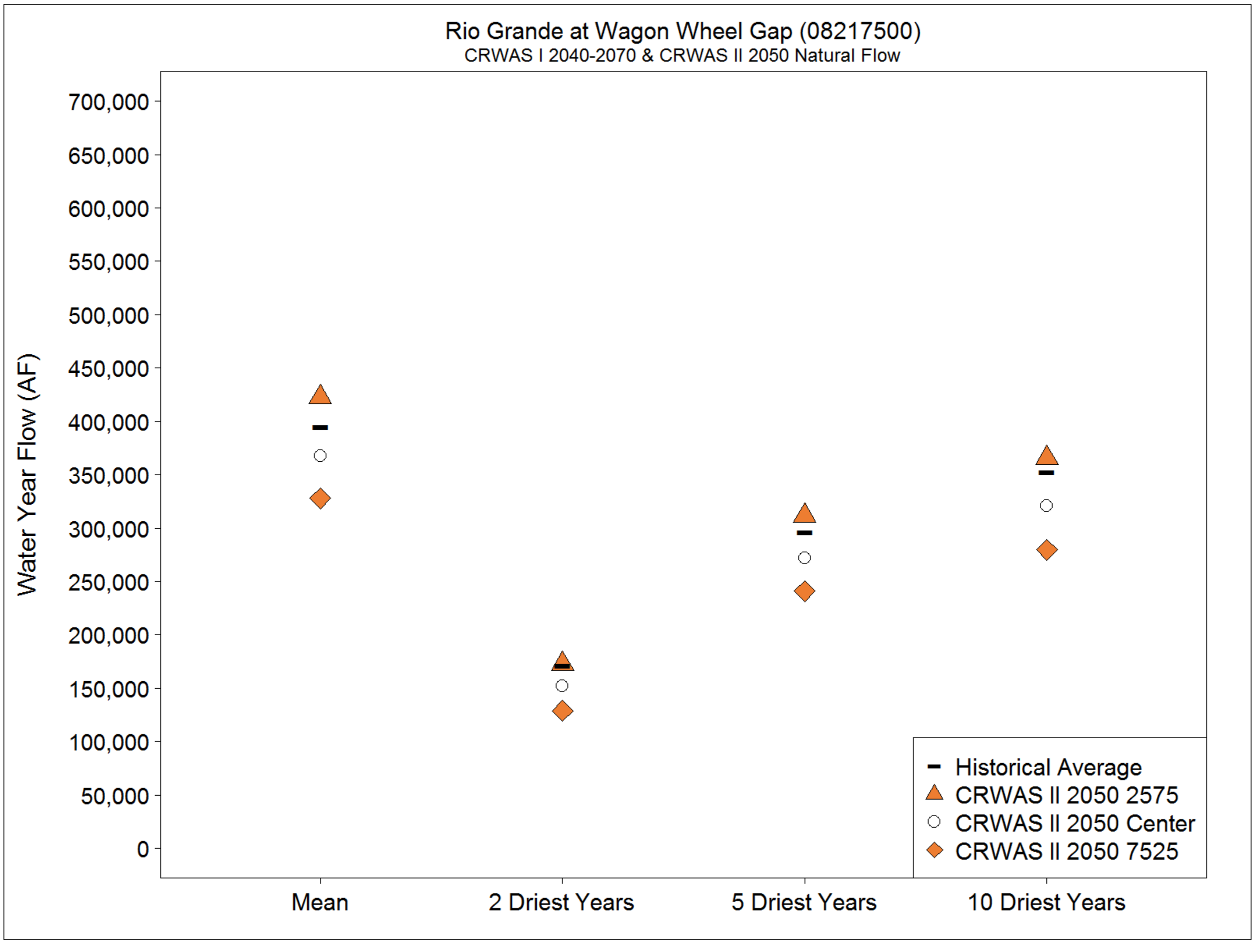
The future climate scenarios for the South Platte River at Julesburg show that the driest 2-year flow represents a 44% reduction from the average annual flow of approximately 1.5 million AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is within 5% of the annual historical flow. The results are shown in Figure 3.18.

Figure 3.18 Low Flow Comparison Chart, South Platte River at Julesburg



The future climate scenarios for the Rio Grande at Wagon Wheel Gap show that the driest 2-year flow represents a 59% reduction from the average annual flow of approximately 370,000 AF, for the CRWAS-II Center scenario. The CRWAS-II Center scenario is 7% drier than the average annual historical flow. The results are shown in Figure 3.19.

Figure 3.19 Low Flow Comparison Chart, Rio Grande at Wagon Wheel Gap



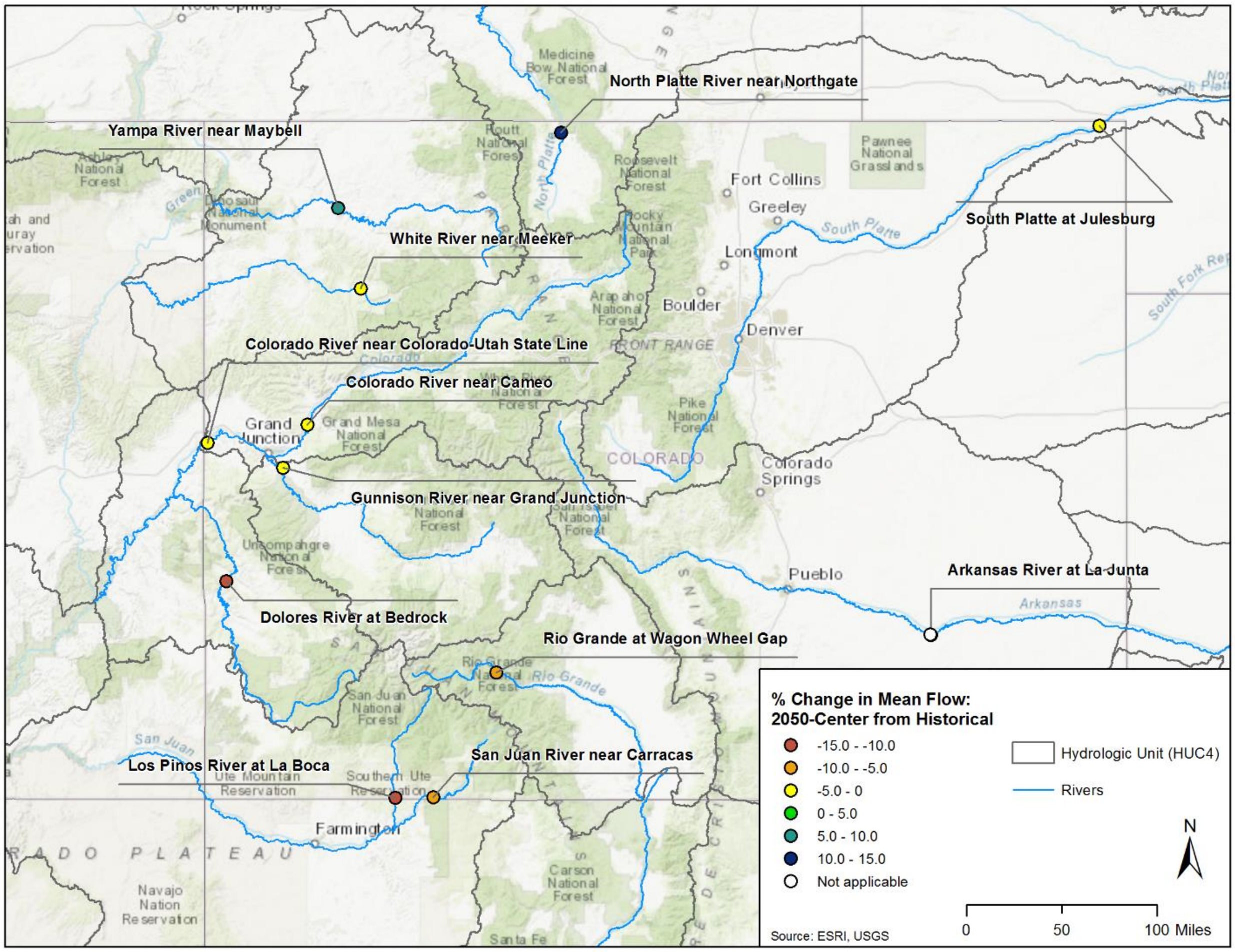
3.2.1.5 Summary of Results

The results of the CRWAS-II climate change study were used to compare future projected flow to historical natural flows for 12 river locations throughout Colorado. The historical flows are typically closest to the CRWAS-II 2575 scenario (25th percentile CIR and 75th percentile runoff), which represents more favorable or wetter future conditions. However, the central tendency of future climate projections, represented by the Center scenario, indicate decreases in flow, on average for Colorado.

The CRWAS-II results show future (2050) projected flows throughout Colorado have a range of uncertainty, with the possibility of both increased and decreased future flows for any given river. However, the average trend of future climate projections (Center scenario, using the 50th

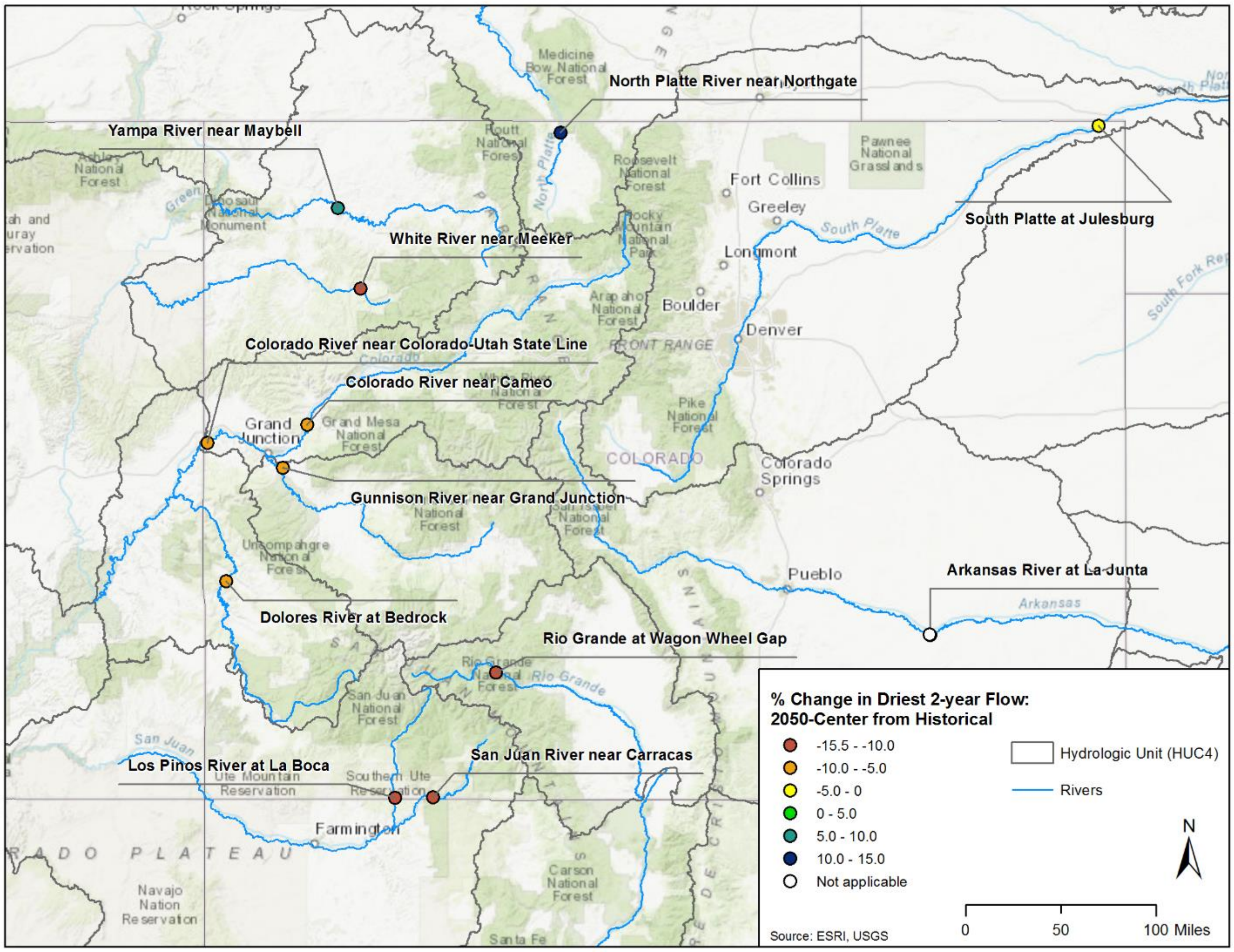
percentile CIR and 50th percentile runoff) indicates a decrease in future average flows compared to historical average flows over the period of record. More specifically, rivers in southern Colorado show the largest decreases in flow, while rivers in northern Colorado show an increase in flow. Of the rivers analyzed for this study, the Dolores River, Los Pinos River, Rio Grande, and San Juan River are projected to have the largest decreases in flow, with changes of -13%, -10%, -6.8% and -6.4%, respectively. The North Platte River and the Yampa River are projected to have the largest increases in flow, with changes of 12.2% and 8.9%, respectively. The projected changes in average annual flow for the 12 river stations are shown in Figure 3.20.

Figure 3.20 Summary of CRWAS-II Average Center (2050) Results



The low flow analysis completed using the CRWAS-II data helps to illuminate how droughts may change in the future. The historical and future (2050) projected lowest consecutive 2-year average flows were calculated for each of the 12 river locations. Most of the stations had a decrease of 5% or more in 2-year low flow indicating that drought conditions will be worse in the future. The Los Pinos River, White River, San Juan River, and Rio Grande show the largest decreases in 2-year low flow, with changes of -15.5%, -12.7%, -11.8%, and -11.2%, respectively. The North Platte River and the Yampa River are projected to have the largest increases in 2-year low flow, with changes of 10.1% and 7.9%, respectively. The projected changes in the driest 2-year flow for the 12 stations are shown in Figure 3.21.

Figure 3.21 Summary of CRWAS-II Driest 2-year Center (2050) Results



3.3 The Boulder Climate Change Study

The potential impacts of climate change on a Front Range municipal water supply system was the subject of a NOAA-sponsored study entitled “Potential Consequences of Climate Change for the City Boulder, Colorado’s Water Supplies” (the Boulder Climate Change Study). This study combined the potential impacts of climate change with long-term climate variability to examine their effects on the City of Boulder’s water supply system. For this project, output from the Boulder Climate Change Study was evaluated to examine the effects of climate change on droughts on Boulder Creek. The hydrology of Boulder Creek is generally representative of the major mountain tributaries of the South Platte River.

The study examined outputs from 21 GCMs for the area covering the Boulder Creek basin and the Colorado-Big Thompson and Windy Gap projects. All of the models project higher temperatures for this area. Roughly half of the models project decreased precipitation, and half project increased precipitation. While there is significant variation from model to model, in general the models tend to project wetter winters and drier summers. Four GCMs were selected to reflect a range of potential changes in precipitation. Outputs from the selected models reflecting three greenhouse gas emission scenarios (B1, A1-B and A2) were evaluated. Estimates of climate change for 20-year periods centering on 2030 and 2070 were used.

The study incorporated long-term climate variability exhibited by 437-year (1566-2002) tree ring-based streamflow reconstructions for Boulder Creek, South Boulder Creek, and the Colorado River (Woodhouse and Lukas 2006). A "nearest neighbor" approach was used to match natural streamflows and observed temperature and precipitation for 1953 through 2004 (for which climate records are available for the mountains above Boulder) with tree ring-derived annual streamflows. Years from 1953 through 2004 were used as proxies for pre-1953 years. A non-parametric re-sampling method was used to generate a 1,000 member ensemble of climate change scenarios (and a base case "no-climate-change" scenario), each comprised of 437 "years" selected from the 1953-2004 population that reflects the statistical properties of the 437-year long paleo-streamflow reconstruction.

