Technical Memorandum | FINAL

To: **Andy Moore, Michelle Garrison, Colorado Water Conservation Board**
From: **Ben Harding, Lynker Technologies**
Subject: **CRWAS Phase II Climate, Task 5, CRWAS-II Climate Hydrology Approach and Results.**
Date: **September 8, 2015**

This Technical Memorandum summarizes information developed as part of Task 5 of the Colorado River Water Availability Study, Phase II, Updating Climate-impacted Hydrology (CRWAS-II or Study).

The objective of Task 5 is to document the process used in developing the CRWAS-II climate-impacted hydrology. This memorandum provides an overall description of the approach used to develop the CRWAS-II climate-impacted hydrology, describes in general terms the products of the work, and compares results of this work to the CRWAS-I climate-impacted hydrology. Details about the approach used to develop CRWAS-II climate hydrology and the data deliverables, can be found in CRWAS Phase II Technical Memorandum Task 1 – *Literature Review*, CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios*, and CRWAS Phase II Technical Memorandum Task 5 – *Description of data products.*

Objectives of CRWAS-II

The CRWAS-II climate hydrology work had the following four primary objectives:

- Update the CRWAS Phase I climate-impacted hydrology (CRWAS-I) to incorporate the CMIP5 projections,
- Develop an improved method for creating climate scenarios,
- Extend the historical baseline through at least 2012, and
- Provide climate-impact adjustments for natural flow and water use across the State.

With the exception of changes to meet these objectives, and other refinements described below, the State wanted to maintain compatibility with the CRWAS-I effort by using the same technical approach to the degree possible. The CRWAS-I approach is described in detail in CWCB (2012). The only other significant change to the CRWAS-I approach was the addition of a new future time frame at 2050 to supplement the 2040 and 2070 time frames adopted in CRWAS-I.

Incorporate CMIP5 projections

As part of CRWAS-I, projections of climate-impacted natural flows were developed for all of the baseflow points in the five models that comprise the Colorado River Decision Support System (CRDSS; CWCB, 2015; CWCB, 2000). The development of these projected natural flows is described in the documentation of CRWAS-I. (CWCB, 2012) The estimates of the impact of projected climate change on natural flows in CRWAS-I were based on projections of future climate made by general circulation models (GCMs; also referred to as climate models) that were conducted and archived as part of the Coupled Model Inter-comparison Project, Phase 3 (CMIP3; Meehl, *et al., 2007;* PCMDI, 2013). Projections developed and archived as part of CMIP3, collectively called the CMIP3 ensemble, were used as the basis for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC, 2007).

In 2012-2013, projections of future climate developed as part of the fifth phase of the CMIP experiment (CMIP5) began to become available for impact studies (Taylor, *et al.,* 2012). The CMIP5 projection ensemble (along with other experiments in the Fifth Phase of the CMIP) serve as the basis for the IPCC Fifth Assessment Report. (There is no fourth phase to CMIP; phase numbering was advanced from three to five to be consistent with the numbering of the Assessment Reports.) Downscaled data for the entire CMIP5 ensemble became available in 2013 (Brekke, *et al.,* 2013). In 2014, Reclamation completed hydrology modeling over the continental U.S. based on the CMIP5 projections (Brekke, *et al.,* 2014). The results of this modeling, referred to as hydrology projections, provides estimates of the impact of projected changes in climate on hydrologic conditions (including runoff and consumptive water use) based on the CMIP5 projections of climate variables.

Research currently makes no distinction between the CMIP3 and CMIP5 projections with respect to reliability or accuracy (Rupp, *et al.,* 2013) but CWCB expects that stakeholders will want to know if the new CMIP5 projections lead to substantially different projections of future water availability. Accordingly, the State requested that CMIP5 projections be incorporated in the CRWAS-II climate hydrology.

For a summary of climate science and projections relevant to Colorado, and for a comparison of the CMIP3 and CMIP5 projections for the State, see Lukas, *et al*. (2014).

