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Technical Memorandum – Final

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Distribution:	**CWCB Staff**
From:	**Ben Harding (AMEC)**
Subject:	**CRWAS Phase I - Spell Statistics (refinement to CRWAS Phase I Task 6.7)**
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Introduction

This Technical Memorandum summarizes information developed as part of the Colorado River Water Availability Study (CRWAS) Phase I.

The objective of this technical memorandum is to: *Refine narratives of the CRWAS Phase I Report in response to public comments.* As part of CRWAS Task 6.7 and Task 7.12, calculations were made of the statistics of annual flows and the statistics of wet and dry spells for the alternate historical hydrology and the alternate hydrology of climate change, respectively. While the methods used to develop those statistics were described in the CRWAS technical memoranda, the results of the analysis of the alternative historical hydrology were summarized for a few stations and the results for the alternate hydrology of climate change were discussed only in qualitative terms. During the outreach process following publication of the draft CRWAS Phase I Report, stakeholders requested that the next draft of the CRWAS Phase I Report provide more information on drought and surplus spells.

This technical memorandum provides for development of an updated approach to that described for the calculation and presentation of spell statistics in previous CRWAS Technical Memorandum: Task 6.7, *Summarize Alternate Historical Hydrology*. This technical memorandum summarizes the development and presentation of spell statistics by the approach used in Task 6.7, describes a revised approach, and presents revised results.

The recommended alternative approach characterizes dry spells and wet spells by the return interval (the average time between the start of a spell) of spells with a length equal to that of the longest spell in the historical record, and the average annual surplus or deficit of those extreme spells. The results vary considerably with the size, latitude and elevation of the basins, but indicate that projected climate conditions generally suggest less favorable water supply conditions. The exceptions to this are parts of the Yampa River basin and smaller, high-altitude drainages. As a very general observation, the categorical condition (e.g. more favorable or less favorable) in 2040 appears to persist in the 2070 time frame.

Developing Alternate Streamflow Traces

This section provides a summary of the approaches used to develop the alternate historical hydrology and the alternate hydrology of climate change. More detailed descriptions of these approaches can be found in CRWAS Technical Memoranda: Task 6.7, *Summarize Alternate Historical Hydrology* and Task 7.12, *Statistical Analysis of Climate Impacts*.

Task 6 of the Colorado River Water Availability Study (CRWAS) involved the development of the alternate historical hydrology. As part of CRWAS Task 6.4, a 100-member ensemble was developed, where each member was a sequence 56 years in length, using the non-homogeneous Markov Chain (NHMC) algorithm of Prairie et al. (2008). Each ensemble member was comprised of 56 historical water year designations (e.g. 1956, 1992, 2002, etc.) taken from the period from water year 1950 through water year 2005 (both 1950 and 2005 included). The 56-year-long sequences (note these are only year sequences) were developed based on paleo-hydrologic reconstructions of the natural flow time-series at the Lees Ferry, Arizona gage using the Prairie et al.(2008) NHMC algorithm. At each site, the reconstruction of historic years (the year sequence) was used to construct a flow trace by replacing the year designation in the sequence with the 12 monthly natural flow values at that site for that year. Each flow trace was one member of an ensemble of traces of natural flow at each of the flow points used in subsequent water availability analyses (227 sites associated with the CDSS models). This ensemble is the *alternate historical hydrology* (AHH).

This approach is referred to as “re-sequencing” because the historical natural flows are arranged in different sequences using information from the paleo-hydrological record. It is described in CRWAS Technical Memorandum 6.7, *Summarize Alternate Historical Hydrology*. The re-sequencing approach has the advantage that the same year sequences that are used to develop the AHH can be used to develop an ensemble of traces of climate-adjusted hydrology. This approach blends information from global climate models (GCMs, also referred to as general circulation models) with information from the historical and pre-historic record. Specifically, the impact of projected climate on mean flows and the seasonal pattern of flows is obtained from climate projections made by GCMs, while information on inter-annual variability is obtained from the historical and prehistoric record in the form of the year sequences (IPCC, 2001). CRWAS Technical Memorandum Task 7.12, *Statistical Analysis of Climate Impacts* describes how the methods developed in CRWAS Task 6.4 were used to develop ensembles of re-sequenced climate-impacted flows to create the *alternate hydrology of climate change* (AHCC).