A runoff model was calibrated using historical (1953-2004) weather data from the Niwot Ridge C1 station located west of Boulder and monthly natural streamflows for Boulder Creek at Orodell, South Boulder Creek near Eldorado Springs, and the Colorado River at Hot Sulphur Springs. Temperature and precipitation changes from the GCMs were applied to the runoff model to generate altered monthly flows that were reflected in the ensembles. Temperature and precipitation changes from the GCMs were also used to adjust Boulder Creek basin irrigation demands and South Platte River calls.

The effects of altered streamflows, precipitation and temperature upon Boulder's water supply system were evaluated using the Boulder Creek Model, developed by the City of Boulder to analyze water supply reliability. The Boulder Creek Model simulates the operation of Boulder's water supply system given natural streamflows, water rights, water demands and return flows, and diversion and storage facilities in the Boulder Creek basin and calls from downstream South Platte rights.

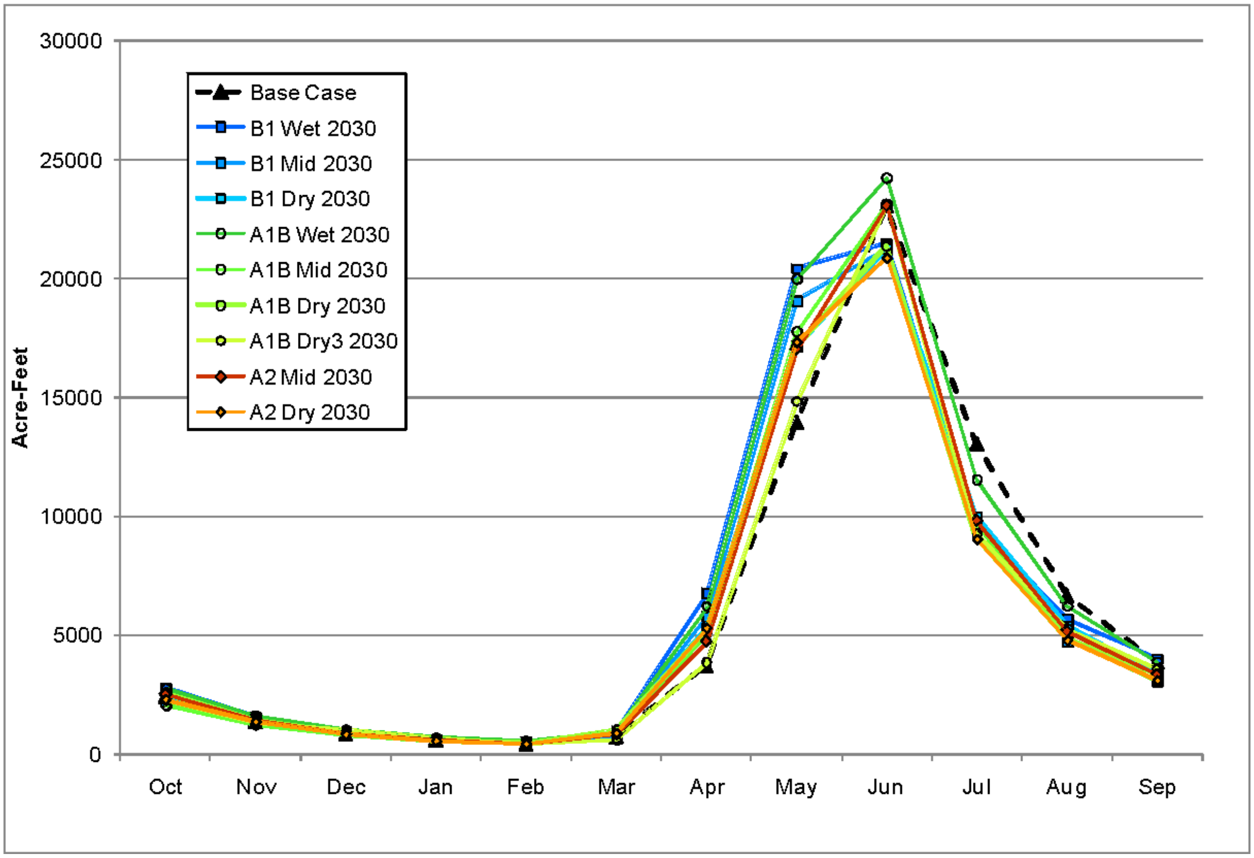
Results from the Boulder Climate Change Study (shown in Table 3.9) indicate that, in seven out of the nine climate change scenarios evaluated, droughts on Boulder Creek are likely to be longer than those simulated in the base-case.

Table 3.9 Drought Lengths, Boulder Creek Near Orodell (2030 Conditions)

Average Length of Maximum Drought (years)	Maximum Drought Length (years)
Base Case Hydrology	
10.6	13
Projected Climate Scenarios	
7.6	11
12.5	20
12.6	20
4.4	5
13.4	21
14.1	20
24.0	24
12.5	20
22.9	24

Increase in temperature alone was estimated to have little effect on the total annual volume of runoff, but by 2030 would result in increases in runoff in April and May and decreases in runoff in July and August, as shown in Figure 3.20. These seasonal changes (e.g., higher spring flows, lower summer flows) were estimated with increased or decreased precipitation. Annual runoff is quite sensitive to change in precipitation, with runoff decreasing with reduced precipitation and increasing with higher precipitation.

Figure 3.22 Mean Monthly Flows for Base Case and Climate Change Scenarios, Boulder Creek Near Orodell



4 INCORPORATING CLIMATE CHANGE INTO PLANNING

The results discussed above highlight possible changes to drought risk in a future climate. While there is no way to be certain what future hydrology may look like, it is important for planners to be aware that the future is unlikely to repeat the observed hydrology, and it is likely that Colorado will experience more severe and sustained droughts than seen in the last 56 years.

There are two main pathways for integrating climate information in water resources management. The first is a top-down perspective, in which projections are used to drive resource models and project future impacts. Conversely, a bottom-up approach starts with knowledge of specific system and analyzes the potential climate changes that would be most threatening to long-range plans or operations (CWCB 2008). No matter the approach, water resources managers and planners must make decisions based on a range of possible future scenarios. Scenario Planning is a widely used long-term planning approach to help managers keep open a wide range of options and maintain flexibility in the face of uncertainty (Water Plan 2015).

The CWCB has adopted scenario planning as an approach to plan for the uncertainties of future water supply and demand. Scenario planning assumes the future is unknown, providing flexibility in responding to future conditions. The use of scenario planning allows for conversations with stakeholders about water resource challenges and helps to answer questions on the future of water in Colorado (Water Plan 2015). Scenario planning has been used by the IBCC and basin roundtables in partnership with CWCB to explore unpredictable factors that will impact Colorado's future such as, climate change and economic and population growth and identify projects and policies that may be needed across various scenarios.

In recent years, the State has been paying increased attention to climate change projections from the IPCC. In 2014 Governor Hickenlooper released the Colorado Climate Plan (CCP) that defined policy recommendations and actions to improve Colorado's ability to mitigate and adapt to climate change, and in July of 2017, Governor Hickenlooper signed an executive order committing the state to additional climate action and specifying greenhouse gas emission reduction goals. An update to the CCP was issued in 2018 and included public input from the water sector.

Future climate change analysis should be used in conjunction with the vulnerability assessment completed here to inform the hazard profile and to support a drought risk assessment that incorporates vulnerability to possible future droughts.

