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Technical Memorandum | Final

To:	**Blaine Dwyer and Matt Brown (AECOM)**
Distribution:	
From:	**Subhrendu Gangopadhyay, Ben Harding (AMEC Earth & Environmental)**
Subject:	**CRWAS Phase I | Task 6.7 | Summarize Alternate Historical Hydrology**
Date:	**~~February 1, 2010~~ January 2012 updates in red**

CRWAS Phase I included a public comment period on the draft CRWAS Phase I Report and public outreach workshops to solicit feedback from stakeholders on the Study. CWCB and the CRWAS technical team used these forms of feedback to refine Study deliverables, such as this technical memorandum, which may include content that has been updated. Please refer to the January 2012 Technical Memorandum, "CRWAS Phase I – Spell Statistics (refinement to CRWAS Phase I Task 6.7)" and the revised CRWAS Phase I Report, both posted at http://cwcb.state.co.us, for updated information associated with this technical memorandum.

Introduction

This Technical Memorandum summarizes information developed as part of Task 6 of the Colorado River Water Availability Study (CRWAS or Study).

The objective of Task 6 is to extend historical hydrologic data using currently available tree-ring data and stochastic methods to develop alternate hydrologic traces in formats usable in the CDSS. Sub-task 6.7 involves conducting statistical diagnostic analyses of the ensemble of alternate hydrology.

This memorandum documents the approach used to perform statistical diagnostic analyses on the ensemble of extended historical hydrology (hereafter referred to as alternate historical hydrology), and the results of only those analyses and not climate change hydrology. At first, we provide necessary background information and description of the development of the alternate historical hydrology in Task 6.4. Subsequent sections of this technical memorandum discuss: 1) Approach to Diagnostic Statistical Analyses, 2) Results of Analyses, 3) Interpretation of Results, and 4) References.

Background

As part of Task 6.4, a 100-member ensemble, where each member was a sequence 56 years in length, was developed 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, hereinafter referred to as sequences or year sequences) were developed based on paleohydrologic[1] 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 (hereinafter referred to as a trace or flow trace) by replacing the year designation in the trace with the natural flow at that site for that year. Each flow trace was used to develop an ensemble of traces of natural flow (hereinafter referred to for a given site as alternate historical hydrology ensemble) at each of the flow points used in subsequent water availability analyses (227 sites associated with the CDSS models and 29 sites associated with the CRSS model).

The objective of this technical memorandum is to characterize the statistical properties of this alternate historical hydrology ensemble – annual and spell statistics, and again, not of climate change hydrology. The following set of five statistics – (1) Mean Annual Flow, (2) Longest Surplus Spell Length, (3) Longest Drought Spell Length, (4) Maximum Surplus volume and (5) Maximum Drought Volume will be used to analyze the alternate historical hydrology ensemble. Note that, these statistics were selected to understand water allocation impacts that may arise from alternate historical hydrologies and not to evaluate the NHMC algorithm. The reader is referred to the Prairie et al. (2008) paper for details on the statistical evaluation of the NHMC algorithm.

1) Mean Annual Flow – Mean annual flow is an estimate of the annual flow conditions averaged over a selected set of years. At each site, 100 values (coming from 100 flow traces each 56-year long, refer to descriptions in earlier paragraphs) of the mean flow statistic was calculated along with the mean flow from the historical unaltered 56-year period, 1950-2005. These results are presented as boxplots which are described in Appendix A (Description of Box and Whisker Plots) with an example from the Lees Ferry gage.

2) Longest Surplus Spell Length - The longest continuous period (i.e. number of years) where flows were greater than the mean annual flow. Again, for each site, 100 values of this statistic from the alternate historical hydrology ensemble and one from the historical statistic were calculated. These results are presented as boxplots which are described in Appendix A.

3) Longest Drought Spell Length - The longest continuous period (i.e., number of years) where flows were at or lower than the mean annual flow. Again, for each site, 100 values of this statistic from the alternate historical hydrology ensemble and one from the historical statistic were calculated. These results are presented as boxplots which are described in Appendix A.

4) Maximum Surplus Volume - The greatest total volume of surplus (above mean flows) in any surplus period; a measure of the intensity of a wet spell. This may not be the surplus during the longest surplus spell if shorter spells have higher surplus magnitudes. Again, for each site, 100 values of this statistic from the alternate

[1] Streamflows for periods prior to modern observations can be estimated using statistical models based on tree ring chronologies or other natural variables. Streamflow records developed in this way are referred to as “paleo records” or “paleo reconstructions” and the science is often referred to as “paleo hydrology”.

historical hydrology ensemble and one from the historical statistic were calculated. These results are presented as boxplots which are described in Appendix A.