Original Calculation of Spell Statistics

As part of CRWAS Task 6.7 and Task 7.12, calculations were made of the statistics of annual flows and the statistics of wet and dry spells for the AHH and for the AHCC, respectively, as described in the task memoranda and summarized below. However, while the methods used to develop statistics for the AHCC were described in CRWAS Technical Memorandum 7.12, the results were discussed only in qualitative terms. During the outreach process following publication of the draft CRWAS Phase I Report, stakeholders requested that the final CRWAS Phase I Report provide more information on drought and surplus spells. At about the same time, the statistics of spells calculated in CRWAS Tasks 6.7 and 7.12 for four sites were reported in the Colorado Drought Mitigation and Response Plan (Drought Mitigation Plan, CWCB, 2010b), which discussed (Annex C) the implications of climate change for drought (the Drought Mitigation Plan covers the entire state, but the CRWAS only quantified the impact of projected climate on spell statistics for the Colorado River Basin.) Subsequently, as part of refinements to the Drought Mitigation Plan, an effort was made to develop more meaningful statistical measures of spell frequency and intensity and to develop better ways of communicating those measures.

Spells are continuous sequences of two or more years of the same category (i.e. dry or wet), regardless of when they occur, that is, every spell is counted even if it is "nested" inside a longer spell (Tarawneh and Salas, 2009). Statistics of spells are used to characterize a hydrologic regime; these include measures of intensity, duration and frequency, which are defined below. The spell statistics originally developed for CRWAS and reported in the Drought Mitigation Plan were based on the conventional hydrologic practice where the threshold is set as the mean of flows in the trace. Using this convention for climate-adjusted flows assumes a point of view at some time in the future when climate change has stabilized and society has adopted the changed conditions as the norm. Using the original CRWAS approach, spell statistics for the AHCC are similar to the corresponding statistics for the AHH, because using the future mean flow as the threshold effectively cancels the climate impact on mean flows. Statistics calculated this way are not useful in answering the question: How much will spells change relative to the conditions of the historical observed record, against which current policies and systems have been designed? This question is most precisely answered through detailed water resources modeling, but an indication of the answer can be obtained by calculating the characteristics of spells for projected flows based on the historical mean rather than the mean of each individual climate scenario.

The work described here calculated spell statistics using the historical mean as a threshold, calculated the return interval of a spell as long as the longest spell in the historical record, used the entire AHH ensemble for this calculation, and reported the results in terms of return interval rather than frequency.

Original Spell Statistics

This section presents the spell statistics calculated by the original methods used in CRWAS Tasks 6.4 and 7.12.

CRWAS Phase I Technical Memorandum, "*Projection Selection (refinement to CRWAS Phase I Tasks 7.1, 7.2 and 7.5)",* describes how the original subset of five projections was selected to characterize 2070 conditions. It also presents the results of an analysis that shows that the original subset was not representative of the full set of 112 projections available to characterize 2070 conditions, and describes the approach used to select a new subset of 2070 projections that is currently being used for all final CRWAS assessments. At the time that the original CRWAS spell analyses and the analyses in support of refinements to the Drought Mitigation plan were conducted, the revised subset of 2070 projections was not yet available, so the analyses were done only on the AHH and the AHCC for 2040. Accordingly, Figure 1, which was developed during the original CRWAS effort, does not include results for 2070, while Table 1 (described in the following section), which was developed after the new 2070 projections were selected, does present results based on projected conditions for 2070. For the same reason, the climate cases in Figure 1 do not correspond to the designations adopted in the final CRWAS Phase 1 Report.