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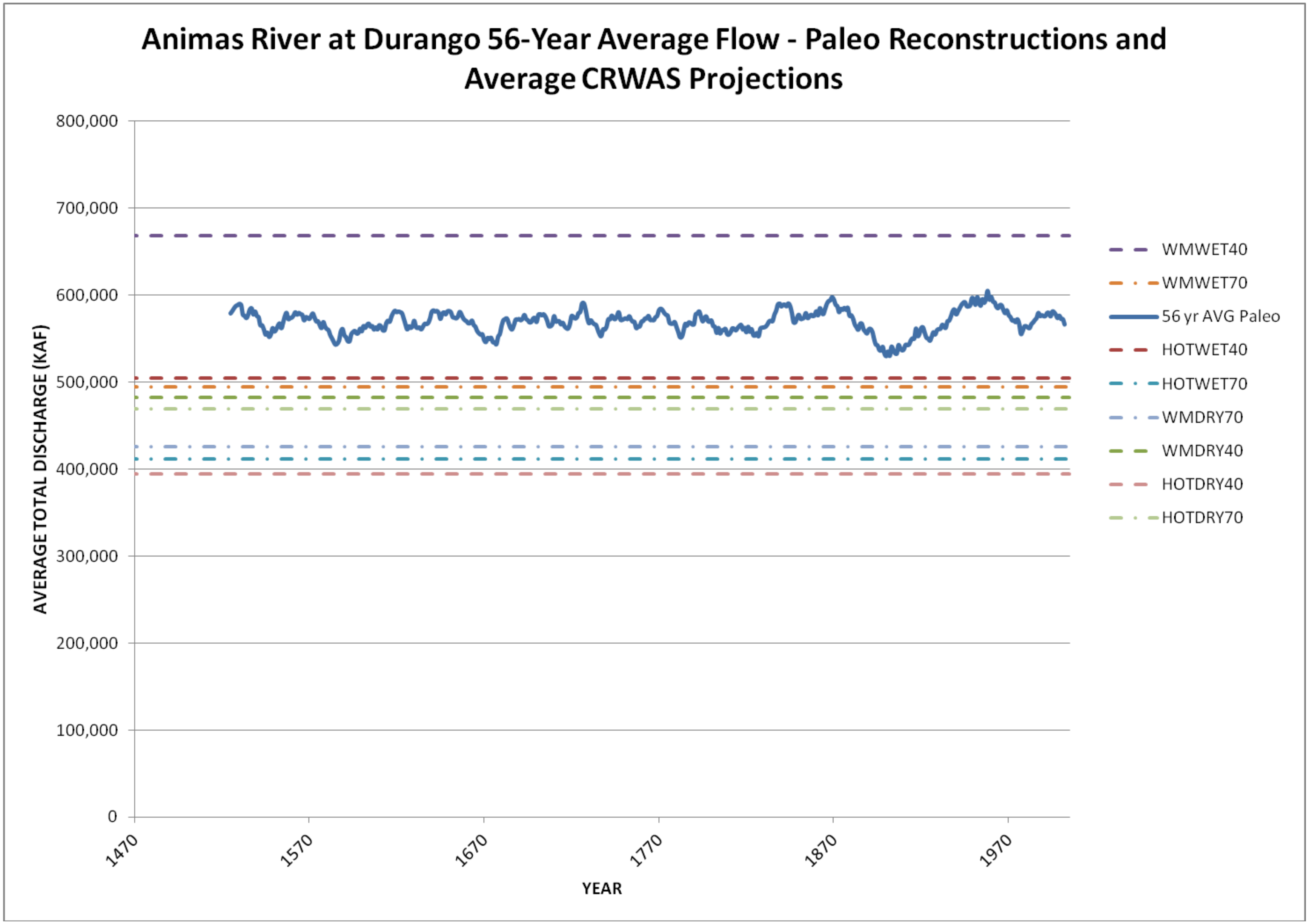
6 APPENDIX 1: FLOW COMPARISON CHARTS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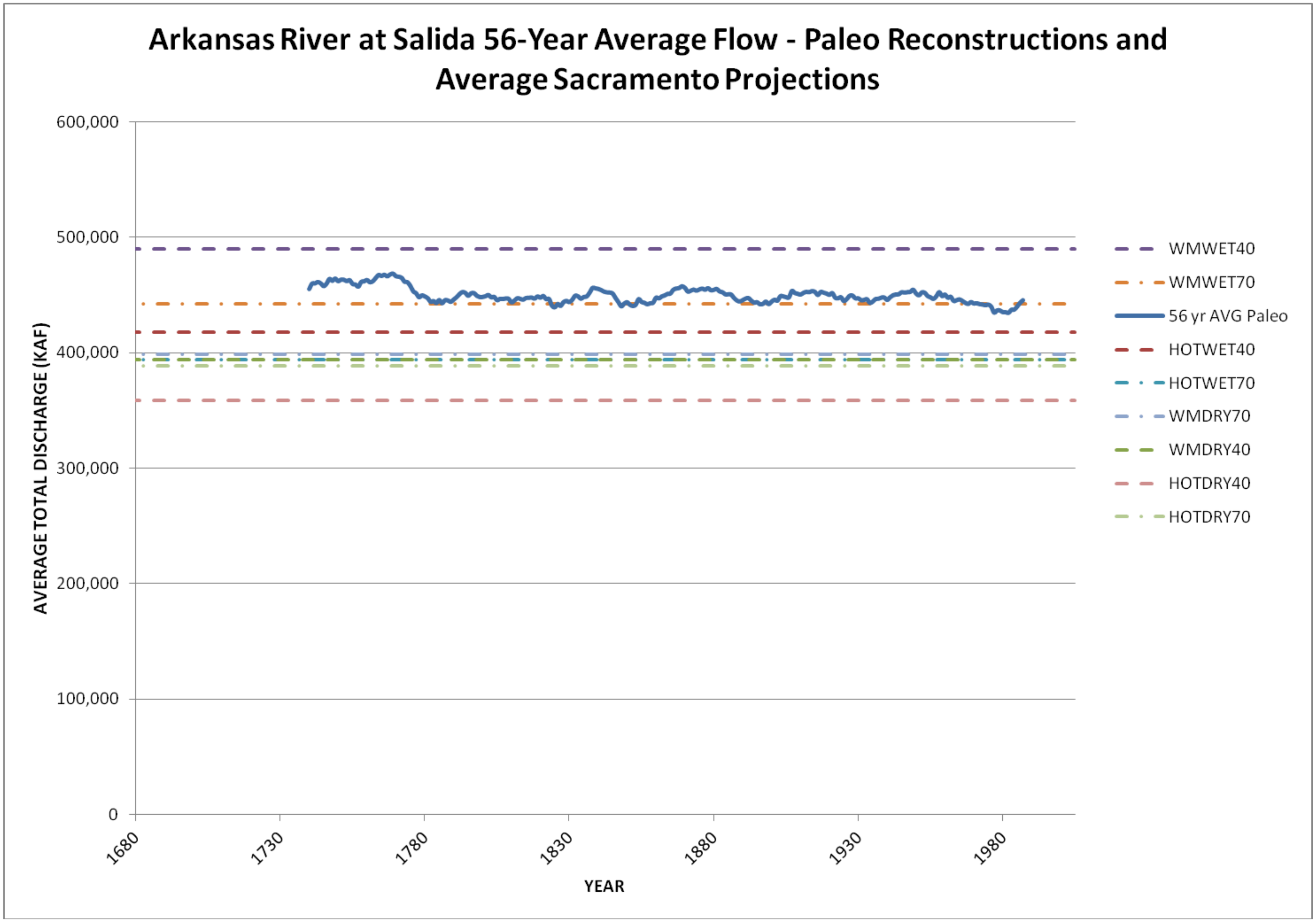
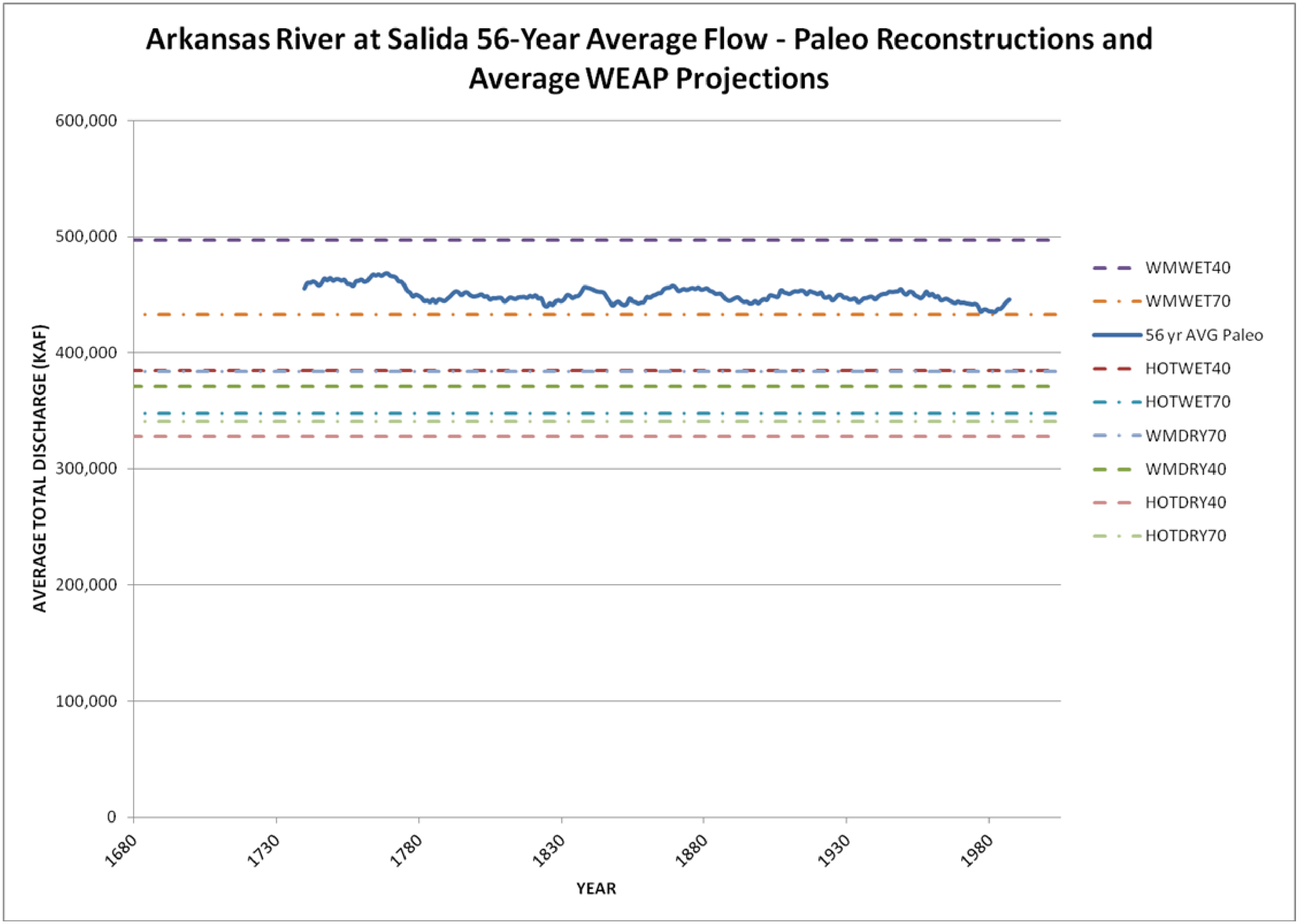
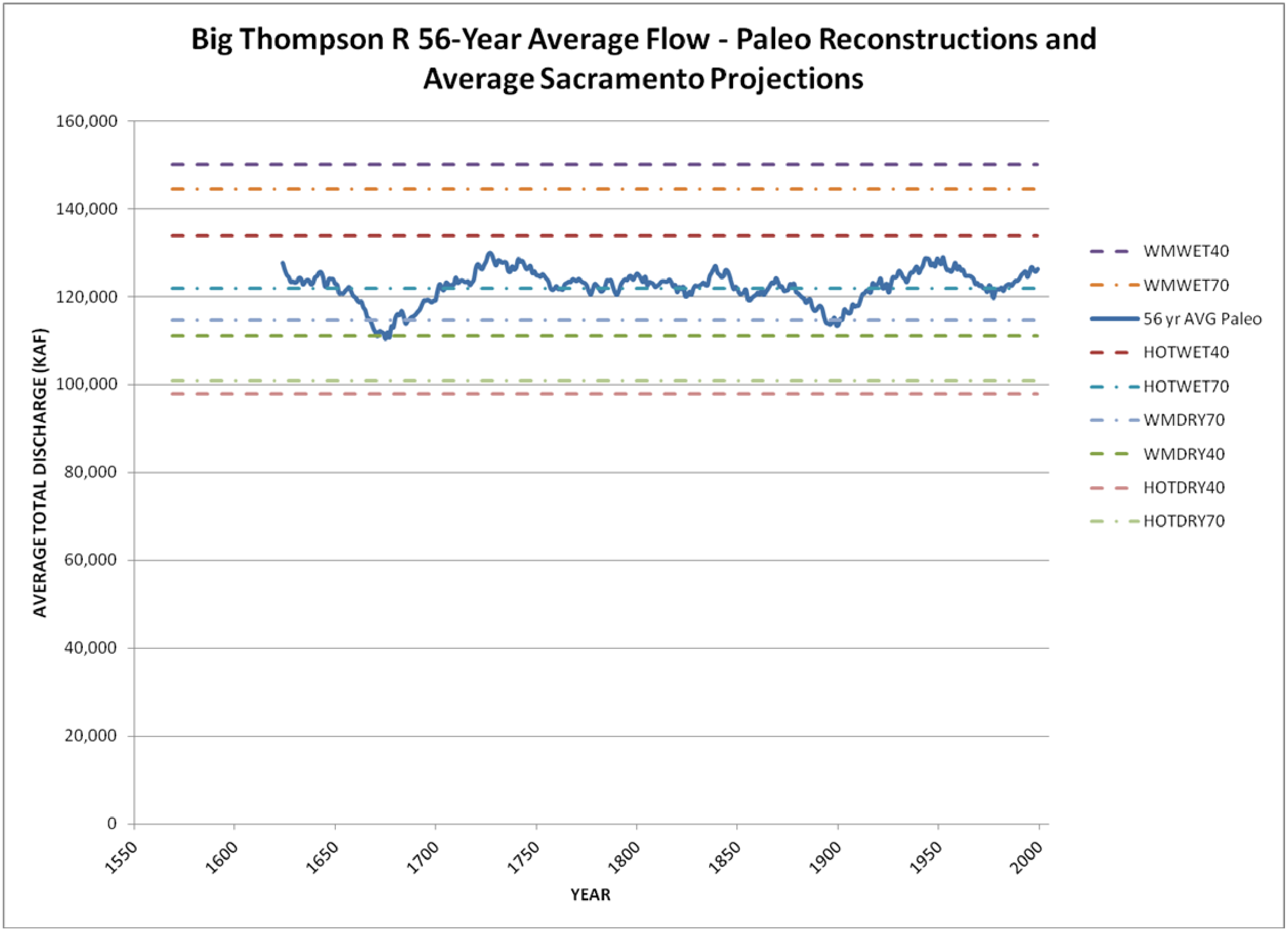
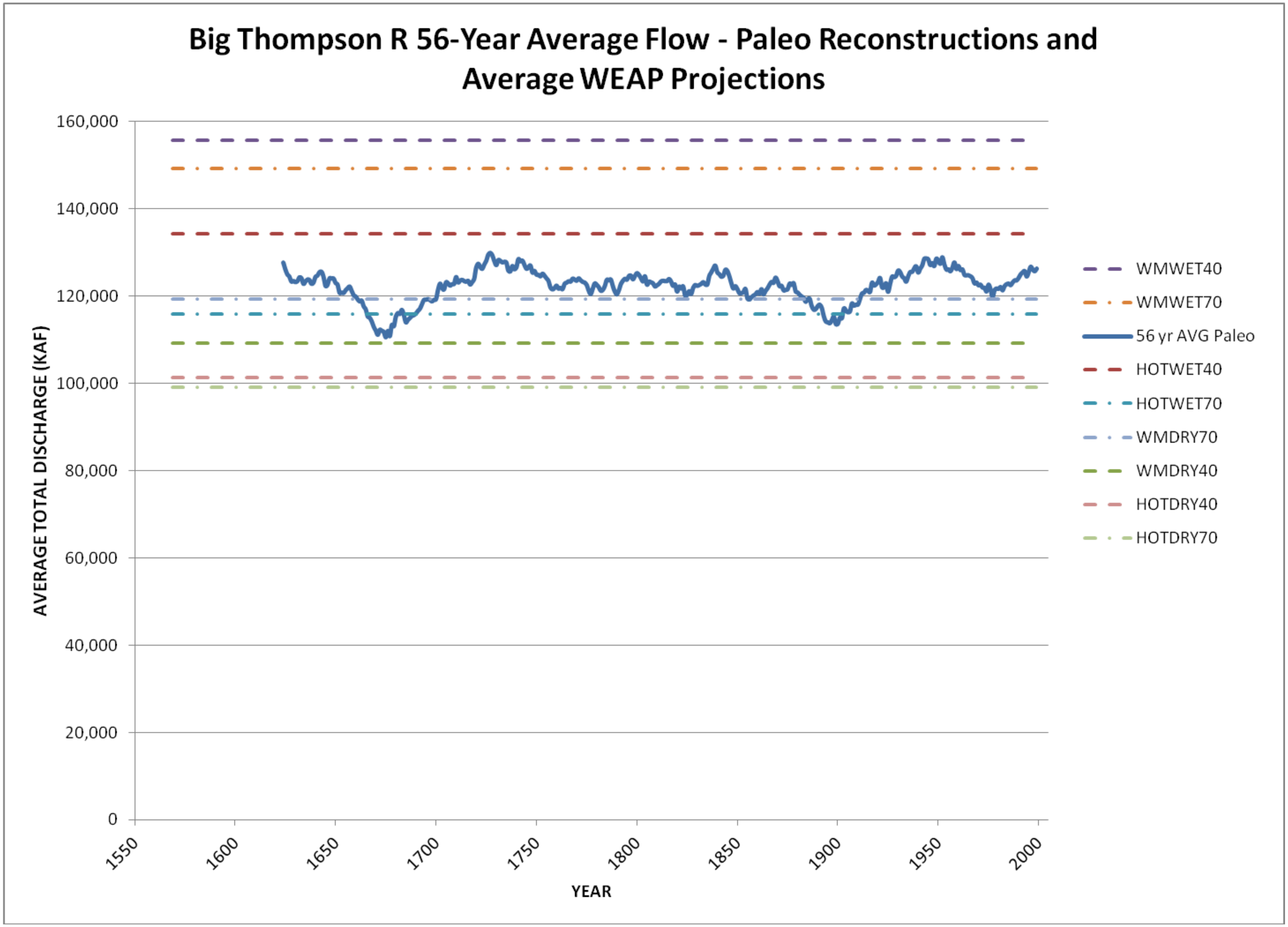
AVERAGE TOTAL DISCHARGE (KAF)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1470
1570
1670
1770
1870
1970
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

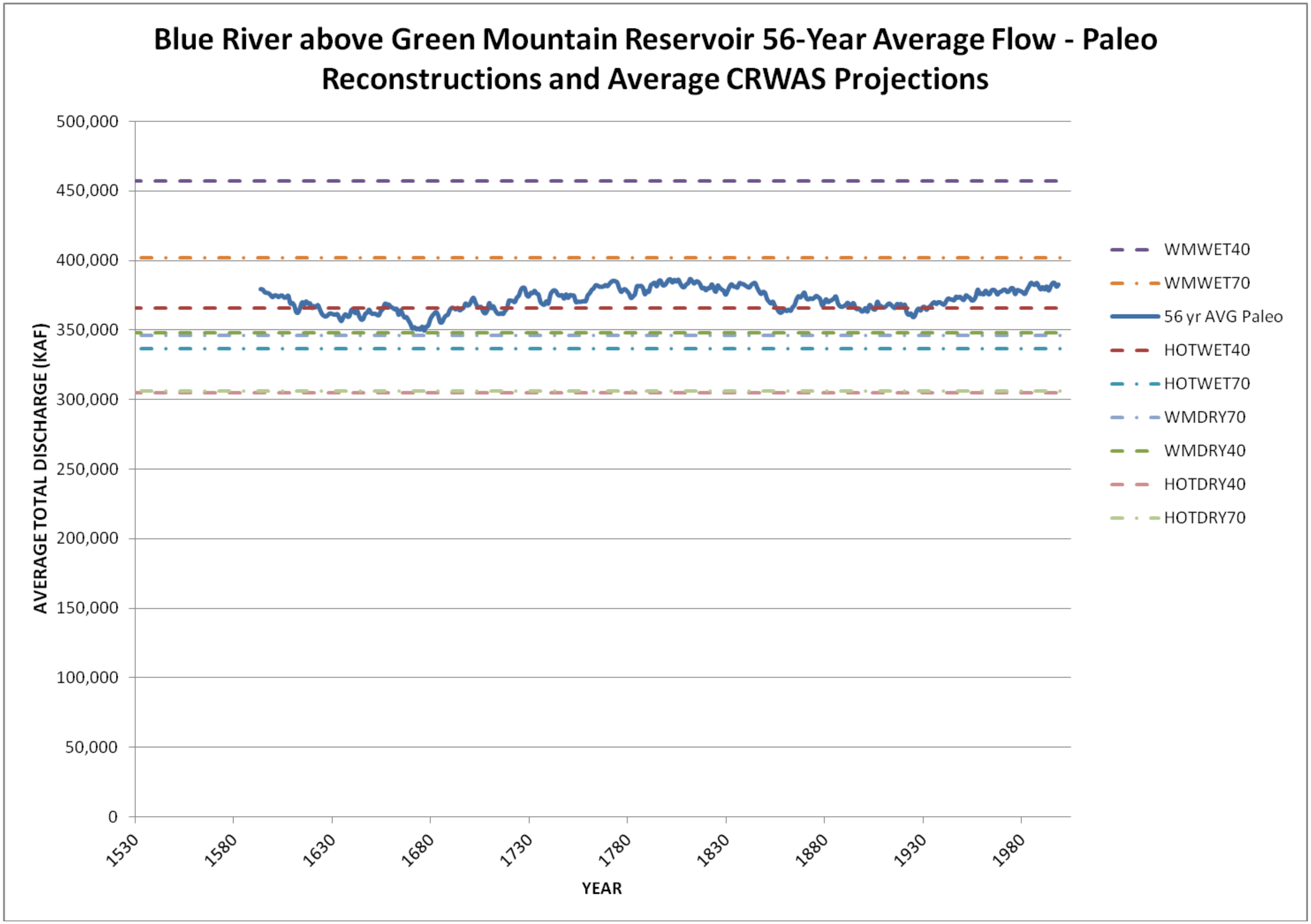

Arkansas River at Salida 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
AVERAGE TOTAL DISCHARGE (KAF)
600,000
500,000
400,000
300,000
200,000
100,000
0
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


Arkansas River at Salida 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
600,000
500,000
400,000
300,000
200,000
100,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