5) Maximum Drought Volume—The greatest total volume of deficit (below mean flows) in any drought period; a measure of the intensity of a drought. This may not be the deficit during the longest drought spell if shorter spells have more severe drought magnitudes. Again, for each site, 100 values of this statistic from the alternate historical hydrology ensemble and one from the historical statistic were calculated. These results are presented as boxplots which are described in Appendix A.

Note that for the spell statistics described above (numbers 2, 3, 4 and 5), the mean annual flow for each trace was used to estimate surplus and drought conditions. Definitions of surplus, drought and relevant technical terms are provided below.

Drought - Period of years of annual flows which are at or below the mean annual flow.

Surplus – Period of years of annual flows greater than the mean annual flow.

Ensemble – A collection of states each of which represents a possible state that the real system might be in. Here, we have developed a 100 member ensemble each 56-year long (a flow trace) which are representative hydrologic states of the Upper Colorado River Basin from the paleohydrologic reconstructions at Lees Ferry. This collection is referred to as alternate historical hydrology flow ensemble.

Stochastic Process (Stochastic) – The term stochastic is used to mean that the described process is based on probability theory.

Approach to Diagnostic Statistical Analyses

The objective of the statistical diagnostic analyses undertaken as part of Task 6.7 is to characterize the nature of the alternate historical hydrology by comparing the statistical characteristics of the alternate historical hydrology with the statistical characteristics of the historical hydrology. Statistical diagnostic analyses are also used to validate the reliability of a model or method; such validation analyses were completed by the developers of the Non-Homogeneous Markov Chain model (NHMC model) that was used to develop the alternate historical hydrology, and are reported in Prairie, et al. (2008).

The measures selected for comparing statistical characteristics of alternate historical hydrology and historical hydrology, fall into two major categories, the statistics of the distribution of annual volumes and the statistics of wet and dry spells. The former helps to understand the frequency with which a single dry (or wet) year may occur, while the latter help to understand the frequency with which a drought (or wet spell) may occur. In the approach selected to develop the alternate historical hydrology, the NHMC model is used to *re-sequence* the historical hydrology. Thus, information about the ***magnitudes*** of annual flows comes from the ***historical*** flow record, while information about the ***sequence*** of annual flows comes from the ***paleohydrologic*** flow record. Accordingly, we expect that the mean of the alternate historical hydrology will be similar to the mean of the historical hydrology. The means of the two records (historical and paleo) will differ if the paleo record indicates that the relative frequency of dry versus wet years is different than that experienced in the historical period.

Paleohydrologic reconstructions at a single site (e.g., Meko et al., 2007) used as input to the NHMC model are based on multiple linear regression. In regression models, both the magnitude and the hydrologic state sequences (e.g., dry and wet) are modeled together so the mean flow may differ more markedly between the reconstruction and the historical record. See CRWAS *Technical Memorandum 6.1, Literature Review and Method Evaluation* for a discussion of the relative advantages and disadvantages of different flow reconstruction techniques.

Where to find more detailed information:

Details on the choice of the Non-Homogeneous Markov Chain Model are provided in the CRWAS Technical Memorandum *Task 6.1 – Literature Review and Method Evaluation, Task 6.2 – Analyses of Tree-Ring Data, and Task 6.3 – Recommendation for Extending Historical Hydrology*. Additional details on the Non-Homogeneous Markov Chain Model are provided in CRWAS Technical Memorandum *Task 6.4 – Methods for Alternate Hydrology and Water Use*.

Results of Analyses

Annual statistic and drought statistic boxplots were developed for the 43 CRWAS reporting sites and for the Lees Ferry site in the CRSS model. Figures 1 through 5 below show results for five sites: Yampa River near Maybell, Colorado River near Cameo, Gunnison River near Grand Junction, San Juan River near Carracas, and Colorado River at Lees Ferry. Each figure shows box-whisker plots for five statistics: annual mean flows, longest surplus spell length, longest drought spell length, maximum surplus volume, and maximum drought volume.

Statistics for annual mean flow, maximum surplus volume and maximum drought volume are normalized (refer to Appendix A) by dividing the value from each ensemble member trace by the corresponding value of the statistic from the historical record. Thus, the filled triangle representing the historical value will be at 1.0 in each of these plots.

Results for all 43 of the CRWAS reporting sites and Lees Ferry, Arizona from the CRSS model are provided in Appendix B. Results for all 227 of the CRWAS flow stations and all 29 of the CRSS inflow points are provided in the electronic data in Appendix C.