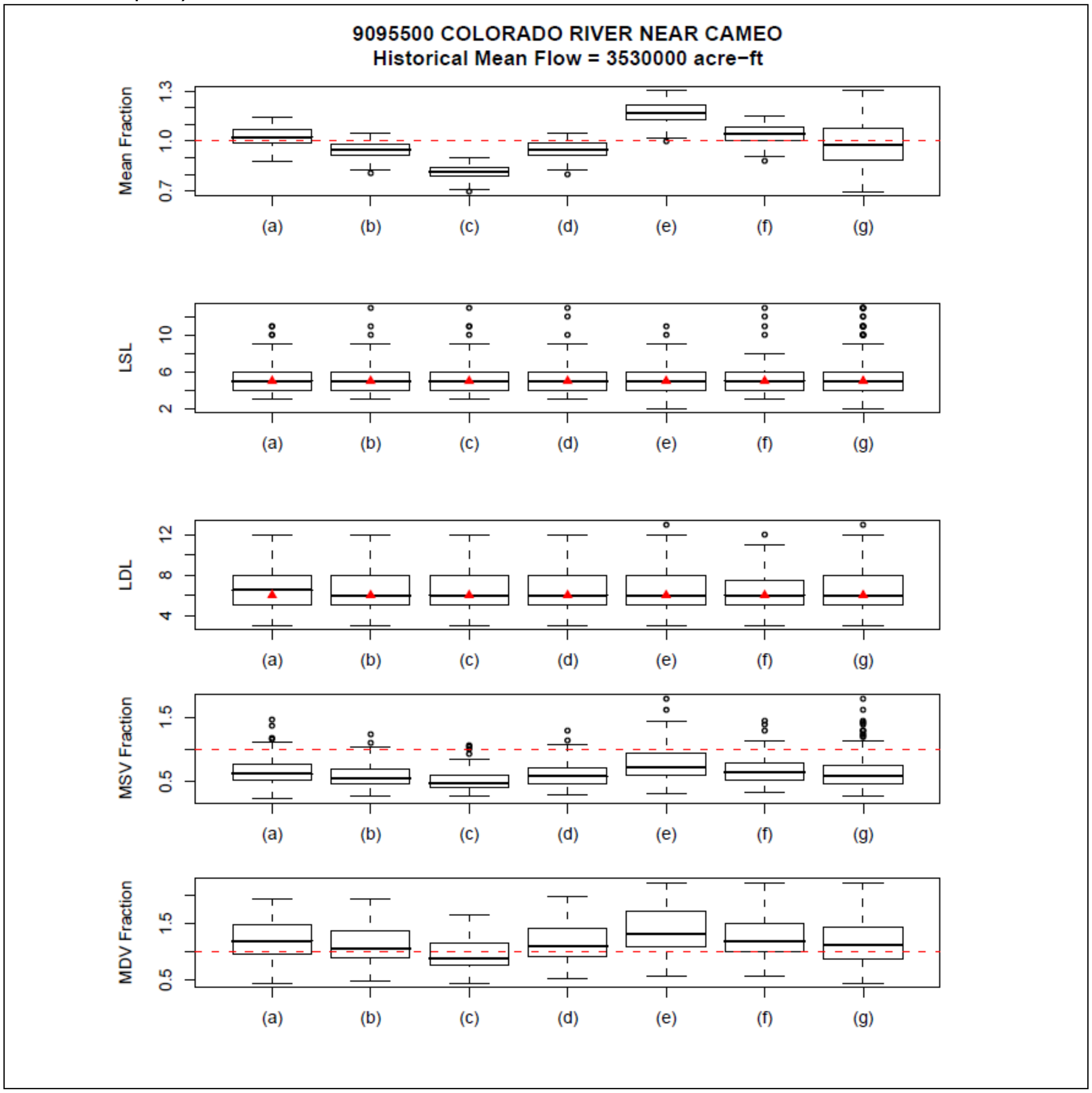
Several statistics are used to characterize spells in this document. The *threshold* is the flow used to characterize years—if total volume of flow in a year is less than the threshold, the year is categorized as a dry year; otherwise, the year is categorized as a wet year (in the unlikely event that an annual flow is exactly equal to the threshold, that year will be classified as a wet year).The *duration* of a spell is the number of continuous years of the same category (wet or dry). The *magnitude* of a spell is the cumulative amount by which the total volume over the duration of the spell varies from the threshold volume (the threshold flow times the duration of the spell). A wet spell produces a *surplus* while a dry spell produces a *deficit*. The *intensity* of a spell is the amount that the average flow during the spell differs from the threshold flow. Wet spells produce positive intensities while dry spells produce negative intensities. The *frequency* of a drought is a measure of how often it is expected to occur. Frequency is often stated as a *return interval*; a "100-year drought" is a dry spell that is expected to recur (return) once every 100 years. Frequency is also expressed as a probability; there is a one-percent probability that a 100-year drought will begin in any year. Spell frequency is most often specified for a particular spell duration. Less often frequency is expressed for a particular spell magnitude or intensity and some research estimates the frequency of combinations of duration and intensity, but this is rare in practice.