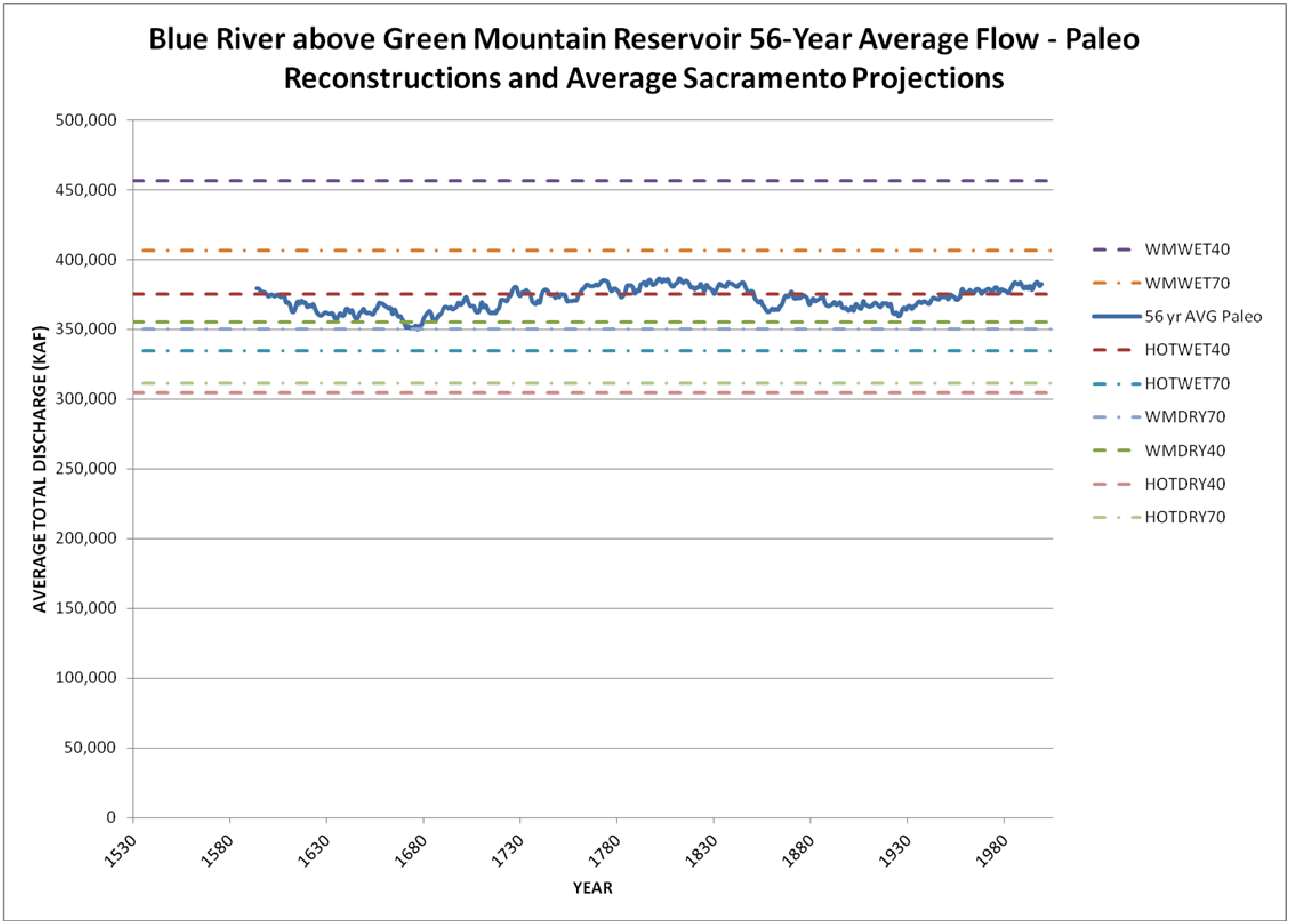

Big Thompson R 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
AVERAGE TOTAL DISCHARGE (KAF)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Big Thompson R 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Blue River above Green Mountain Reservoir 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
AVERAGE TOTAL DISCHARGE (KAF)
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1530
1580
1630
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70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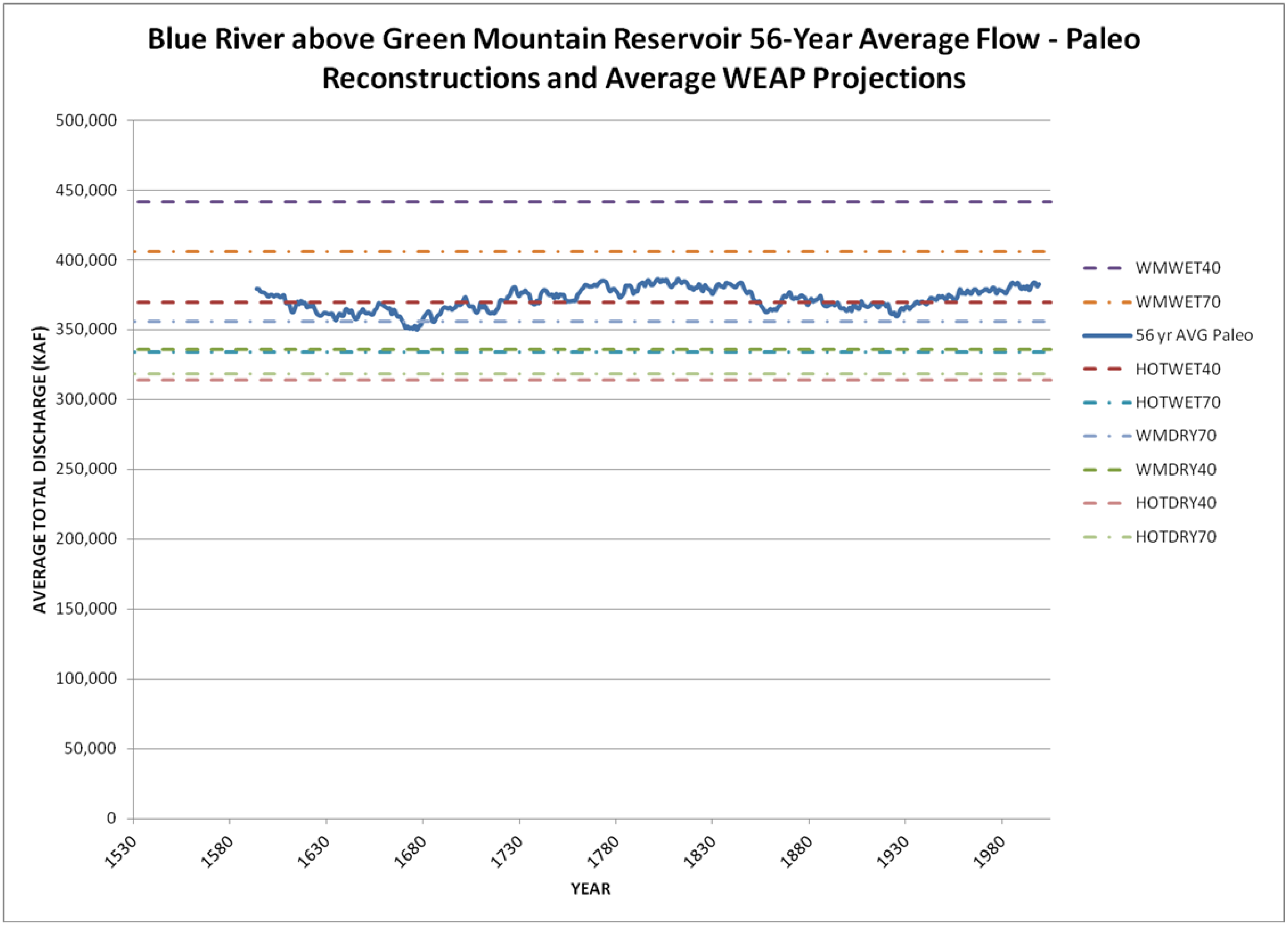
AVERAGE TOTAL DISCHARGE (KAF)
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1530
1580
1630
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70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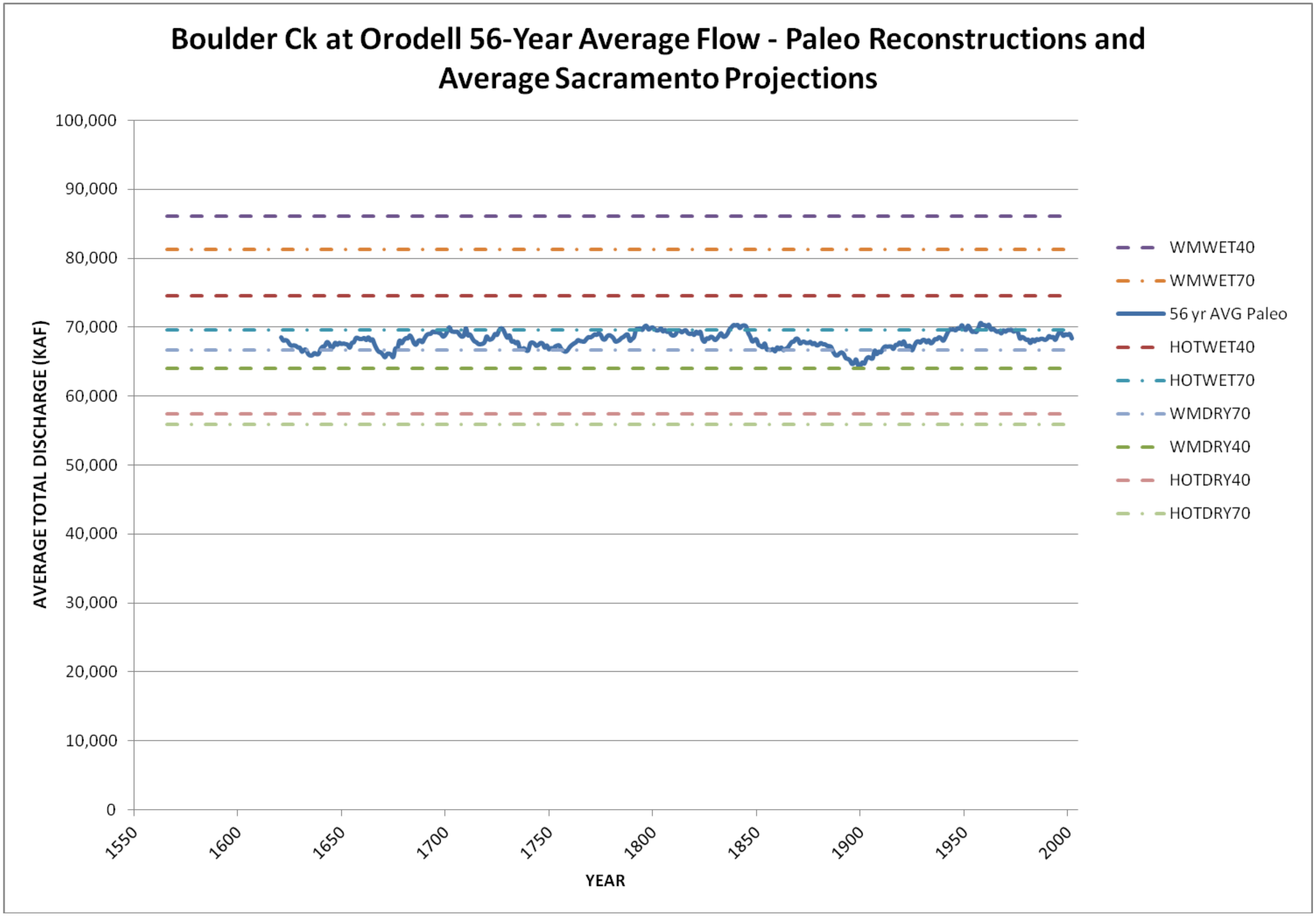
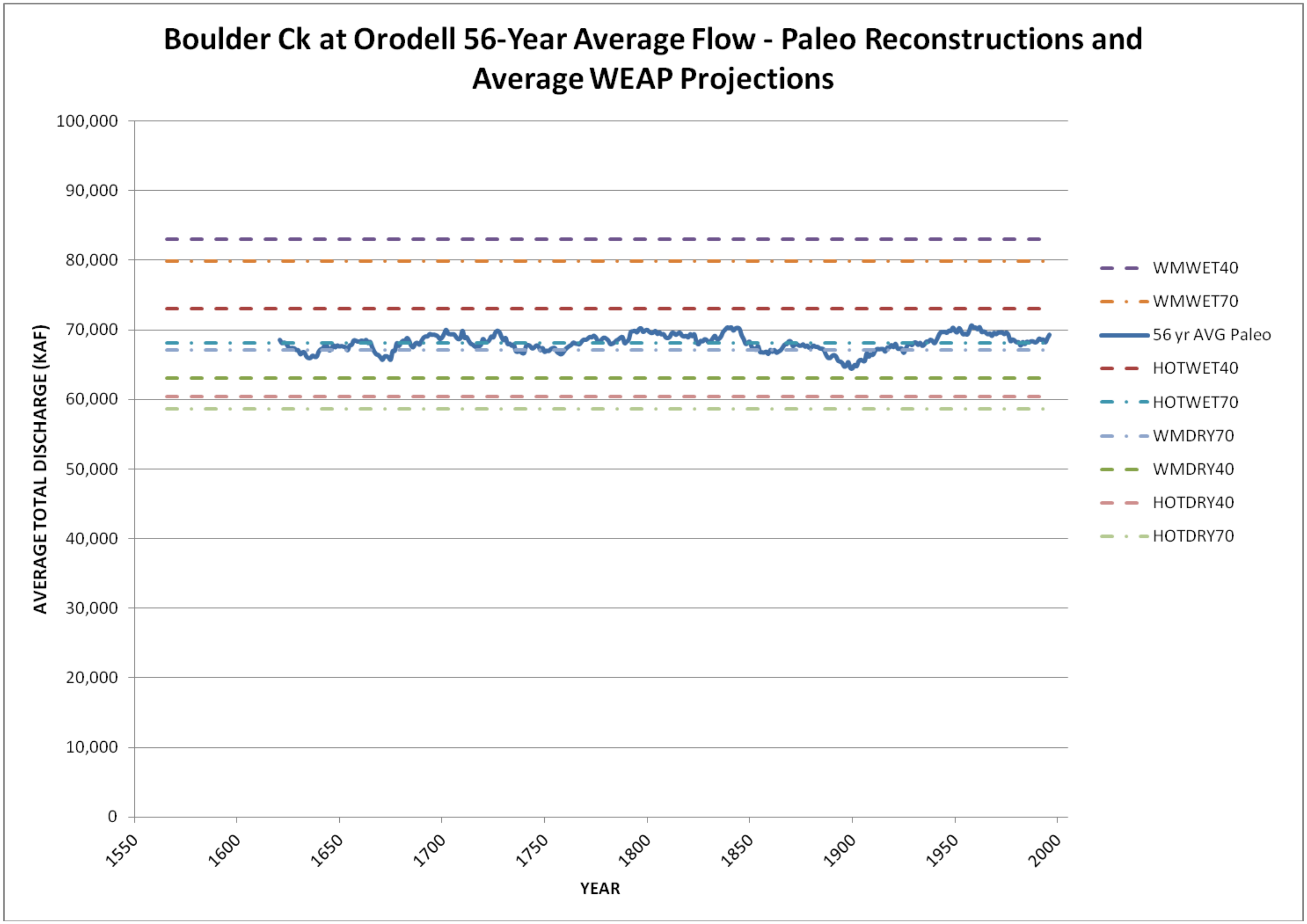
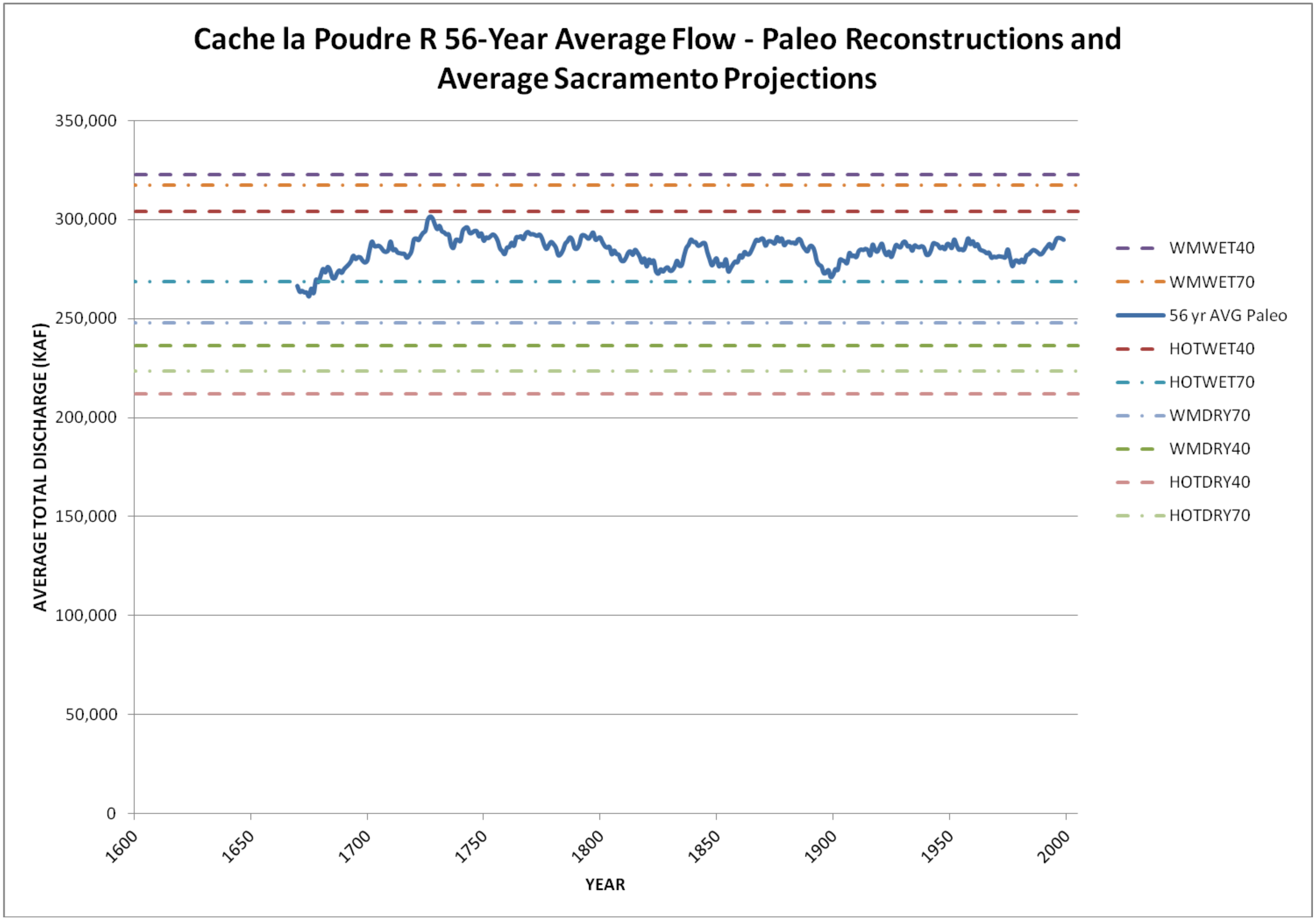
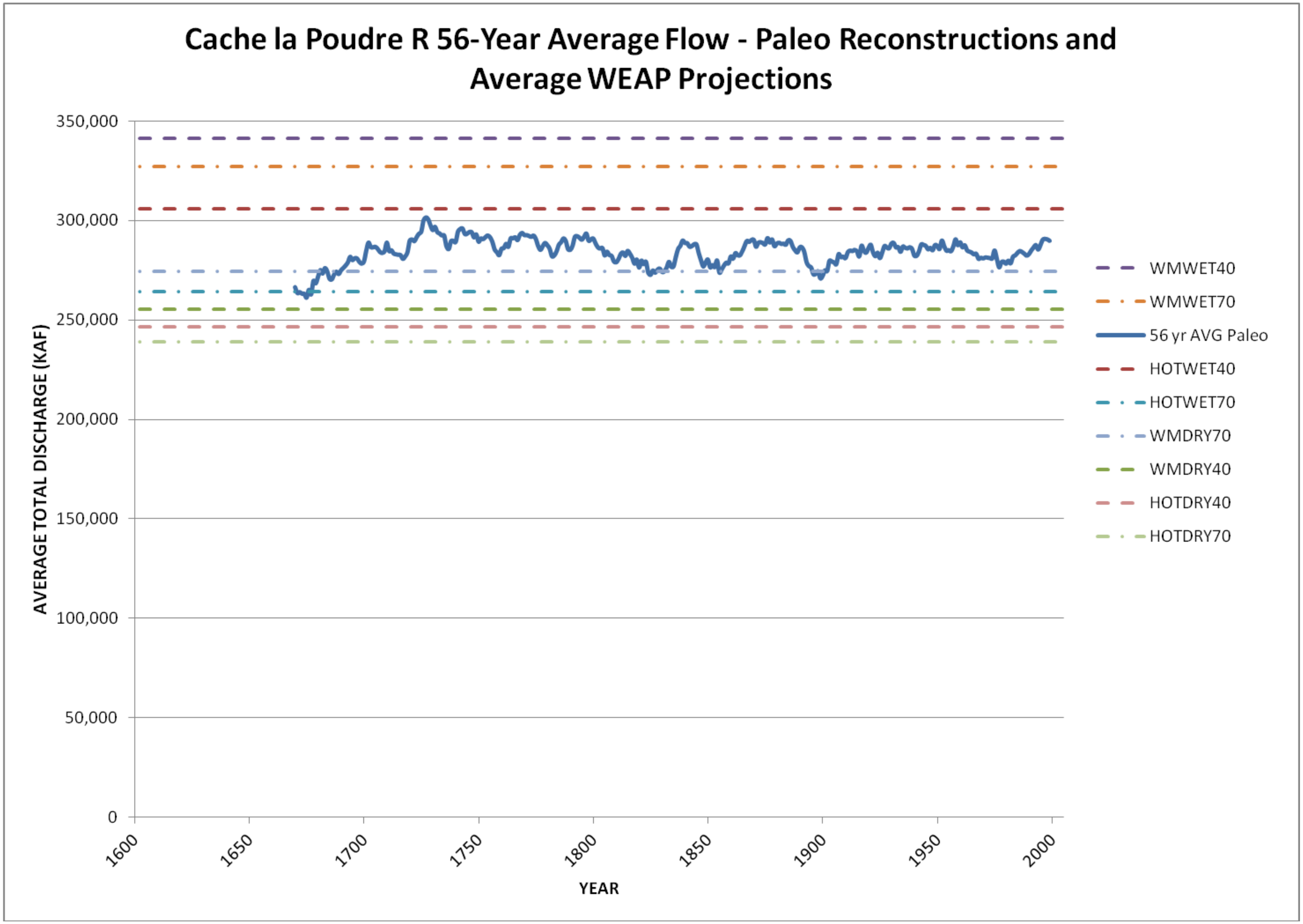
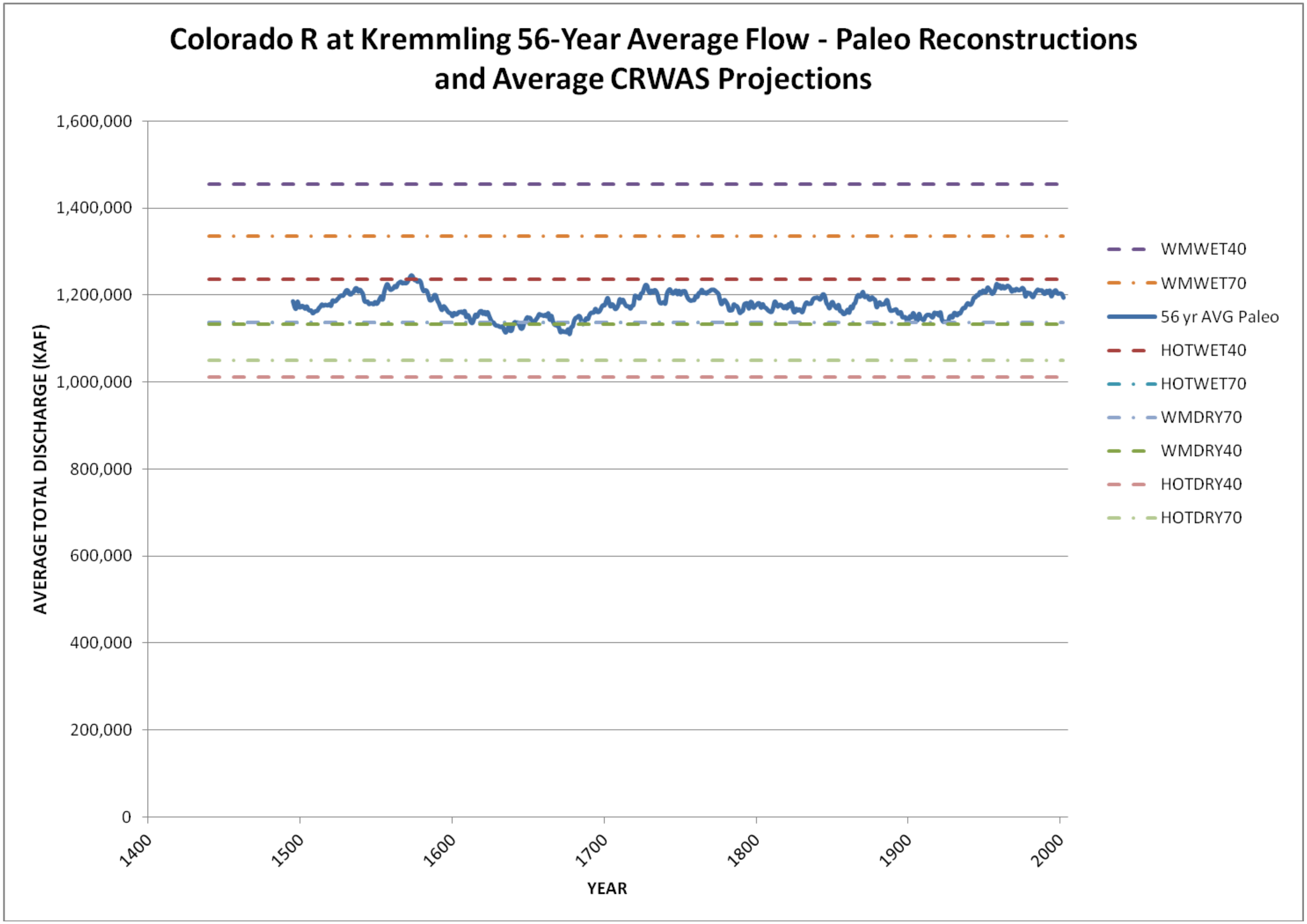
AVERAGE TOTAL DISCHARGE (KAF)
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1530
1580
1630
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