Interpretation of Results

Information from the paleo record was used to develop a stochastic model of hydrologic conditions, which was used to generate an ensemble consisting of 100 traces of streamflow. This model was applied to the historical streamflow record to create the alternate historical hydrology, an ensemble of 100 streamflow traces, each 56 years in length.

The sequence of wet and dry years that will occur over the next 56 years (or for any other period of 56 years in the future) cannot be predicted. Each of the traces in the alternate historical hydrology, though, represents one alternative possible future with respect to the distribution and sequencing of wet and dry years, assuming that the conditions reflected in the paleo record are representative of those conditions that will occur in the future. Each of these alternative possible futures (represented by a flow trace) is equally probable, but differs from all other traces (i.e. other possible futures) in the ensemble in its precise sequence of flows. Taken together, the traces reflect the statistics gleaned from the paleo record so that, collectively, the alternative historical hydrology ensemble can be used to quantify the likelihood of future hydrologic conditions, again assuming that the conditions represented in the paleo record are similar to those in the future. The results of the statistical analysis described in this memorandum, as illustrated in the following charts, summarize the statistics of alternative possible future conditions and suggest the following findings:

- Generally, the median mean annual flow from the alternate historical hydrology was slightly higher than the historical mean natural flow. This is shown in the boxplot by the median line being higher than the filled triangle representing the historical mean flow. This means that the statistics of the paleo record indicate that in the long-term record wet years were slightly more frequent relative to dry years than was the case in the historical period (1950-2005).

- The median longest surplus and drought spell lengths are generally reasonably similar to the longest spell lengths in the historical record. The San Juan River near Carracas shows a tendency toward a shorter maximum surplus length and a longer maximum drought length.

- At all five sites the paleo record indicates that there was a tendency toward smaller surplus volumes and higher deficit (drought) volumes. This characteristic will manifest in more challenging conditions to the operation of water storage projects as in many traces the opportunities for storage will be reduced while the need for reservoir releases will increase.

- A broad range of hydrologic conditions is found in the ensembles of streamflows, so the use of the alternate historical hydrology in water availability analyses using CDSS models and the CRSS models will provide information about the impacts of droughts and wet spells of longer duration and greater intensity than those that have occurred during the historical period.

References

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight[1], J.J. Lukas, M.K. Hughes, and M. W. Salzer, 2007. Medieval drought in the upper Colorado River Basin *Geophysical Research Letters* Vol. 34, L10705.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp (2008), A stochastic nonparametric approach for streamflow generation combining observational and paleo reconstructed data, *Water Resour. Res.*, 44, W06423, doi:10.1029/2007WR006684.

Figure 1. '9251000 YAMPA RIVER NEAR MAYBELL'