The results for the calculation of extreme spell statistics using the original CRWAS approach are presented in Figure 1 below for the Colorado River near Cameo. This approach analyzed 100 separate 56-year traces and used the mean of each individual trace as the wet/dry threshold when defining spells. For each of the 100 traces, the trace mean, the longest surplus length and maximum surplus (wet spell), and longest deficit length and maximum deficit (dry spell) were determined. The distribution of these values is presented in Figure 1 in terms of probability as box-whisker plots which are described in Appendix A (Description of Box and Whisker Plots) with an example from the Lees Ferry gage.

In Figure 1, each of the box-whisker plots shows the distribution of the 100 values for each of the 100 56-year traces that were generated and analyzed. The top panel displays the distribution of the mean fraction, which is the mean flow for a trace divided by the historical mean. For the alternate historical hydrology (a in Figure 1) the median value (the heavy horizontal bar inside the box) of the mean fraction is very close to 1.0 (individual traces vary from the historical mean); the median values for the climate-impacted cases vary from 1.0 by greater amounts, with cases b, c and d being lower than 1.0 (drier) and cases e and f being higher than 1.0 (wetter). (Case g shows the statistics if all of cases a-f were combined.) Moving down, the next two panels show statistics of drought duration. The second panel shows the distribution of longest surplus length (LSL), the length of the longest wet spell in each of the traces. The third panel shows the distribution of longest deficit length (LDL), the length of the longest dry spell in each of the traces. The next two panels represent the distribution of spell magnitudes and show how spell magnitudes change with different assumptions about future hydrology. The fourth panel shows the distribution of maximum surplus volume fraction (MSV fraction). This is the maximum surplus volume (from a wet spell) divided by the mean of the trace; the maximum deficit volume fraction (MDV fraction) in the bottom panel is the maximum deficit volume (from a dry spell) divided by the mean of the trace.

Figure 1. Extreme spell statistics for Colorado River near Cameo calculated using the original CRWAS approach.

Climate conditions projected only to 2040. a) alternate historical hydrology, b-f) climate cases for 2040, and g) aggregate statistics over all cases. Mean fraction is the mean flow for a trace divided by the historical mean, LSL is length of longest surplus, LDL is length of longest deficit (drought), MSV fraction is the maximum surplus volume divided by the mean of the trace, MDV is the maximum deficit volume divided by the mean of the trace. (See Appendix A for an explanation of a box-whisker plot.)



The mean fraction indicates the impact of projected future climate conditions on mean flows (e.g. case c is the driest case and case e is the wettest case). The mean fraction of the alternate historical hydrology (case a) is very slightly above 1.0, indicating that the paleo reconstruction shows slightly more wet years relative to dry years than was the case during the period 1950-2005. The maximum spell lengths (LSL and LDL) show what maximum spell length can be expected in future 56-year periods. The volume fractions show what maximum deficit or maximum surplus can be expected in future 56-year periods, expressed as a fraction of the annual mean flow. That is, a volume fraction of 1.0 would mean that the total surplus or deficit in a spell would be equal to the annual mean flow. The maximum deficit or surplus volume may or may not occur in the longest spell; in some cases a shorter but more intense spell (one with a bigger average deviation from the threshold) may result in a spell with a larger magnitude than the longest spell in the trace.

The central tendency of the length of spells (LSL and LDL), as represented by the median, are all essentially equal to the historical value (the triangle) for both dry spells and wet spells. This is expected because using the trace mean as a threshold cancels the projected effect of climate change. The maximum surplus and deficit volumes do change with the climate cases, but they simply scale according to the mean fraction. So, for case c, the driest case, both surplus *and* deficits become smaller and the reverse is true for case e, the wettest case. If a climate case is wetter, with a higher mean flow, the scale of surpluses or deficits measured against that mean flow will also increase. The converse is true when mean flows are smaller. Essentially, the spell magnitudes scale up or down in rough proportion to the change in mean flow.

Revisions to Calculation of Spell Statistics

The results presented above are legitimate given the assumption adopted for the original CRWAS analysis (i.e., a perspective from a distant future where climate change has fully stabilized at a projected level, and spells are being evaluated against the future mean flows). However, the original results are not focused on the central question of adaptation planning as climate change is developing, which is how existing infrastructure and institutions, that have been designed to perform against our historical record, will perform against future dry and wet spells that are superimposed on a different mean flow.