Boulder Ck at Orodell 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

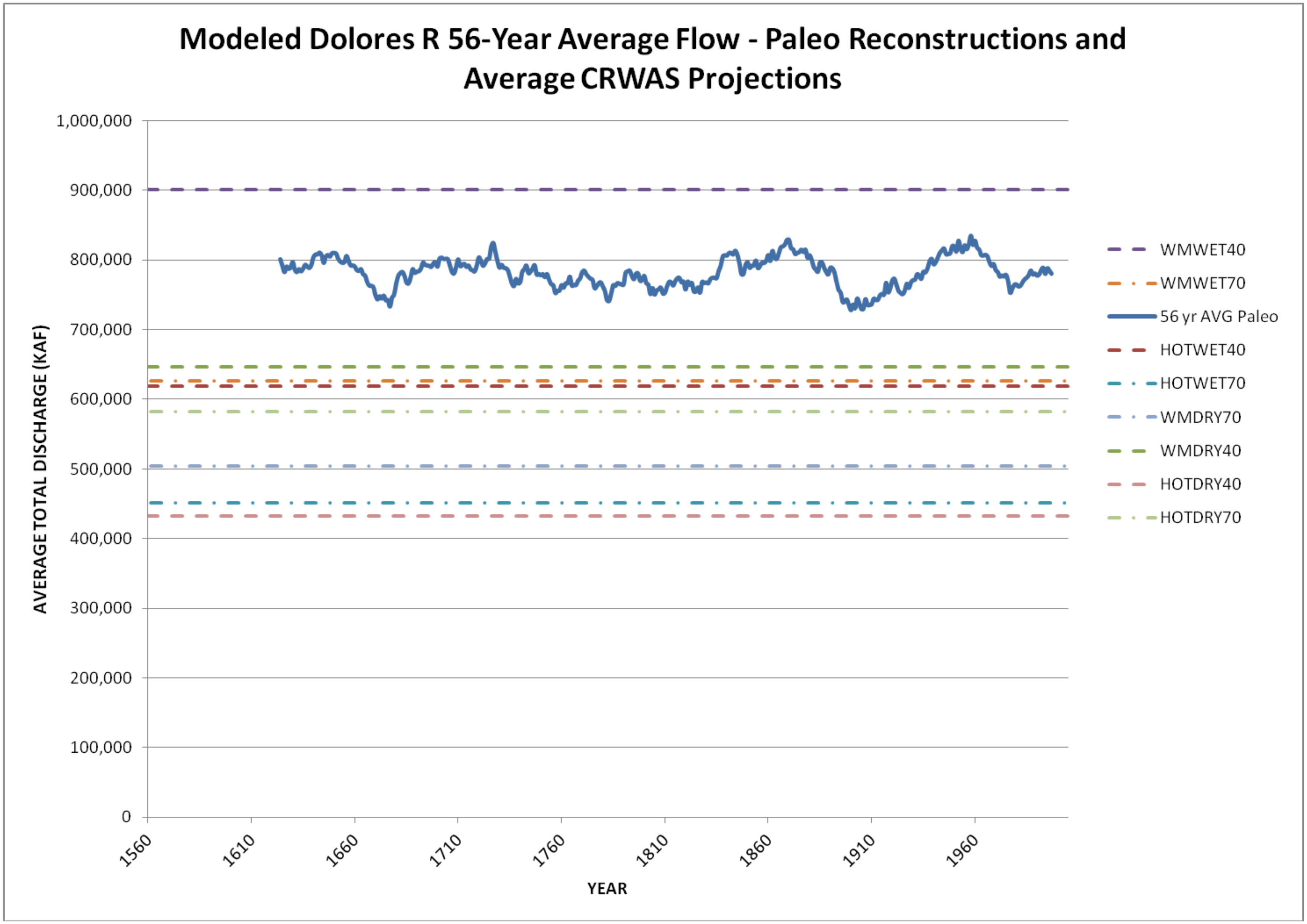

Boulder Ck at Orodell 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


Cache la Poudre R 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

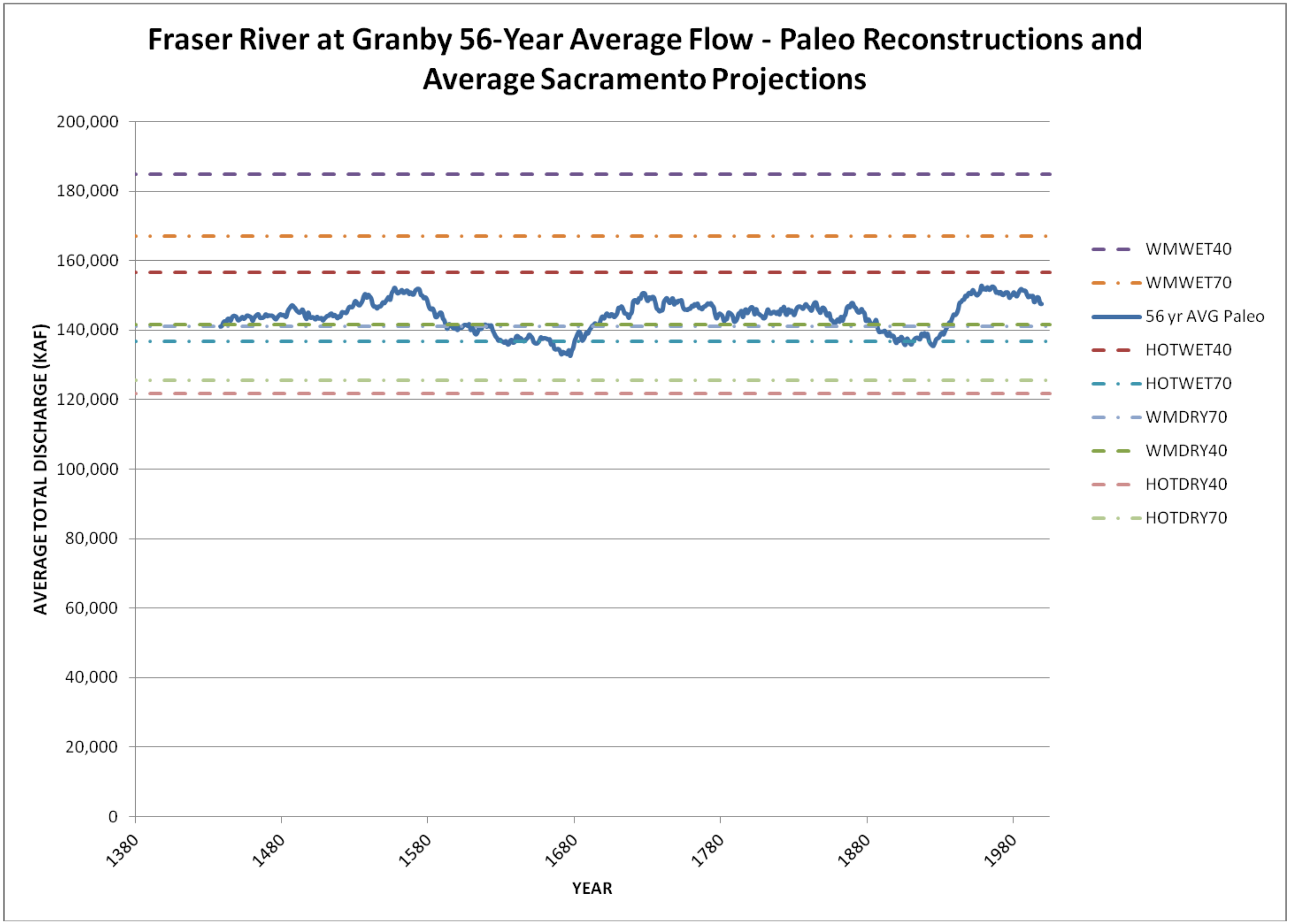

Cache la Poudre R 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
AVERAGE TOTAL DISCHARGE (KAF)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Colorado R at Kremmling 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1400
1500
1600
1700
1800
1900
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Modeled Dolores R 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1560
1610
1660
1710
1760
1810
1860