CRWAS-II evaluated three different projection ensembles. To provide direct comparability with CRWAS-I, the entire 112-projection CMIP3 ensemble was evaluated. In addition, a 97-projection subset from the CMIP5 ensemble (those projections for which Reclamation conducted hydrology modeling) was also evaluated, which was designated the CMIP5 (hydrology) ensemble. The most comprehensive ensemble is a combination of the CMIP3 ensemble with the CMIP5 (hydrology) ensemble, which is designated the CMIP3+5 ensemble and consists of 209 projections. For more details on the ensembles used, refer to CRWAS Phase II Technical Memorandum Task 1 – *Literature Review* and CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios*.

Develop improved climate scenarios

Projections of future climate are uncertain and this uncertainty is evident in substantial disagreement among climate models about future conditions, particularly about precipitation in Colorado. In the CRWAS study domain, almost all model runs show a continuous increase in temperature over this century, but models don’t even agree on whether future precipitation will increase or decrease. In the full ensemble of CMIP3 model runs, approximately half of those runs project an increase in average annual precipitation along the Continental Divide at the headwaters of the Colorado River (Harding, *et al.*, 2012; Bureau of Reclamation, 2012).

Broadly speaking, researchers have suggested three different approaches to addressing the uncertainty in climate projections. Some research suggests that the range of impact estimates based on a large ensemble of projections places a minimum bound on future conditions. (Stainforth *et al.*, 2007; Wilby, 2010). More information may be available in the ensemble of projections; it may be possible to develop probabilistic estimates of impacts (Tebaldi and Knutti, 2007) and a skillful ensemble mean (Gleckler *et al.*, 2008, Pierce, *et al.,* 2009).

All of these methods depend on evaluation of a large ensemble (Salath´e, *et al.*, 2007), the largest being all available projections, what some have termed "ensemble of opportunity" (EOO). However, evaluation of a large ensemble of projections is often not practical because of the large computational effort required. Water resources impact assessments of the sort conducted in CRWAS-I are called end-to-end studies, and involve not only hydrology modeling but impact studies employing water resources models, environmental models and sometimes economic and social models. Ignoring hydrology modeling, evaluating the CMIP3+5 ensemble using the CRDSS suite of models would require several days of solid computation. In planning studies, multiple model runs are required to evaluate different operational and infrastructure alternatives, and it is simply not practical to evaluate a full ensemble for all such iterations, regardless of the scientific merit of that approach. This practical reality motivates development of a small set of scenarios for which a level of conservatism can be estimated as the basis for planning studies.

In CRWAS-I, scenarios were developed by selecting five individual projections for each of the two time frames. The approach used for this selection is described in detail in CWCB (2012) and further in CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios.* One fundamental limitation of the CRWAS-I approach was that it was based solely on projected changes in natural flow, whereas water resources systems are sensitive to changes in both streamflow and water use (among other things; these are the principal factors). In addition, the use of individual projections invited the possibility that peculiarities of a particular projection could affect a water resources system in unexpected ways. In other words, projections that are located in a certain region of the distribution of changes to natural flows could be in that region due to changes in different processes, and those differences, such as the seasonal pattern of precipitation, could significantly affect impacts on water resources systems. Thus, there was little scientific basis for mapping the distribution of impacts to natural flows to the distribution of impacts to systems.

It is impacts to systems that interest water resources planners, managers and operators. Accordingly, CRWAS-II adopted a method that is designed to provide a better mapping of projected climate conditions to system impacts. The central elements of the approach are:

- *Use change in runoff and CIR as proxy variables.* The CRWAS-II approach uses runoff and consumptive irrigation requirement (CIR) to characterize future conditions much as CRWAS-I used temperature and precipitation. Projections of change in runoff represent changes in system water supply. Projection of change in CIR represent changes in system water use. (CIR, also termed irrigation water requirement, is a measure of how much irrigation water must be applied to fully satisfy the evapotranspiration off of a crop.) These two variables were not readily available for all projections when CRWAS-I was conducted; CRWAS-II is taking advantage of large improvements in data availability that have occurred over the last five years.