This question is most precisely answered using detailed water resources modeling, such as simulations using the CRDSS models that are anticipated for subsequent phases of CRWAS, or similar follow-on work. However, an indication of the answer can be obtained by calculating the characteristics of spells for projected flows using a threshold flow equal to the historical mean flow.

The original CRWAS analyses examined the frequency of the longest spell in each 56-year trace in the AHH. This allowed stakeholders to understand how different a future 56-year period might be from the one we have just experienced, but required that stakeholders perform their own calculations to understand the frequency of a given event, that is, to understand the likelihood that a spell of a particular length will begin next year.

The original spell analysis was revised to focus more directly on adaptation during transition from current conditions. The new approach used the historical mean flow as the threshold for defining spells and examined the entire AHH ensemble to calculate the frequency of a spell as long as the longest spell in the historical record, the *historic spell*.

Drought statistics presented in terms of non-exceedance values may be difficult to relate to experience--a small change in the non-exceedance value for a rare event can substantially affect vulnerability. For example, the return interval of an event with a 98% non-exceedance frequency is 50 years while the return interval for an event with a 96% non-exceedance frequency is 25 years; what at first glance appears to be a two percent change actually represents a doubling of frequency. Further, presenting the length and severity of droughts as probabilities or in terms of frequency, which is often confused with probability, may introduce confusion with the unknown probabilities of the climate cases. For these reasons, spell frequency is expressed as return interval in the revised spell statistics presented below.

Revised Spell Statistics

Table 1 shows an example of the results of this analysis for the Colorado River near Cameo. It presents a focused set of information intended to convey the impact of projected climate change on wet and dry spells. Table 1 presents the characteristics of the observed spells in the top panel and the return interval and average intensity for an event of the same length as the observed spell in the lower panel.

Table 1. Spell return intervals and average intensities for the Colorado River near Cameo.

09095500 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%

For example, at Cameo on the Colorado River, 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% below the long-term mean flow. Similarly, the observed surplus was five years in length and flows were 46% greater than the mean during that period.

The statistics of the alternate historical record (developed by re-sequencing) are shown in the first row of the bottom panel. The results in Table 1 for Cameo 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 somewhat greater than the historical intensity (-24% versus -19%), while the intensity of surplus spells of five years in length was considerably lower than the historical surplus (27% versus 46%).

The statistics for the climate cases are in the ten rows below the alternate historical hydrology 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 climate projections and the AHH are based on the same year sequences, it is best to compare those two results rather than trying to compare the climate cases to the historical observed event. On that basis, we can see that for the 2040 time frame, cases A, B and C show more frequent six-year droughts than is the case in the AHH (though case B is not very different) and cases D and E show droughts that are substantially less frequent. For 2070, cases F, G, H and I show six-year droughts that are more frequent than the AHH (though cases H and I are not very different) and case J shows droughts that are substantially less frequent. For the 2040 time frame, case E shows that five-year surpluses are more frequent than was the case in the AHH, while cases A, B, C and D show less frequent surpluses (though case D is not very different). For the 2070 time frame, case J shows that five-year surpluses are more frequent than was the case in the AHH, while cases F, G, H, and I show less frequent surpluses (though case I is not very different). Deficit intensities range from -19% to -32%; surplus intensities range from 17% to 38%.

Tables 2 through 4 show spell statistics for three additional sites, the Gunnison River near Grand Junction, the Yampa River near Maybell and the San Juan River near Carracas. 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 appropriate cell. For example, a surplus of six years in length was not encountered in climate case F for 2070 on the Gunnison River near Grand Junction (Table 2).

Table 2. Spell return intervals and average intensities for the Gunnison River near Grand Junction.

09152500 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. Spell return intervals and average intensities for the Yampa River near Maybell.

09251000 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 4. Spell return intervals and average intensities for the San Juan River near Carracas.