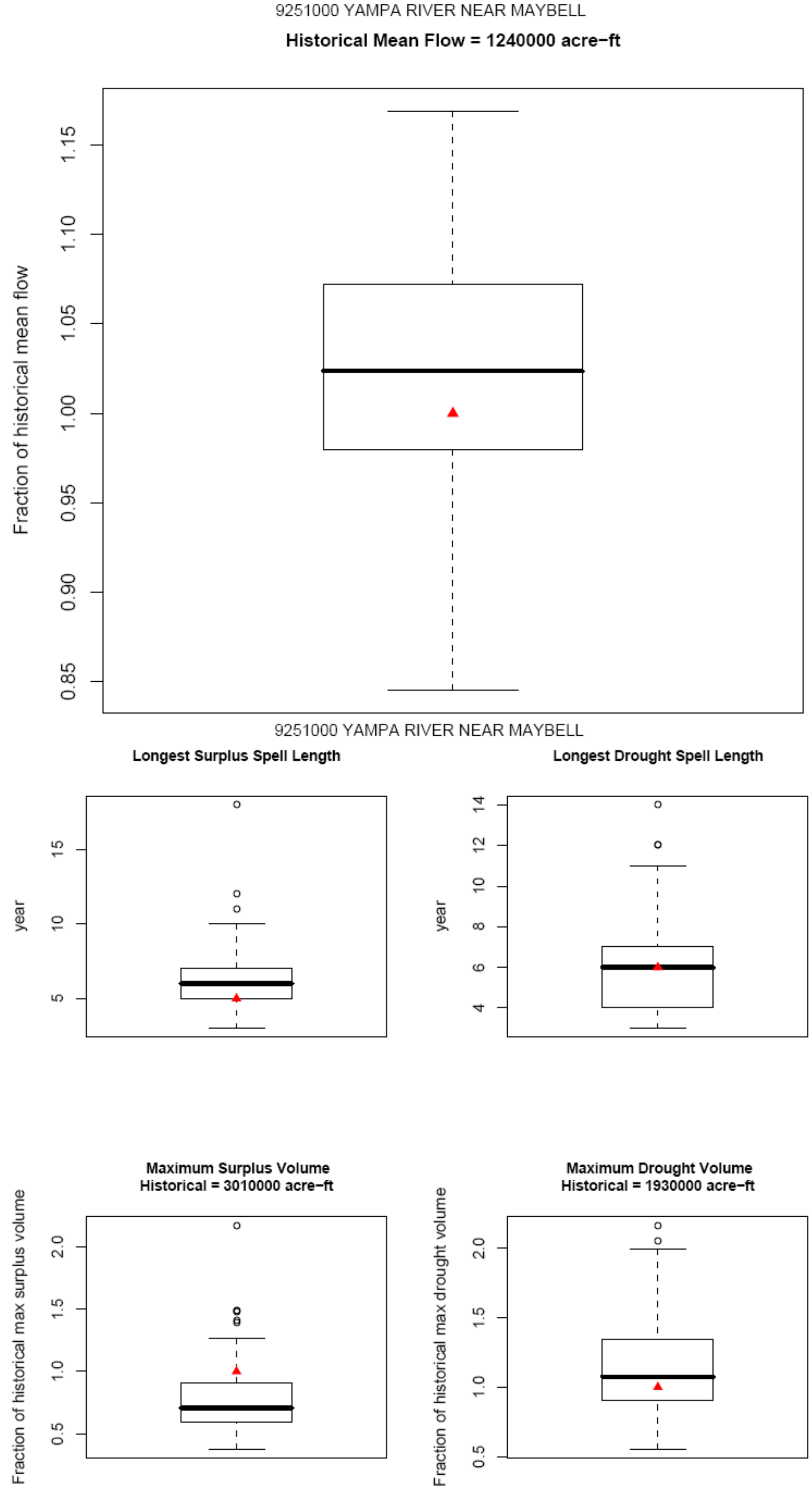


Figure 2. 9095500 COLORADO RIVER NEAR CAMEO'