- *Use pools of projections to characterize future conditions.* Rather than select individual projections, the CRWAS-II approach uses pools consisting of ten projections, grouped by the similarity in their projected change in runoff and CIR. The projected changes from the ten members of a pool are averaged to determine the change associated with the pool. Seven pools are used in CRWAS-II, with each pool constituting a future scenario. Using the average change across the pool makes the scenario less dependent on the peculiar characteristics of any individual projection, and better characterizes the scenario than any single projection (Pierce, *et al.*, 2009).
- *Characterize pools to cover the broad range of future conditions.* A projection that shows the largest decrease in runoff and the largest increase in CIR will present the greatest stress to a water resources system, at least with respect to the overall system water budget. Conversely, a projection that shows the largest increase in runoff and the largest decrease in CIR will present the lowest stress to a water resources system. CRWAS-II uses a spatial approach to characterize pools at the extreme boundaries of projected system stress and those with intermediate characteristics.

The selected approach has several advantages over the CRWAS-I approach:

- By pooling several projections it exploits the superior skill of an ensemble mean compared to any individual ensemble member (Pierce, *et al.,* 2009), but
- Through the use of several pools it attempts to capture the range of model disagreement (Stainforth *et al.*, 2007; Wilby, 2010), and
- By the use of runoff and CIR to characterize pools *a priori*, it is expected to provide a better mapping of the distribution of projected hydrologic conditions to stresses on water resources systems.

The performance of the CRWAS-II approach cannot be fully verified until such time as all (or a large fraction) of the future projections can be used to evaluate the performance of the systems of interest. In the Colorado River basin in Colorado that means using projected streamflows and demands as input to all of the CRDSS StateMod models. Until that time, confidence in the CRWAS-II approach must be based on its scientific rationale.

Update the historical baseline

CRWAS-I used a historical baseline running from 1950 through 2005. Notable wet and dry years occurred in 2011 and 2012, so the CRWAS-II effort was specified to extend the historical baseline to or beyond 2012. The historical baseline of weather has been extended through September of 2014. Extension of CRDSS baseflows is in progress as part of other efforts.

Provide climate and hydrology adjustments across the State

Other ongoing and expected planning activities require estimates of projected natural flows, including the SWSI 2016 planning effort and the Colorado Water Plan. SWSI 2016 is a statewide effort that encompasses basins for which Colorado Decision Support System (CDSS) models have not yet been developed and for which, as a result, there are not widespread and consistent estimates of natural flows. As part of CRWAS-II, the State specified that change factors for natural flow and CIR be developed for the entirety of the State. These change factors, spatially disaggregated to the USGS 12-digit hydrologic units, can be used by SWSI, future CDSS modeling efforts, or other efforts, to adjust estimates of natural flow to reflect climate impacts.

Products of work

For each of the three ensembles (CMIP3, CMIP5 and CMIP3+5), CRWAS-II developed projections for seven climate scenarios at each of the three time frames, 2040, 2050 and 2070. The seven climate scenarios are listed in Table 1. Each scenario is characterized by the projected change in runoff and CIR, which are quantified in relative terms by their percentile position in their respective distributions. The largest change (a positive value, or increase) is at just less than 100 percent and the lowest change (a negative value, or decrease) is at just above zero percent. The most stressful combination is the scenario labeled lower left, which has the largest increase in CIR and the largest decrease in runoff. The upper right scenario is the least stressful.

Table 1
Characteristics for CRWAS-II 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%

For each of the 21 combinations of time frame and scenario, CRWAS-II provides the following products:

- Projected change factors for baseflow for all baseflow points for each CRDSS model,
- Projected changes in precipitation and temperature for each weather station used by StateCU in the CRDSS domain,
- Projected changes in natural flow at gauges used by the Joint Front Range Climate Change Vulnerability Study (JFRCCVS; Woodbury, *et al.*, 2012, and
- Projected change factors for runoff and CIR for 12-digit hydrologic units across the entire State.

For more details, see CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios.*

Comparison to CRWAS-I

CRWAS-II will provide an expanded perspective on the range of future conditions, and incorporates information from the most recent set of climate projections, the CMIP5 archive. However, the work products of CRWAS-II are intended to supplement the products of CRWAS-I, which remain valid and useful. The figures in this section provide a comparison of the results of CRWAS-II to those of CRWAS-I. The CRWAS-II results used in this comparison are based on the CMIP3+5 ensemble. Shown are all five CRWAS-I scenarios and the most comparable CRWAS-II scenarios: 9010, 7525, C, 2575 and 1090. The comparisons are for the 2070 time frame.