09346400 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%

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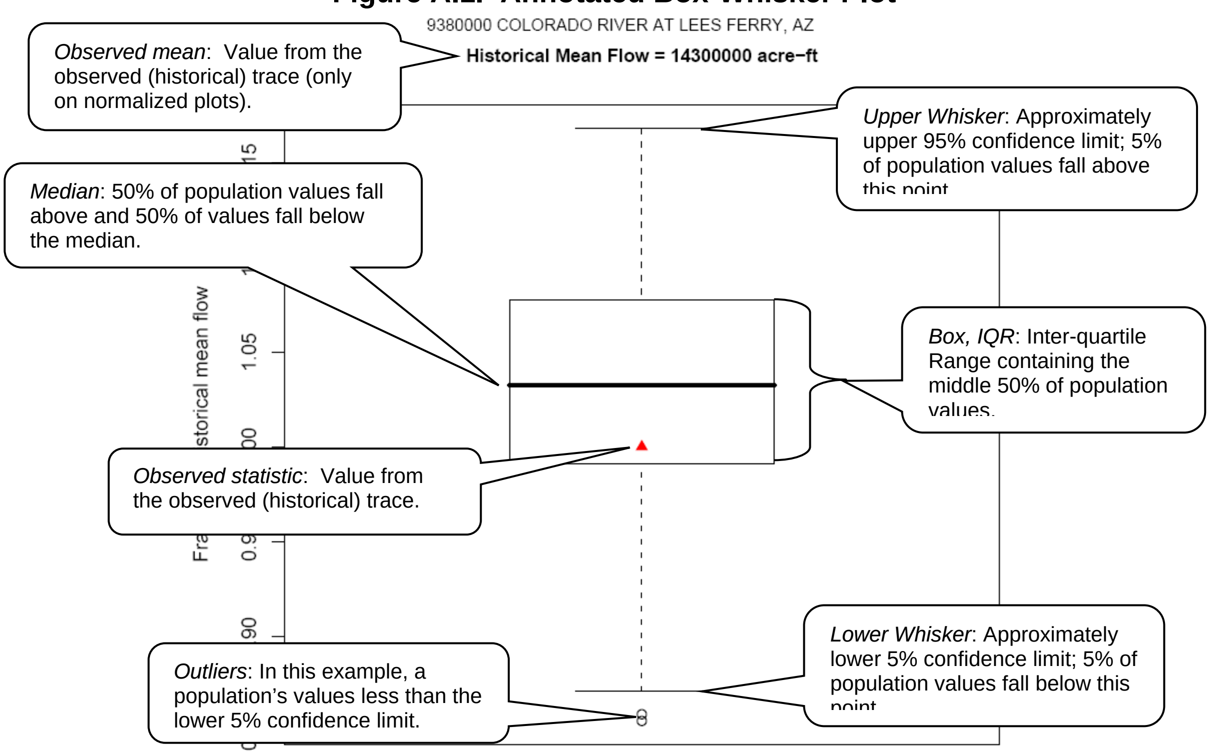
Appendix A: Description of Box and Whisker Plots

In this technical memorandum, the statistical measures of the different hydrologic records (historical and paleo) are shown using box-whisker plots.

A box-whisker[1] plot is a means to visualize the frequency with which a value from a population falls within, above or below a specified range. In the work described in this memo, the term population refers to alternate paleo reconstructed traces of one of the following values for a flow station: mean annual flow volume, maximum surplus volume, maximum drought volume, longest surplus spell length and longest drought spell length. Each of these statistics is calculated for each of the 100 flow traces, so the chart represents statistics from 100 values. Charts that display volumes (the first three statistics in the list above) have been *normalized*, i.e. the values from the population are all divided by the value from the observed record. Thus, the observed value will always fall at 1.0 and the other values will be represented by their ratio to the observed value. In the work described in this memo, the observed value is the historical value from the historical record for one of the following: mean annual flow volume, maximum surplus volume, maximum drought volume, longest surplus spell length and longest drought spell length. On the normalized charts the absolute value of the historical variable is presented below the chart title.

Figure A.1 is an annotated example of a chart of mean annual flow volume.

Figure A.1. Annotated Box-Whisker Plot



[1] Helsel D.R., and R.M. Hirsch, 1991. *Statistical Methods in Water Resources*. US Geological Survey, Techniques of Water Resources Investigations, Book 4, Chapter A3. *Available at: http://pubs.usgs.gov/twri/twri4a3/#pdf*.