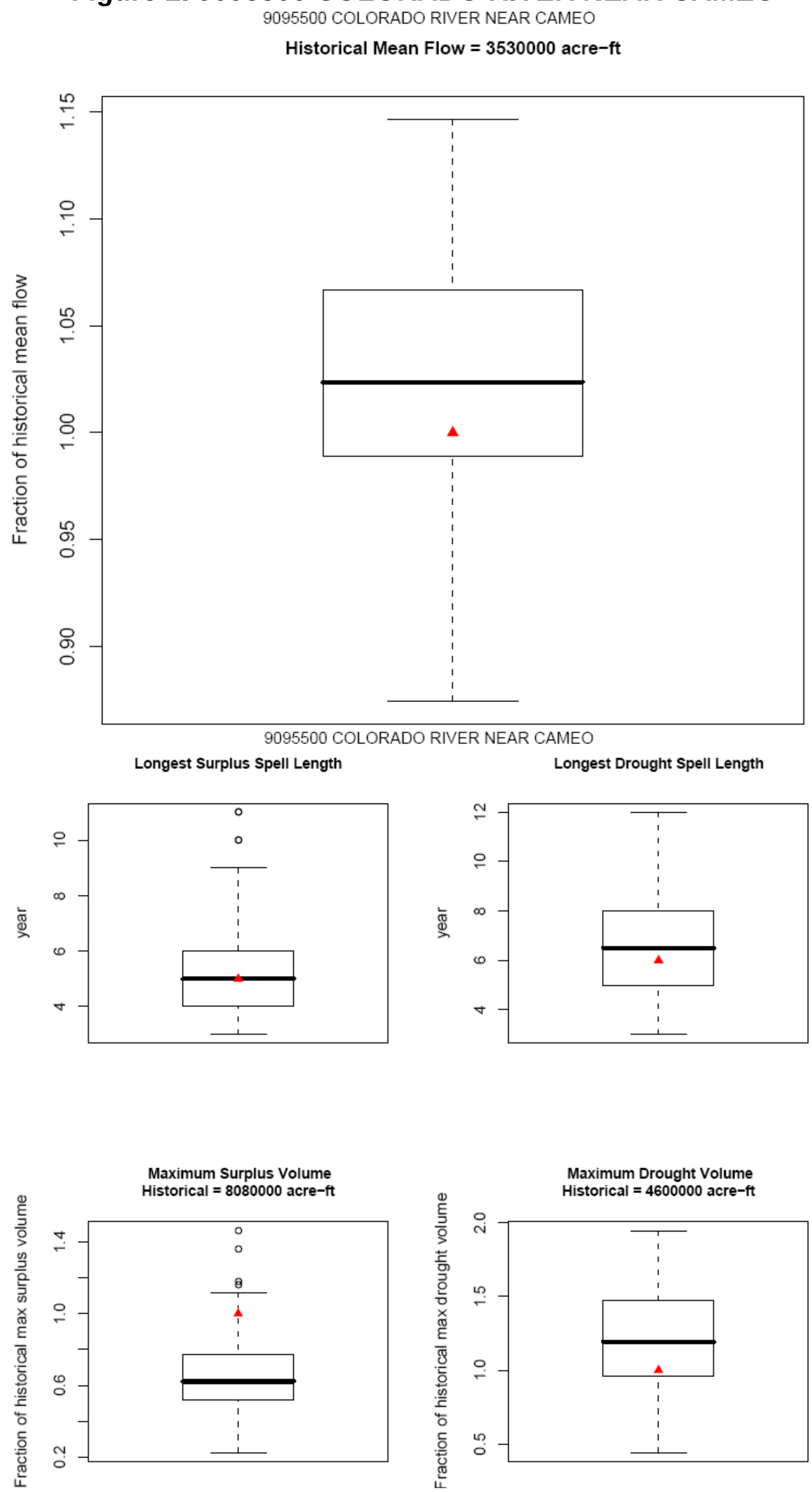


Figure 3. 9152500 GUNNISON RIVER NEAR GRAND JUNCTION