1910
1960
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


Fraser River at Granby 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1380
1480
1580
1680
1780
1880
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
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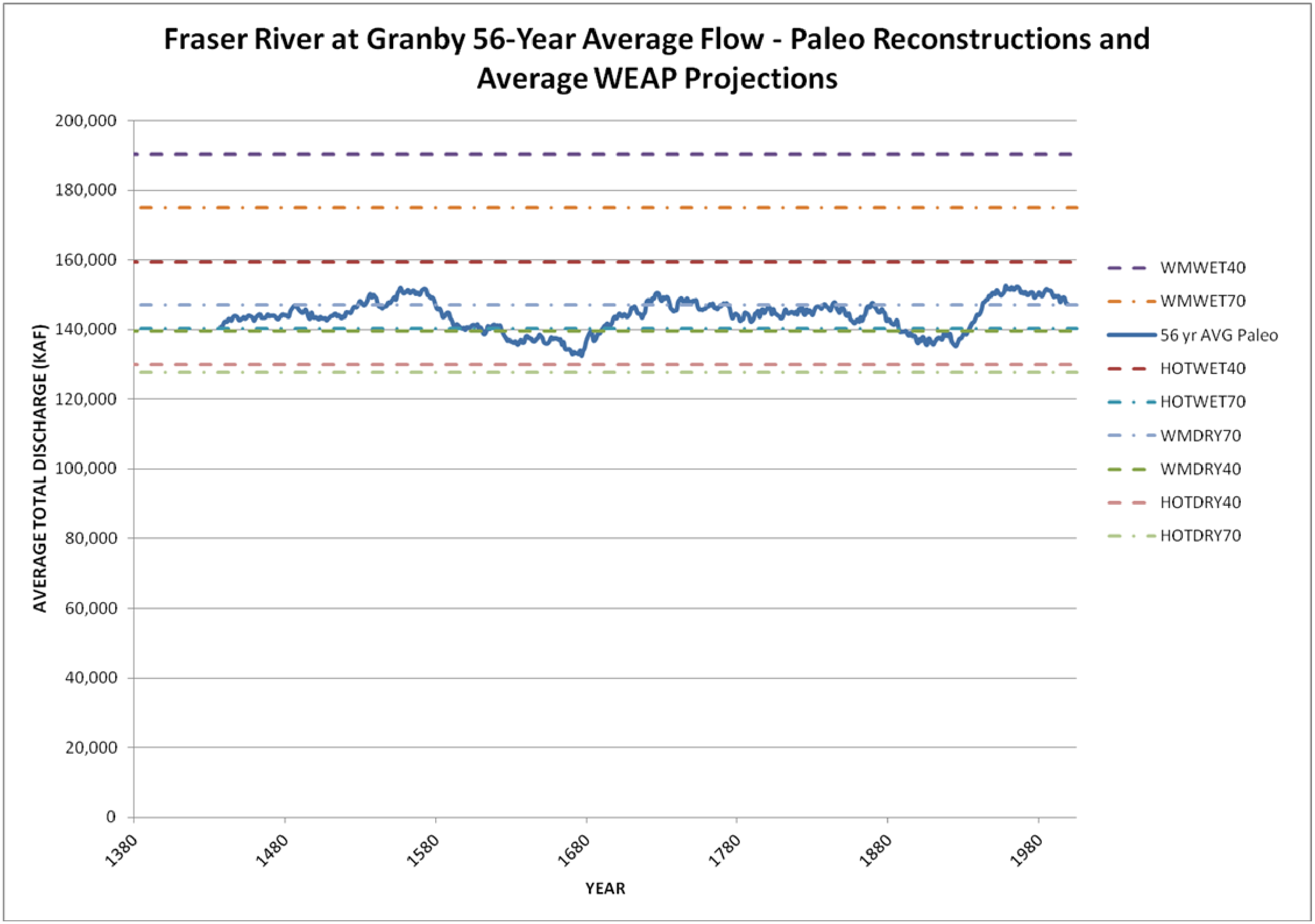
HOTDRY40
HOTDRY70



Fraser River at Granby 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1380
1480
1580
1680
1780
1880
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
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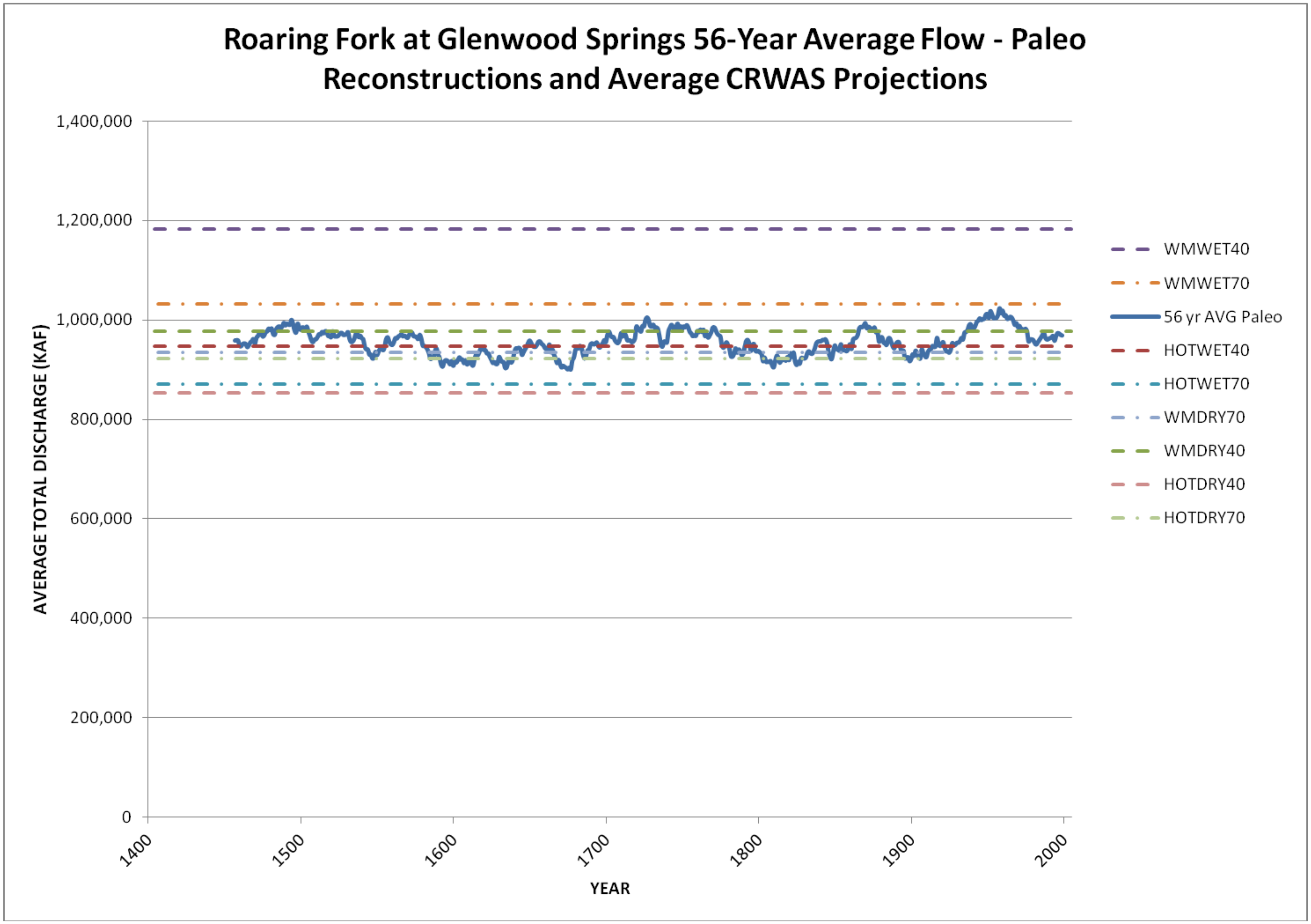
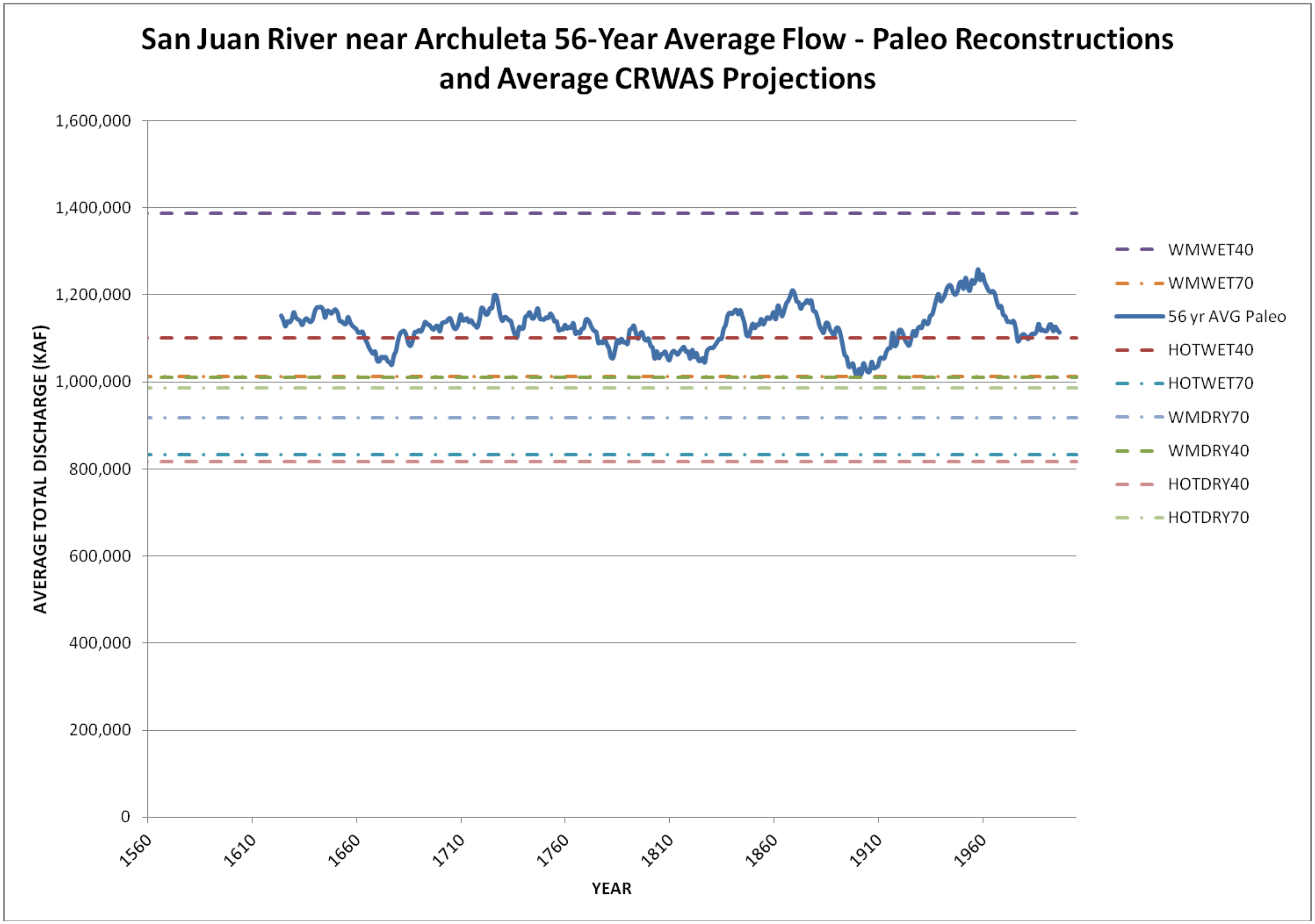
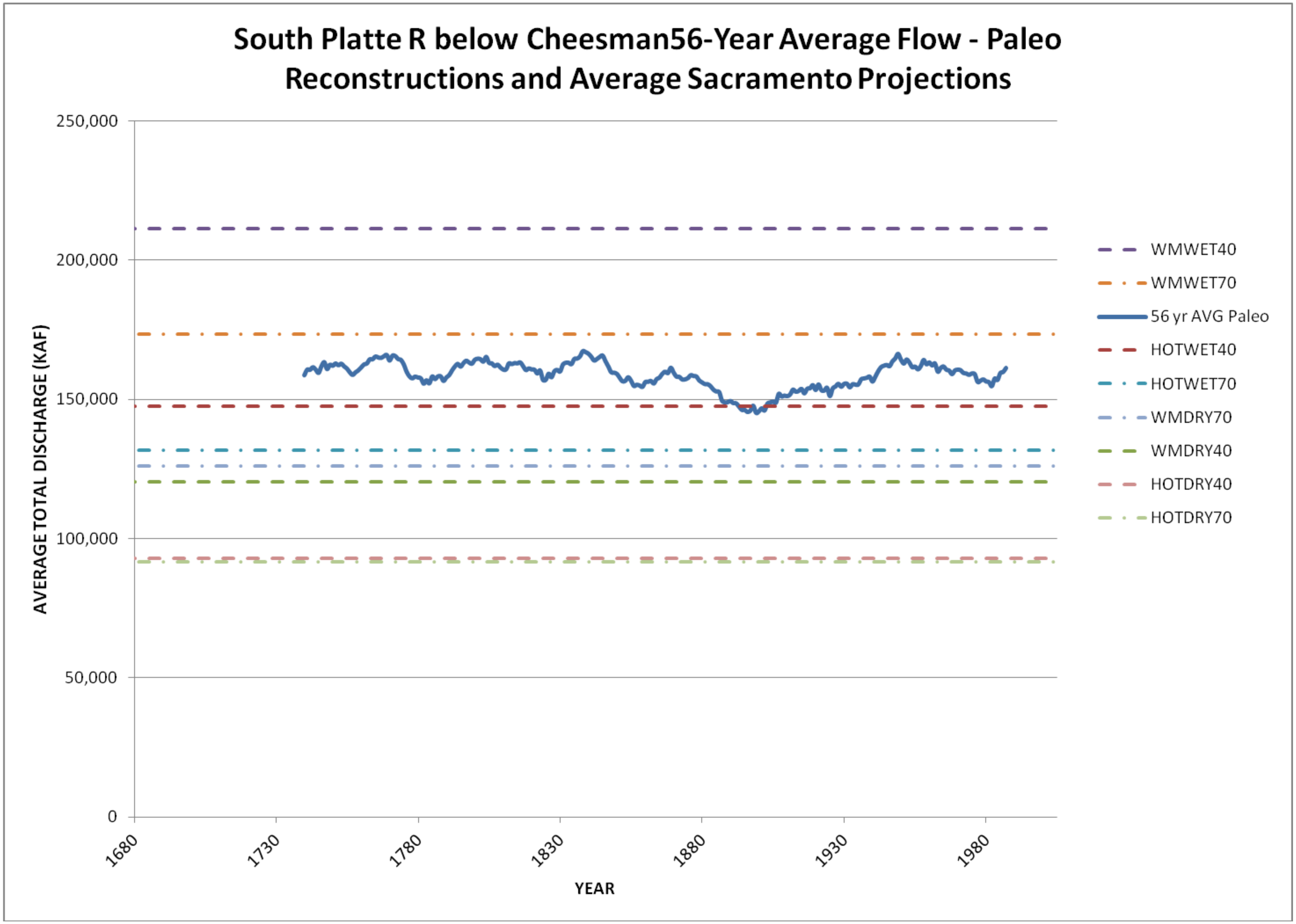
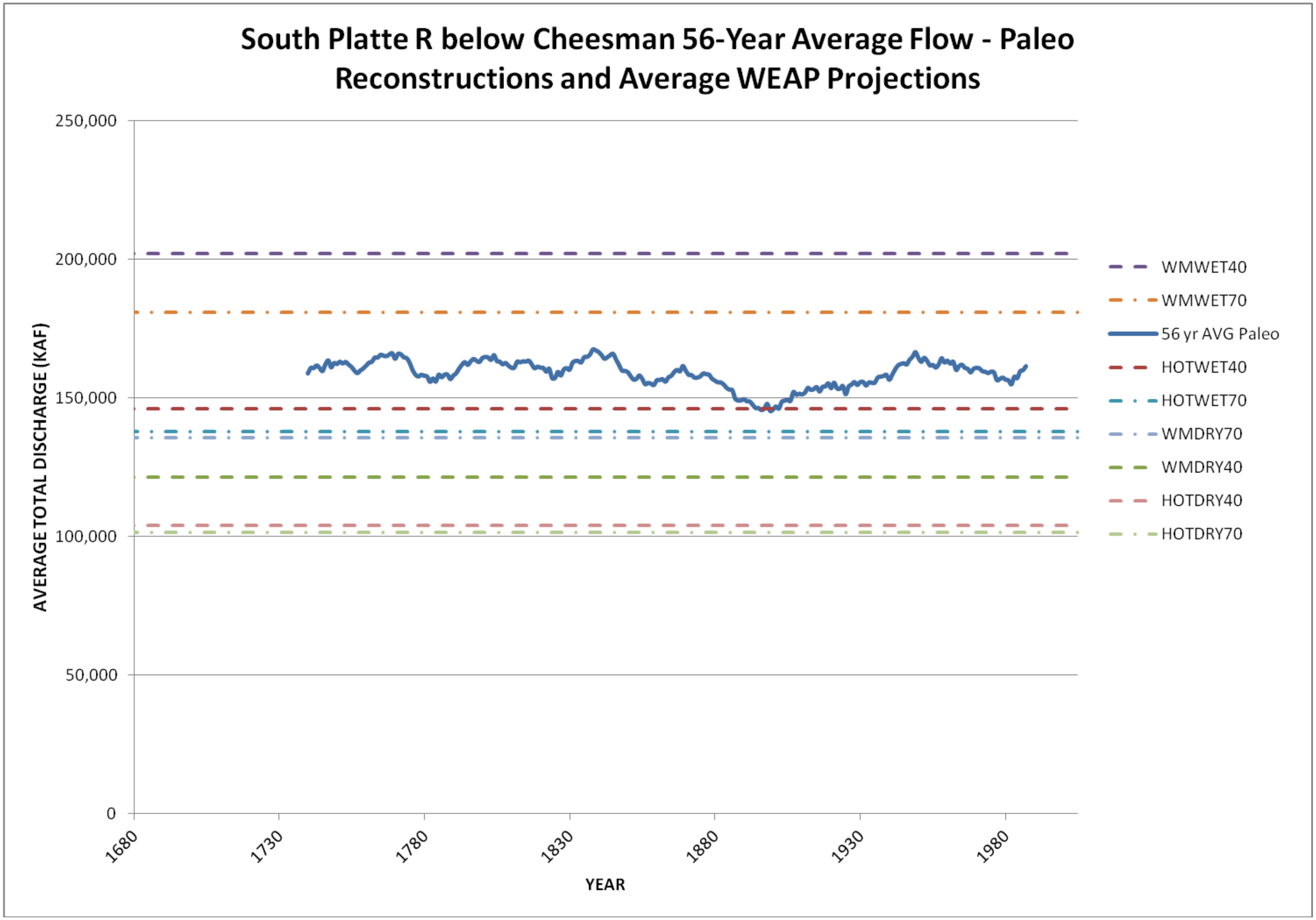
HOTDRY40
HOTDRY70