CRWAS-II evaluated seven scenarios. The five used for comparison have the same nominal objective as the five CRWAS-I scenarios—to cover approximately 80% of the range of model disagreement. The lower left and upper right scenarios in CRWAS-II are meant to characterize the extremes of the distribution and are not included in this comparison. Those two scenarios extend the range of projected conditions represented in CRWAS-II to include drier dry conditions and wetter wet conditions.

Figure 1 shows the mean annual flow for five scenarios from CRWAS-I and CRWAS-II. The range of projections is highlighted with a shaded box. In Figure 1, CRCAM is Colorado River near Cameo, 09095500; DRBED is Dolores River near Bedrock, 09171100; GNGRJ is Gunnison River near Grand Junction, 09152500; SJRCA is San Juan River near Carracas, 09346400; WRCUT is White River near Colorado-Utah State Line, 09306395; and YRMBL is Yampa River near Maybell, 09251000.

Figures 2 through 7 show the average monthly hydrograph for the same stations as in Figure 1. In each of those figures, the top panel is the hydrograph for the CRWAS-I scenarios and the bottom panel is the hydrograph for the CRWAS-II scenarios.

See CWCB (2012) and CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios* for explanation of each scenario.

Figure 1 shows that at all sites the driest scenario in the CRWAS-II results is slightly wetter than the driest scenario in the CRWAS-I results. In all cases but for the Yampa River near Maybell the wettest scenario in the CRWAS-II results is wetter than the wettest scenario in the CRWAS-I results. The most notable difference between the two approaches is for the Dolores River near Bedrock. At that gauge all of the CRWAS-I projections showed conditions that would be drier than historical conditions. In the CRWAS-II results two scenarios show wetter future conditions, though one of these is virtually identical to historical conditions.

Comparisons of CRWAS-I and CRWAS-II average monthly hydrographs in Figures 2 through 7 do not reveal large differences, except for the Dolores River near Bedrock.

The differences between CRWAS-I and CRWAS-II results may arise due to several factors. First and most prominent is the use of the combined CMIP5 and CMIP3 ensembles as the basis for design of scenarios. Research has shown that the CMIP5 ensemble projects wetter conditions in the Upper Colorado River basin and over the State of Colorado compared to the CMIP3 ensemble (Brekke, *et al.,* 2014; Lukas, *et al.,* 2014) so this is not surprising. The fairly dramatic difference for the Dolores River near

Bedrock hints at some other effect; understanding this difference will require diagnosis that is beyond the scope of this work.

The other differences relate to methodology. CRWAS-II used a completely different approach to developing scenarios than did CRWAS-I. The three most significant of those differences is the use of runoff and CIR as explanatory variables, the use of pooling of several projections into a single scenario, and the use of the entire state as the domain for estimating the explanatory variables (CRWAS-I used a smaller spatial domain established by the JFRCCVS, as described in Woodbury, *et al., 2012.)*

The choice of spatial domain for estimating explanatory variables used to create scenarios means that climate scenarios are homogeneous across the state—the same projections are used to estimate conditions in the South Platte as in the Upper Colorado. In other words, the spatial correlation of changes simulated by the climate models is preserved. Initial analyses indicate that these scenarios may show relative greater decreases in projected natural flow on watersheds on the east side of the Continental Divide.

Currently, there is no scientific basis that establishes the superiority of one or the other set of results. The initial results for 2070 for CRWAS-I were biased relative to the project objectives to a substantial and unacceptable degree, but this bias was resolved after it was recognized, so the current (revised) 2070 results are valid with respect to the CRWAS-II objectives. The CRWAS-II results are also consistent with the CRWAS-I objectives, which was to cover approximately 80% of the range of model disagreement. CRWAS-II has a further objective to cover the same 80% of the range of model disagreement to impacts to water resources systems. The success of CRWAS-II in meeting this second objective has not yet been verified and will have to wait for an evaluation of the comprehensive CMIP3+5 ensemble by the entire suite of CDSS models, including the soon-to-be developed South Platte Decision Support System.