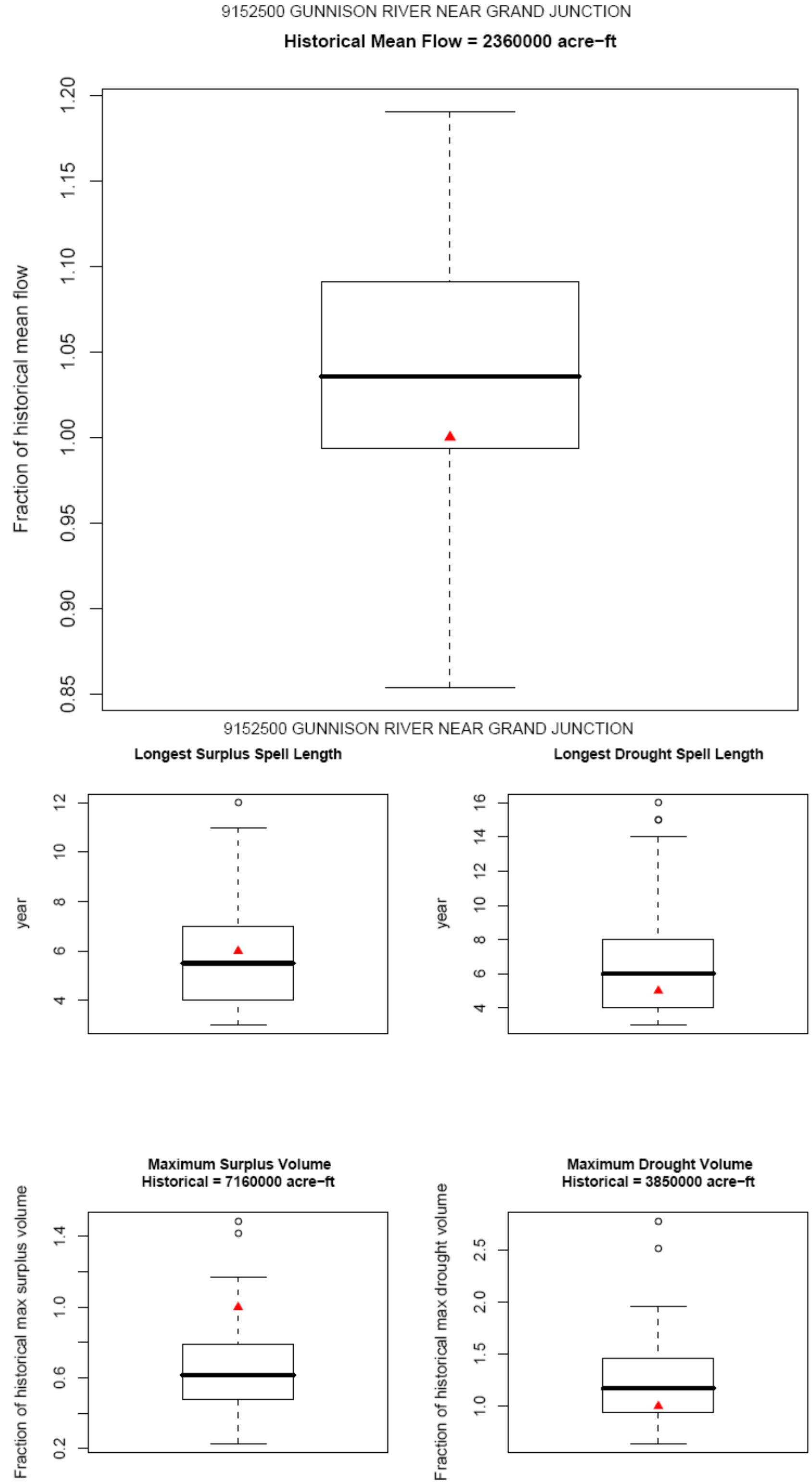


Figure 4. 9346400 SAN JUAN RIVER NEAR CARRACAS