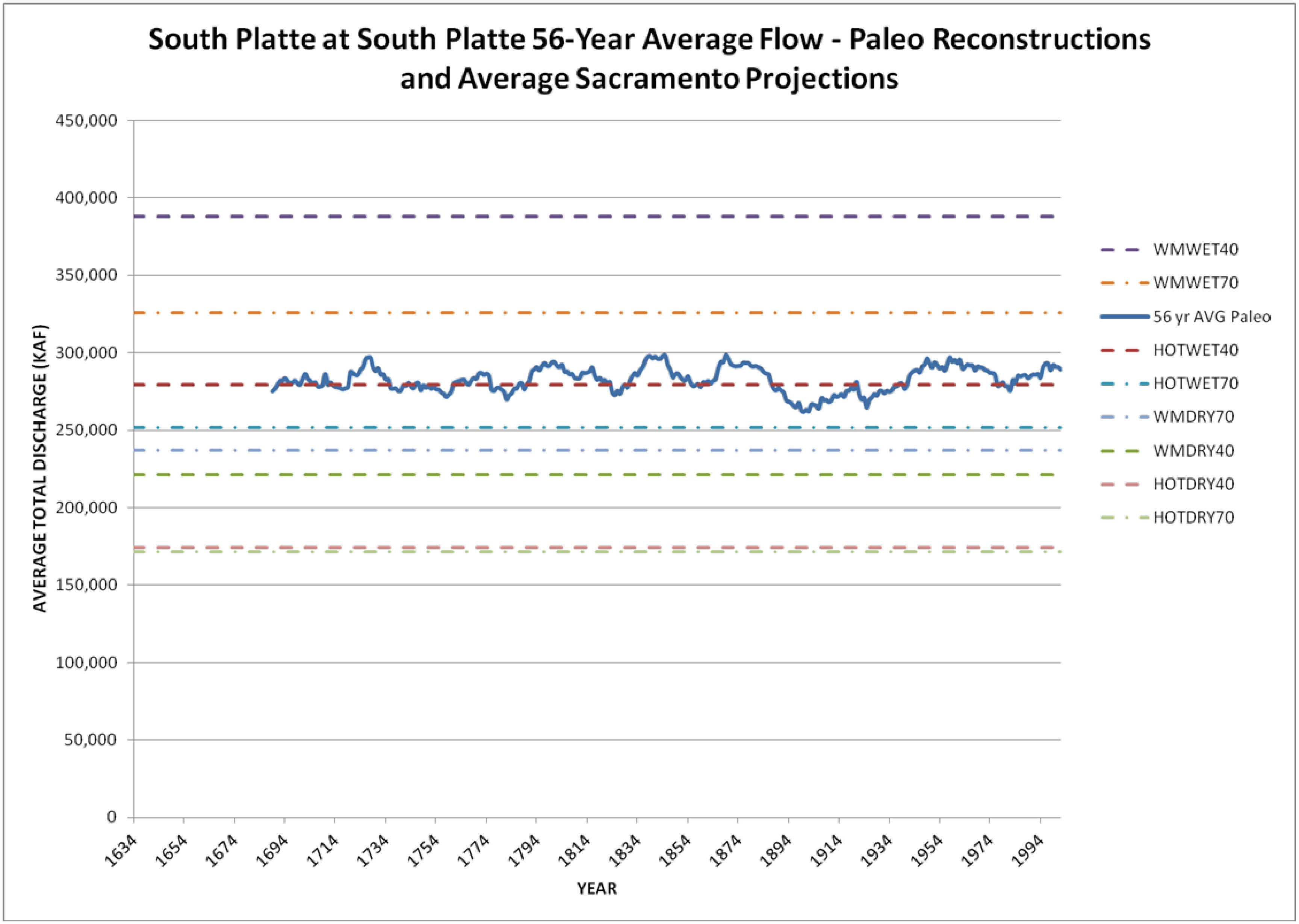

Roaring Fork at Glenwood Springs 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
AVERAGE TOTAL DISCHARGE (KAF)
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1400
1500
1600
1700
1800
1900
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