Figure 1. Mean 2070 Annual Natural Flows for CRWAS-I and CRWAS-II Scenarios.

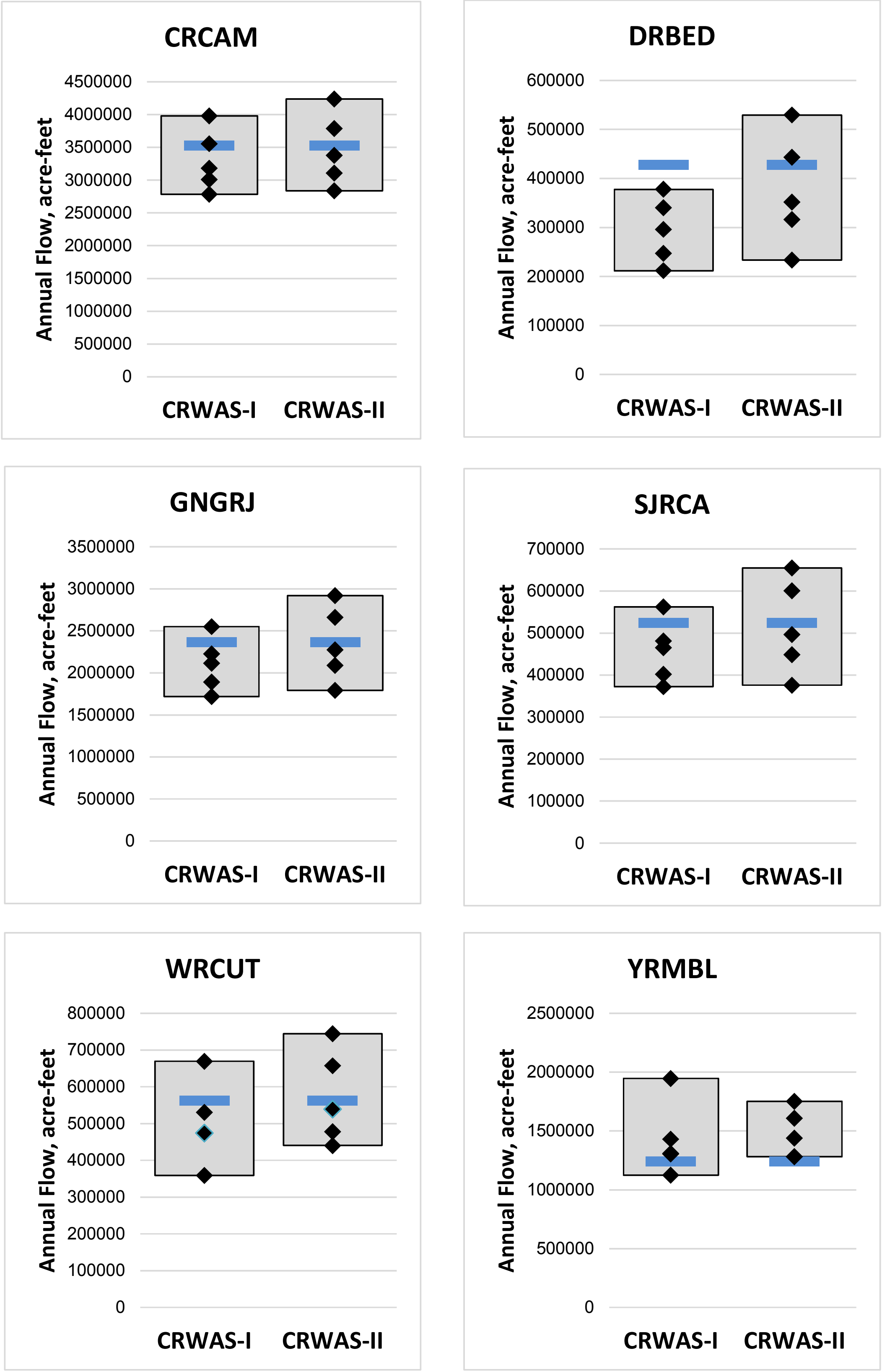


Figure 2. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, Colorado River near Cameo, 09095500.