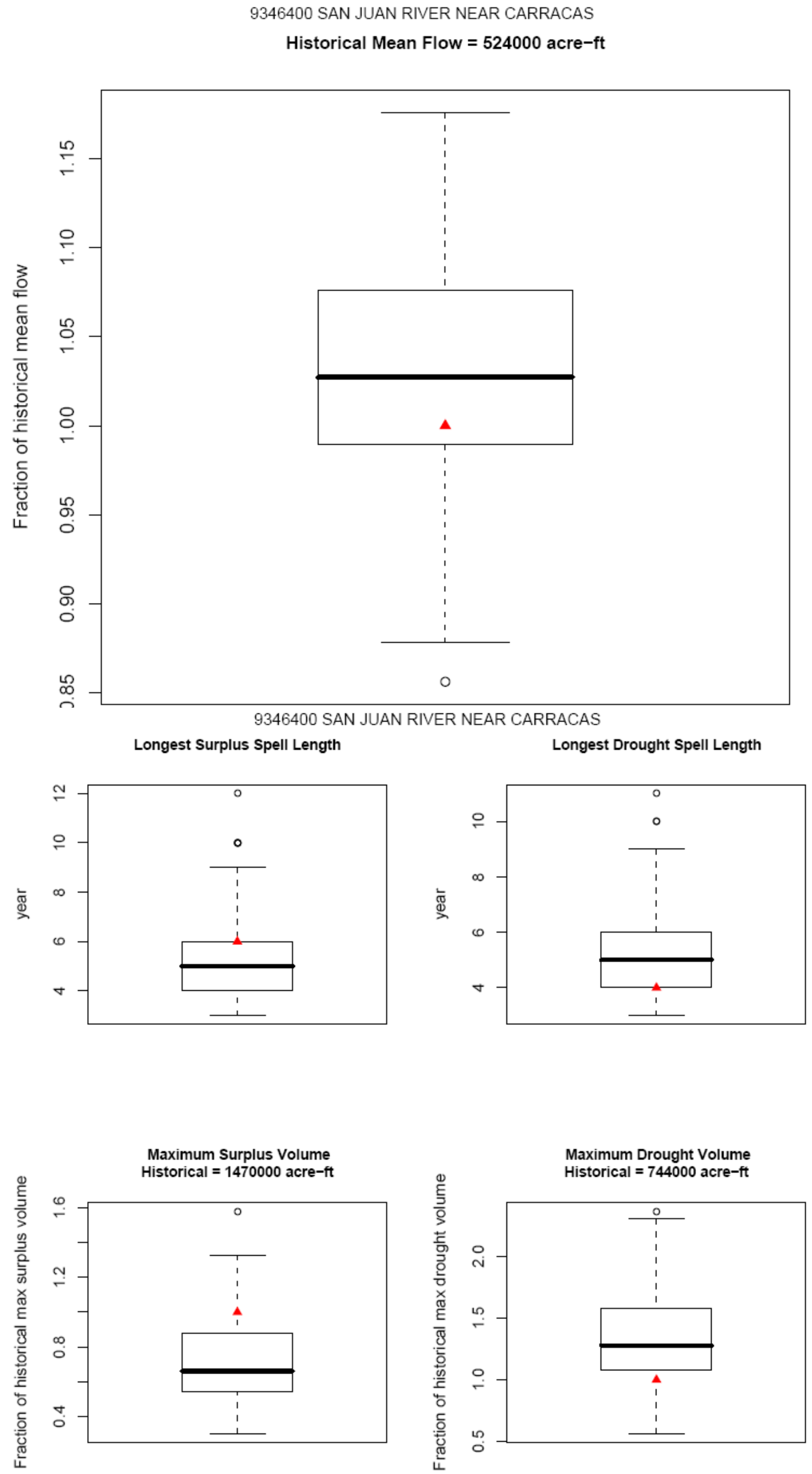
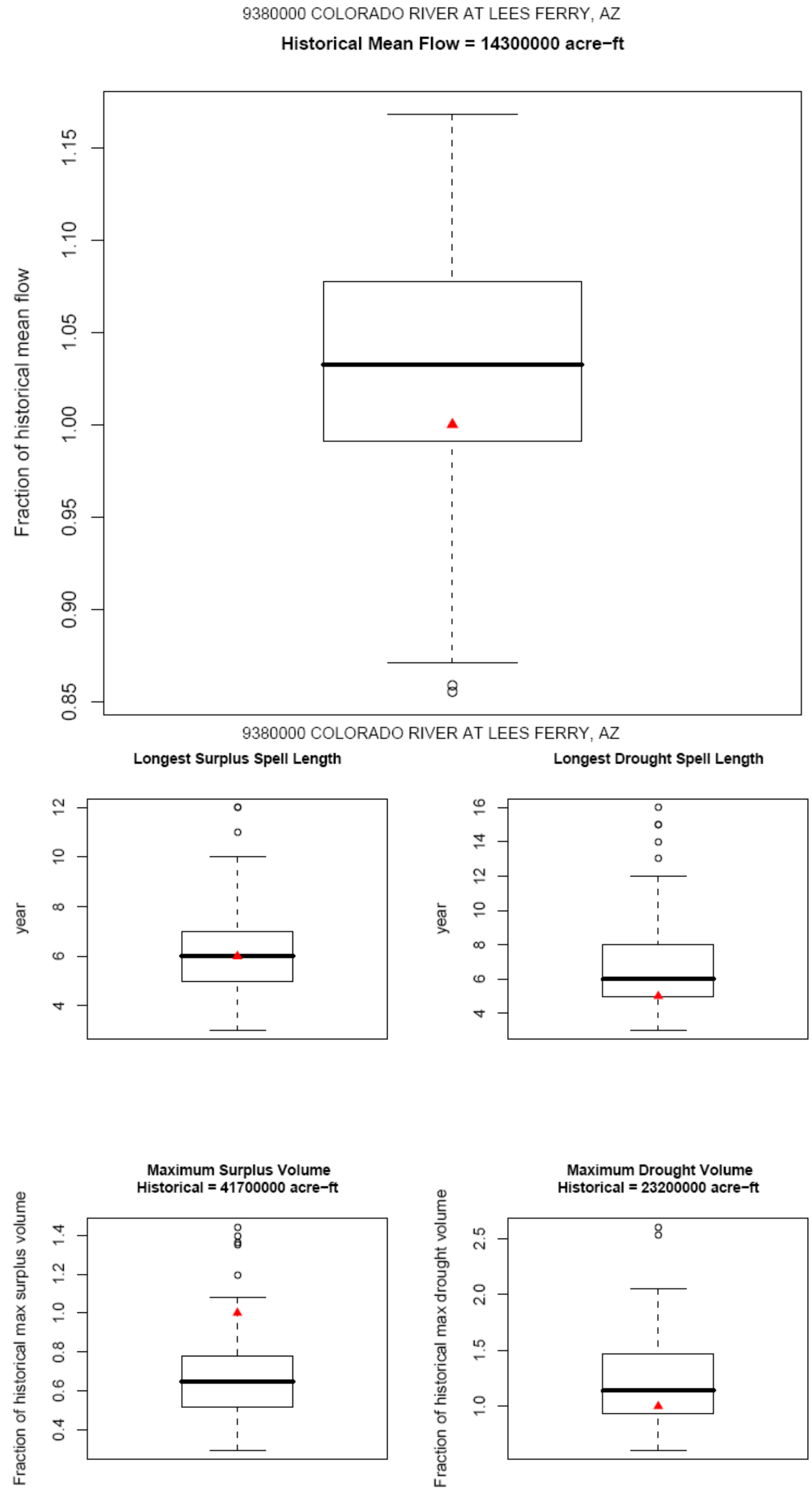