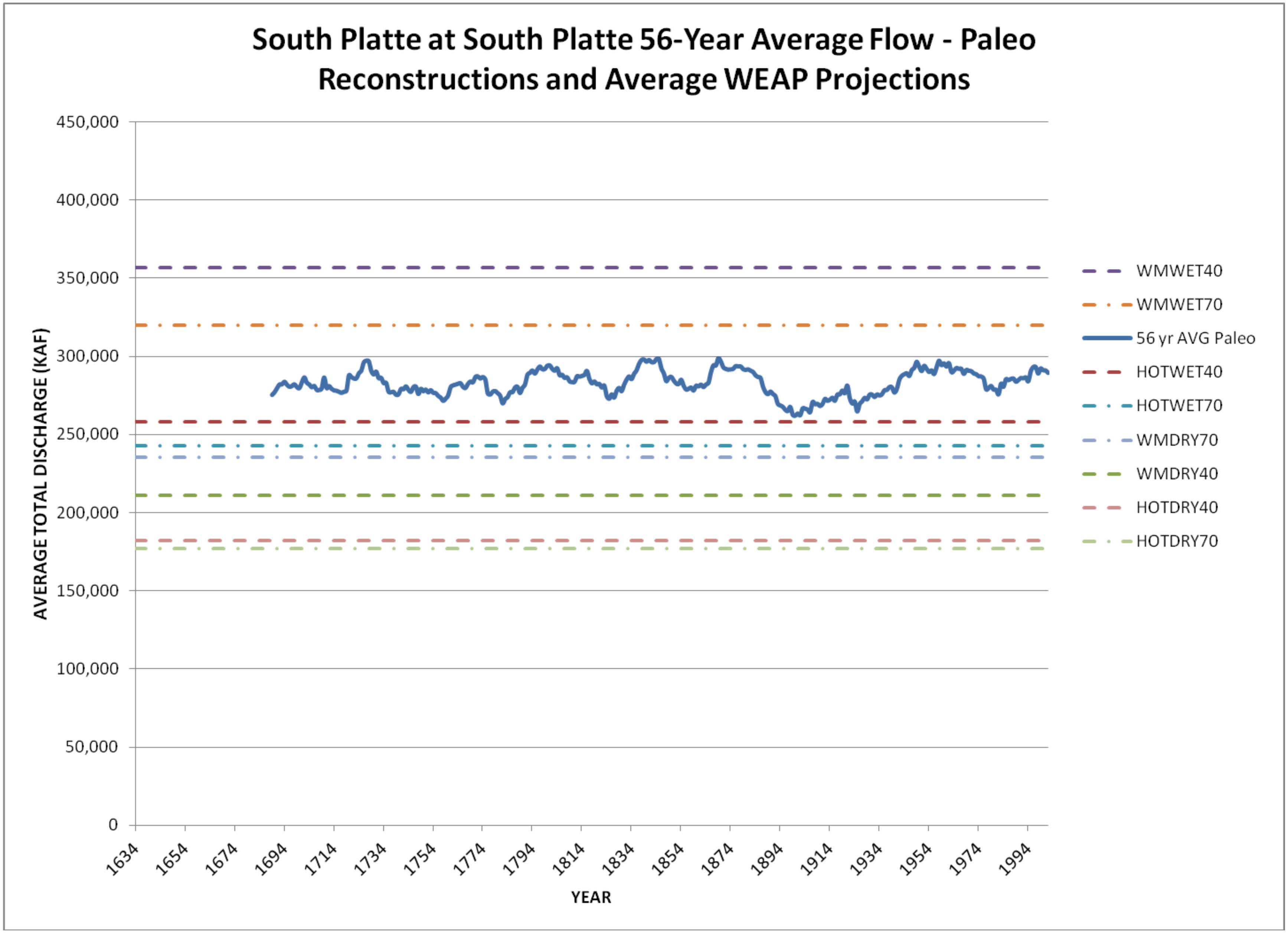


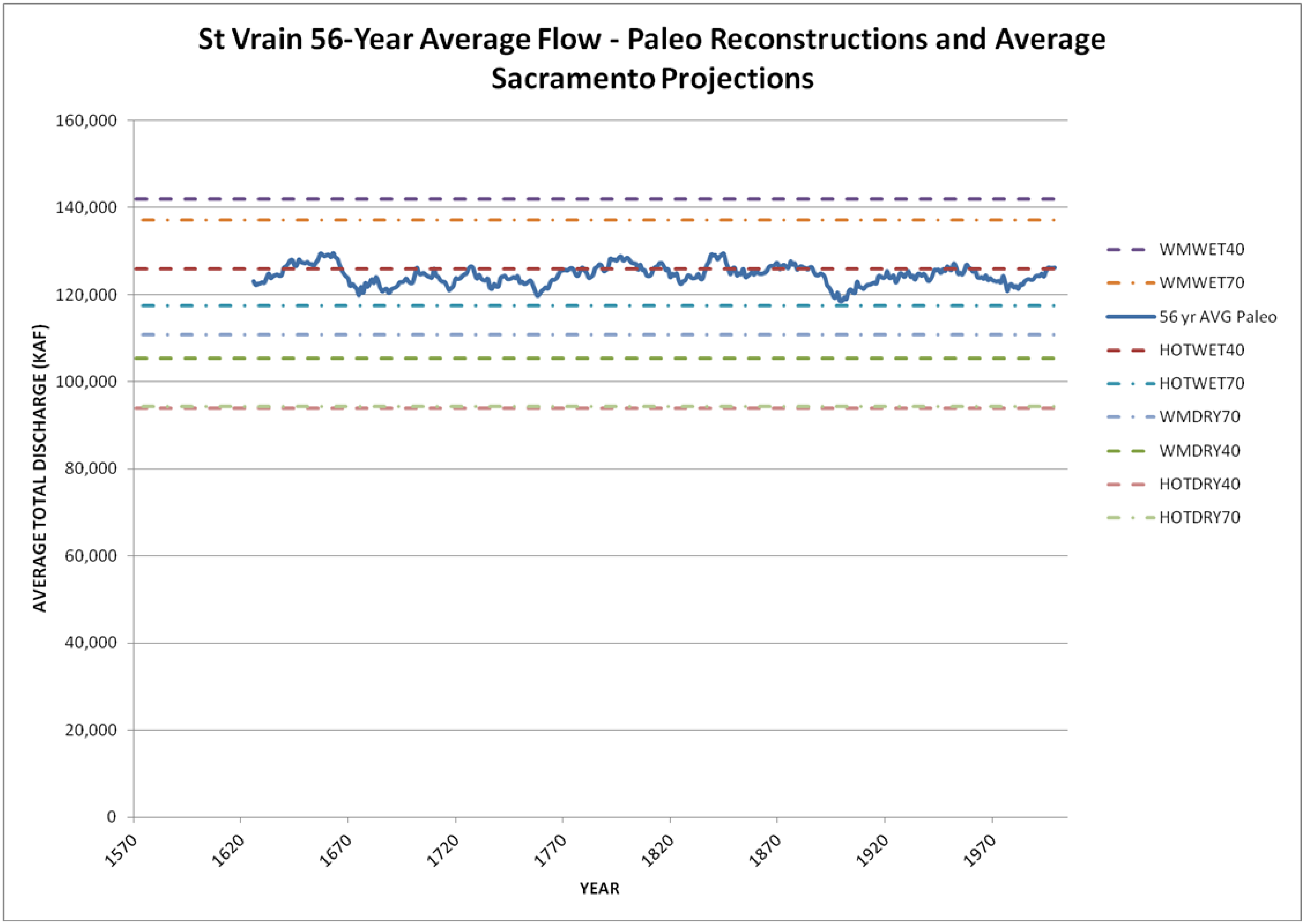
San Juan River near Archuleta 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
AVERAGE TOTAL DISCHARGE (KAF)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1560
1610
1660
1710
1760
1810
1860
1910
1960
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

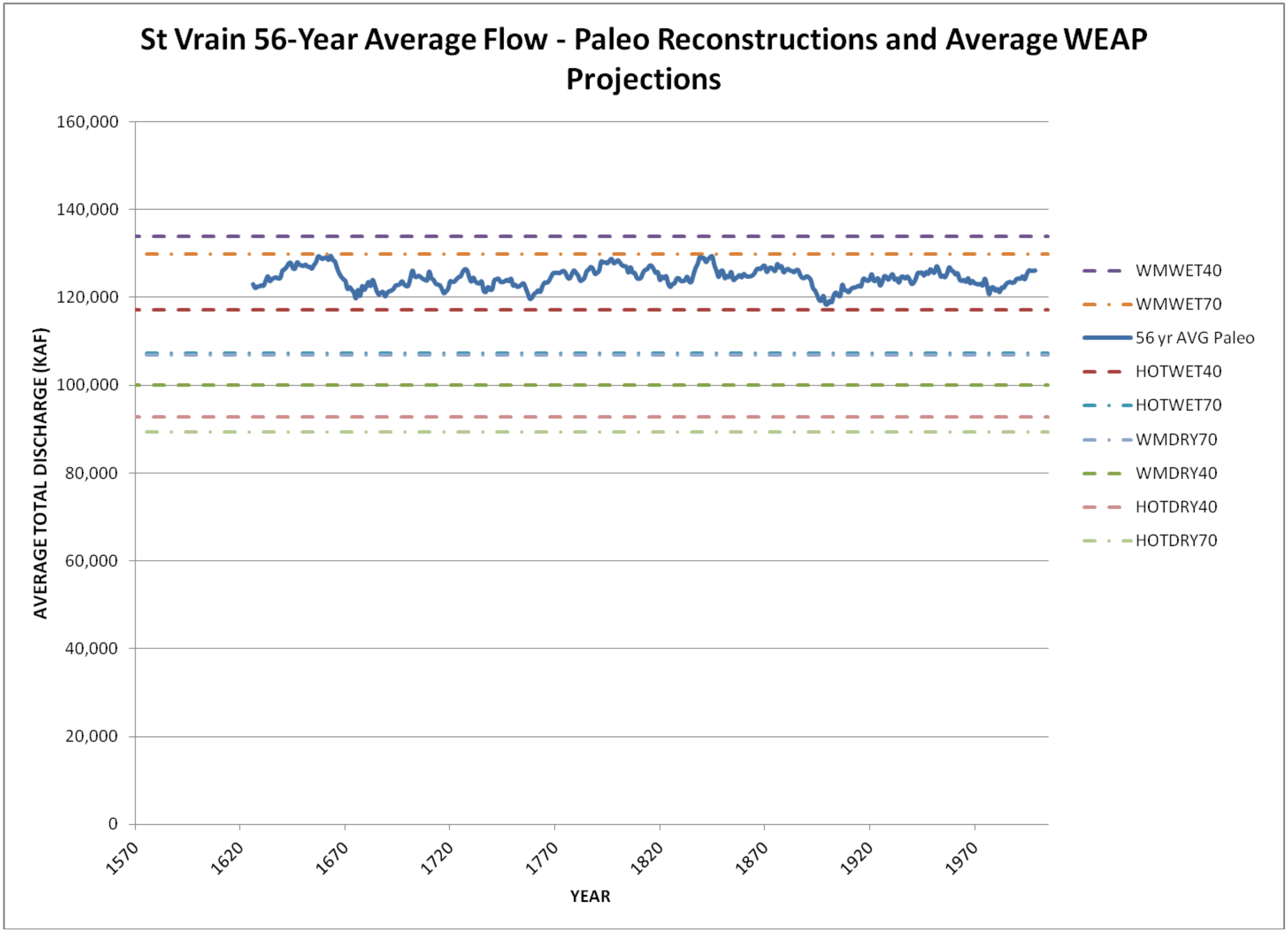

South Platte R below Cheesman56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
AVERAGE TOTAL DISCHARGE (KAF)
250,000
200,000
150,000
100,000
50,000
0
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

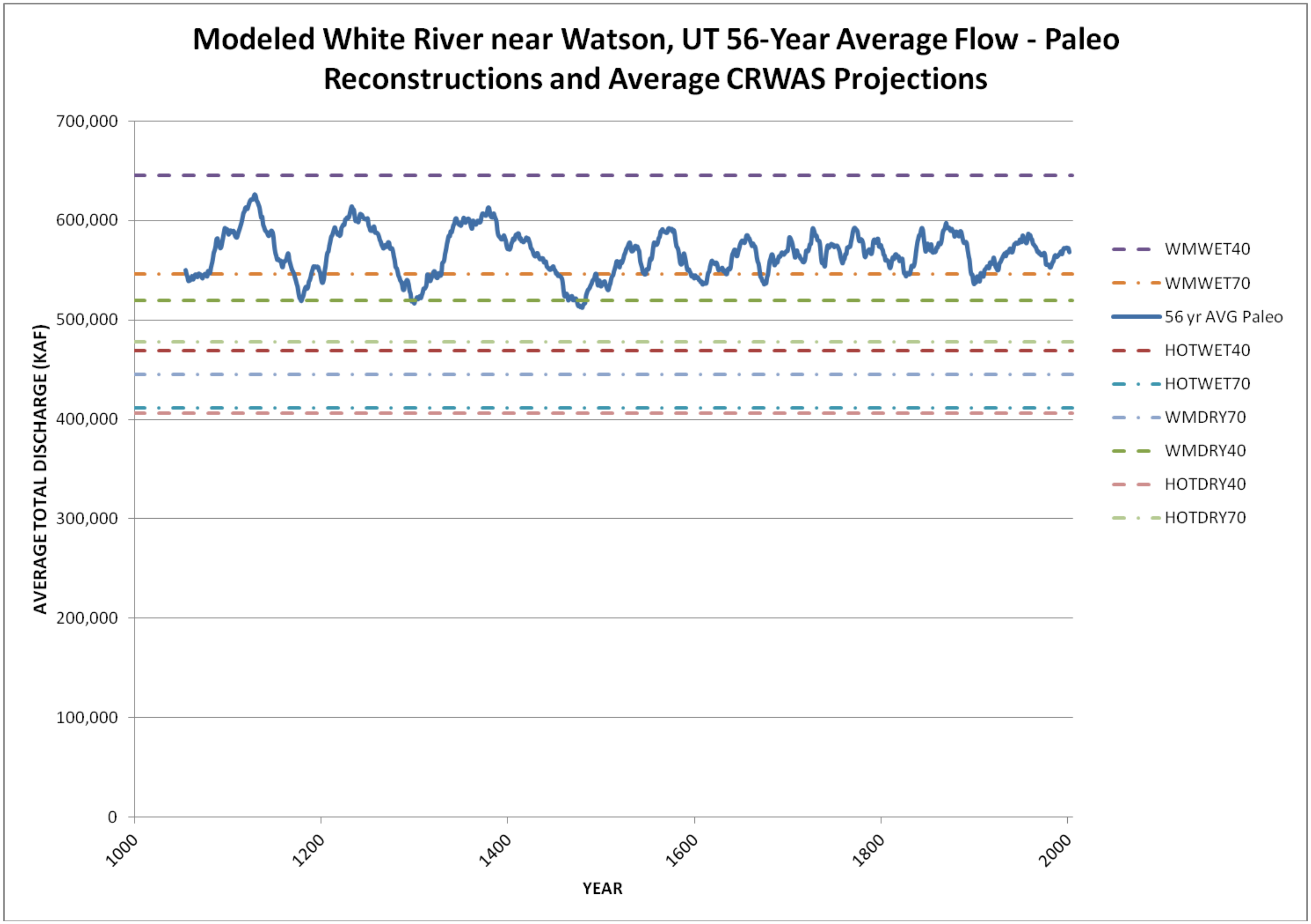

South Platte R below Cheesman 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
AVERAGE TOTAL DISCHARGE (KAF)
250,000
200,000
150,000
100,000
50,000
0
1680
1730
1780
1830
1880
1930
1980
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


South Platte at South Platte 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
AVERAGE TOTAL DISCHARGE (KAF)
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1634
1654
1674
1694
1714
1734
1754
1774
1794
1814
1834
1854
1874
1894
1914
1934
1954
1974
1994
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70

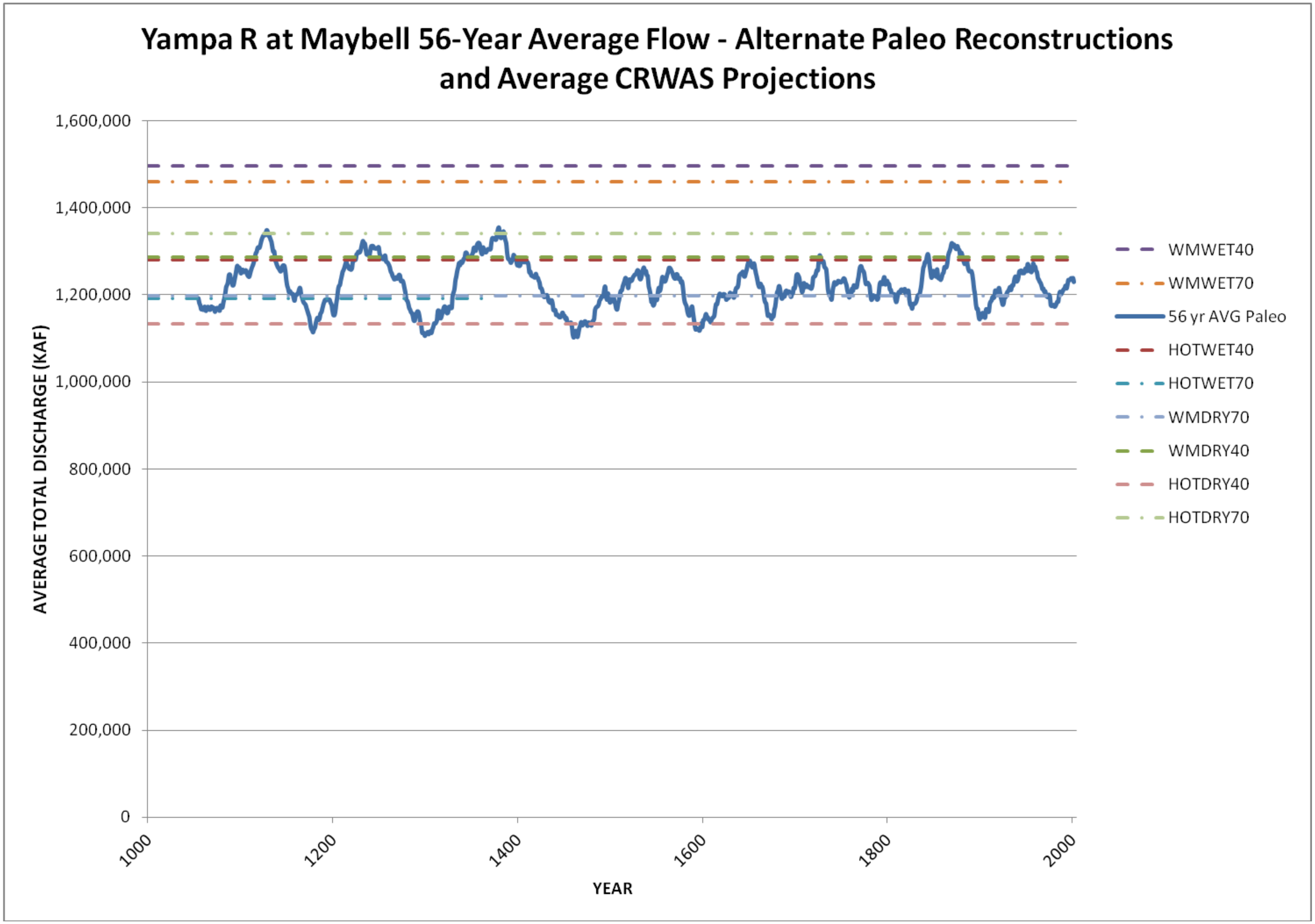

South Platte at South Platte 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
AVERAGE TOTAL DISCHARGE (KAF)
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1634
1654
1674
1694
1714
1734
1754
1774
1794
1814
1834
1854
1874
1894
1914
1934
1954
1974
1994
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


St Vrain 56-Year Average Flow - Paleo Reconstructions and Average Sacramento Projections
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1570
1620
1670
1720
1770
1820
1870
1920
1970
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70


St Vrain 56-Year Average Flow - Paleo Reconstructions and Average WEAP Projections
AVERAGE TOTAL DISCHARGE (KAF)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1570
1620
1670
1720
1770
1820
1870
1920
1970
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Modeled White River near Watson, UT 56-Year Average Flow - Paleo Reconstructions and Average CRWAS Projections
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
AVERAGE TOTAL DISCHARGE (KAF)
1000
1200
1400
1600
1800
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70



Yampa R at Maybell 56-Year Average Flow - Alternate Paleo Reconstructions and Average CRWAS Projections
AVERAGE TOTAL DISCHARGE (KAF)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1000
1200
1400
1600
1800
2000
YEAR
WMWET40
WMWET70
56 yr AVG Paleo
HOTWET40
HOTWET70
WMDRY70
WMDRY40
HOTDRY40
HOTDRY70