The box-whisker plot is anchored by the *median*, the value located in the middle of all the values in a population when they are sorted by magnitude; 50% of the values in the population are above the median and 50% of the values in the population are below the median. The median is designated by the bold horizontal line shown in Figure A.1. The *interquartile range (IQR)* contains the middle 50% of the values in the population. That is, 25% of the values in the population will fall between the value at the uppermost end of the IQR and the median and 25% of the values will fall between the median and the value at the lowermost end of the IQR. The IQR is designated by the *box* shown in Figure A.1. The two *whiskers* together contain approximately 90% of the values in the population; the lower whisker represents the 5% confidence[2] limit, while the upper whisker represents the 95% confidence limit. The whiskers are designated by thin horizontal lines and dotted vertical lines arranged in a T or inverted T shape shown in Figure A.1. *Outliers* are values that fall outside the 5% or 95% confidence limits. Outliers are designated by small circles above or below the whiskers. The *observed statistic* is the value from the observed (historical) record and is shown to illustrate how the observed record fits into the range of values in the alternate historical hydrology. The observed statistic is designated by a filled triangle shown in Figure A.1.

[2] Confidence limits provides the bounds – lower bound (e.g., 5%) and upper bound (e.g., 95%) for the statistic of interest (e.g., mean) thereby providing an interval (confidence interval, e.g., 90%) which in turn gives an indication of how much uncertainty there is in our estimate of the true statistic. The narrower the interval, the more precise is our estimate. As a technical note, a 90% confidence interval does not mean that there is a 90% probability that the interval contains the true statistic. Instead, for a 90% confidence interval, if samples are collected and the confidence interval computed, in the long run about 90% of these intervals would contain the true statistic.

Figure A.2 is the same as Figure A.1 but without the annotations, so that the values of the statistics can be seen. (Figure A.2 shows the statistics of the mean annual flow, as a fraction of the historical mean flow, of the Colorado River at Lees Ferry, Arizona.)

Figure A.2. Example Box-Whisker Plot

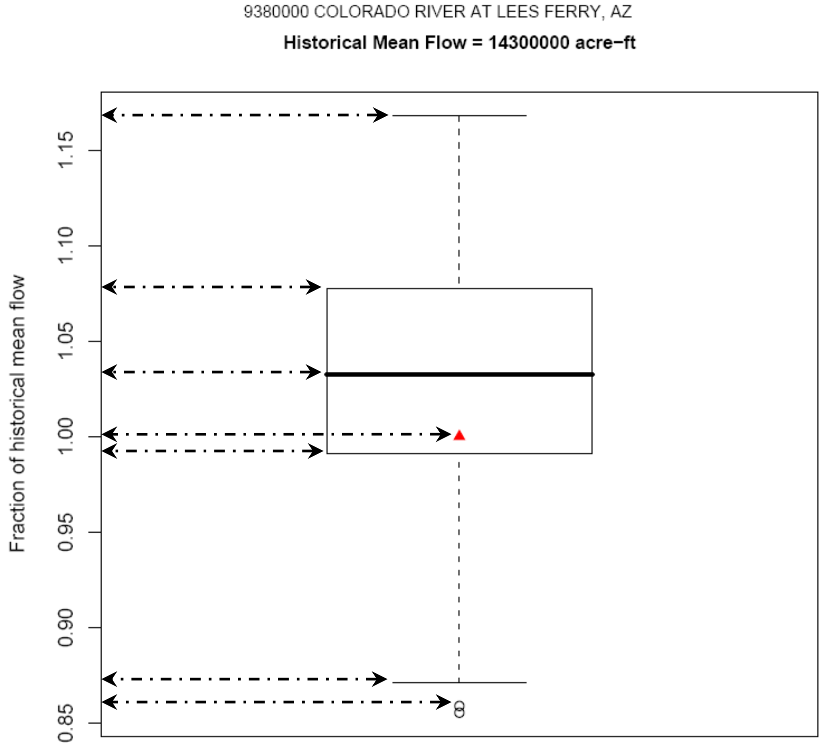


Table A.1 shows the approximate values taken from Figure A.2.

Table A.1. Approximate Values from Figure A.2

Statistic	Approximate Flow (fraction of observed value)
Median	1.03
Upper bound of IQR (75th percentile)	1.07
Lower bound of IQR (25th percentile)	0.99
95% confidence level	1.16
5% confidence level	0.87
Lower outlier (uppermost) (what value is this – should we report?)	0.86
Observed flow	1.00

Each of the fractional values in Table A.1 can be multiplied by the value reported at the top of the chart to obtain an absolute value in the units of the statistic. In this example the observed mean flow is 14.3 million acre-feet, so the median value of the ensemble means is about 14.7 million acre-feet. Statistics of duration of droughts and wet spells are reported as absolute values in units of years.