Figure 5. 9380000 COLORADO RIVER AT LEES FERRY, AZ



Appendix A

Description of Box and Whisker Plots.

Appendix B

Electronic data with charts for all 43 CRWAS reporting points and Lees Ferry, Arizona from the CRSS model.

Appendix C

Electronic data with charts for all 227 CRWAS flow stations and all 29 CRSS inflow points.

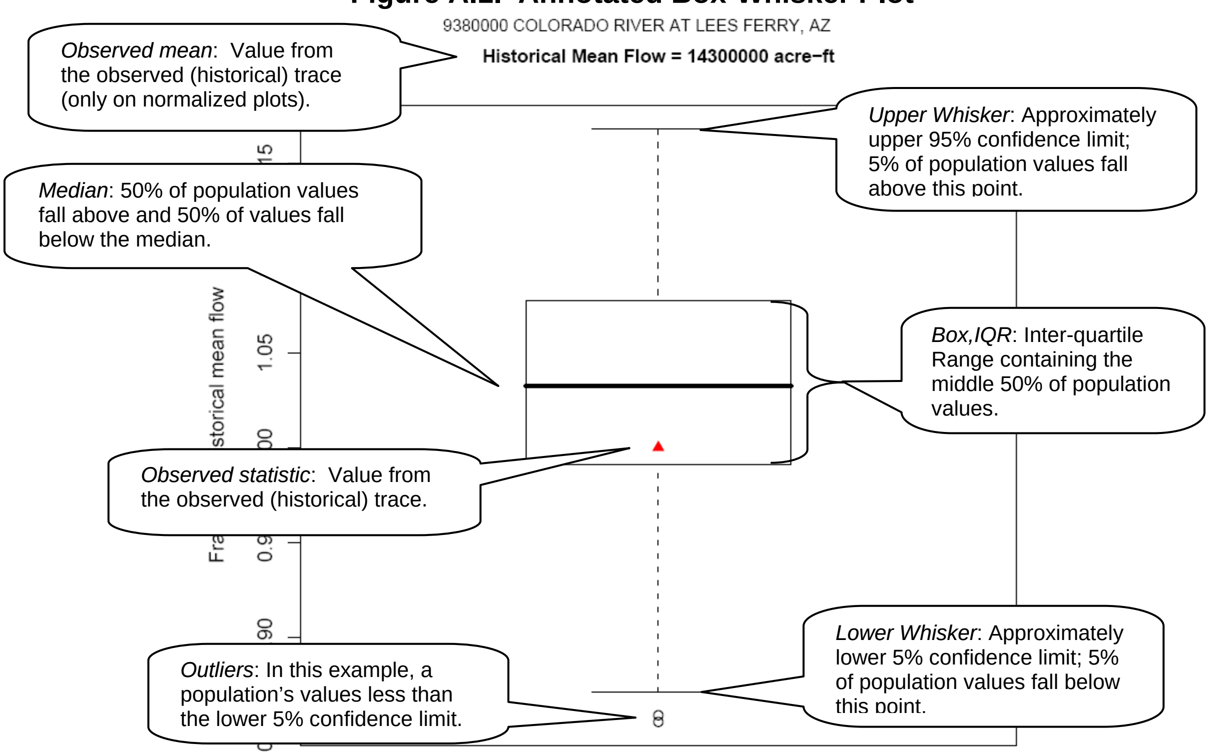
Appendix A: Description of Box and Whisker Plots

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

A box-whisker[2] 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



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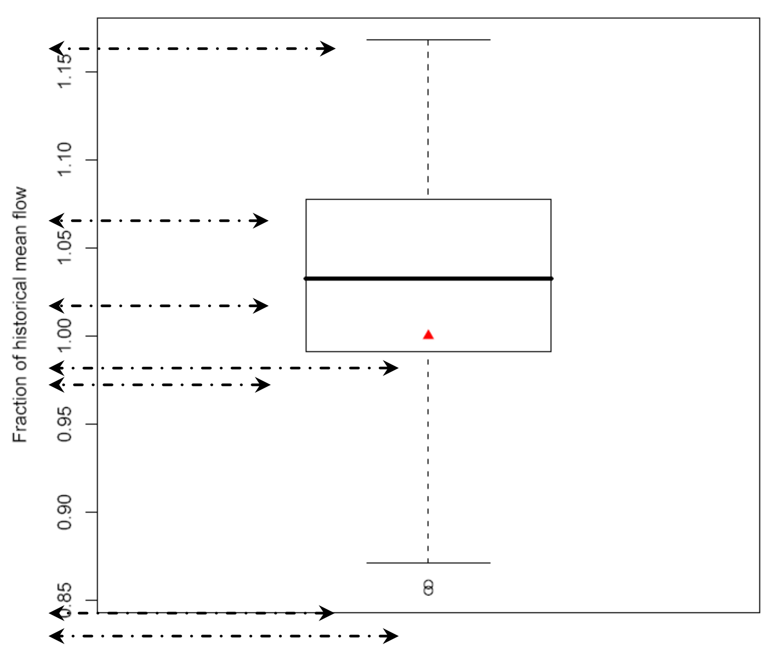
[2] Helsel D.R., and R.M. Hirsch, 1991. *Statistical Methods in Water Resources*. US Geological Survey, Techniques of Water Resources Investigations, Book 4, Chapter A3 . *Available at: http://pubs.usgs.gov/twri/twri4a3/#pdf*.

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[3] 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.

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



[3] 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.

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

Table 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 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.