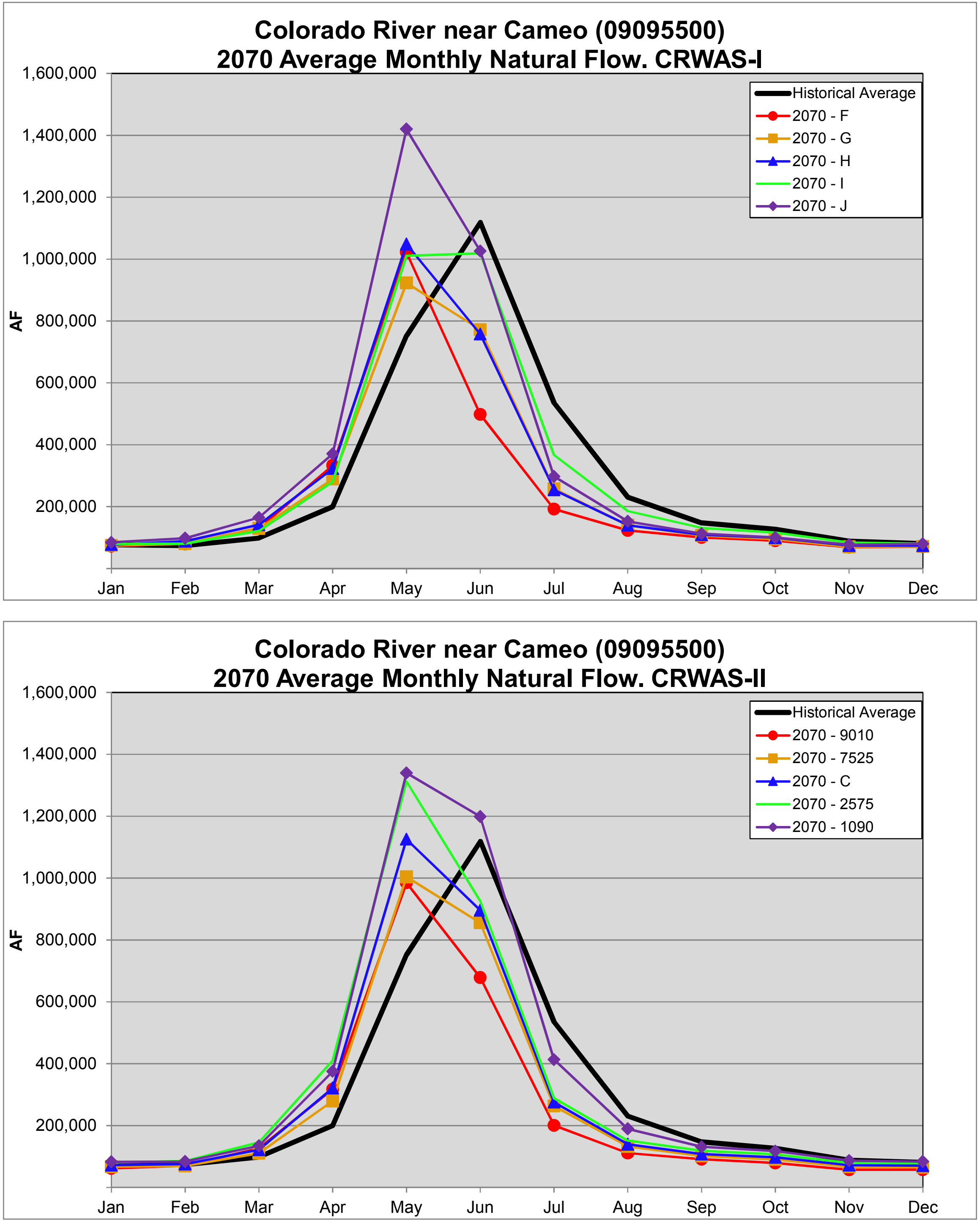
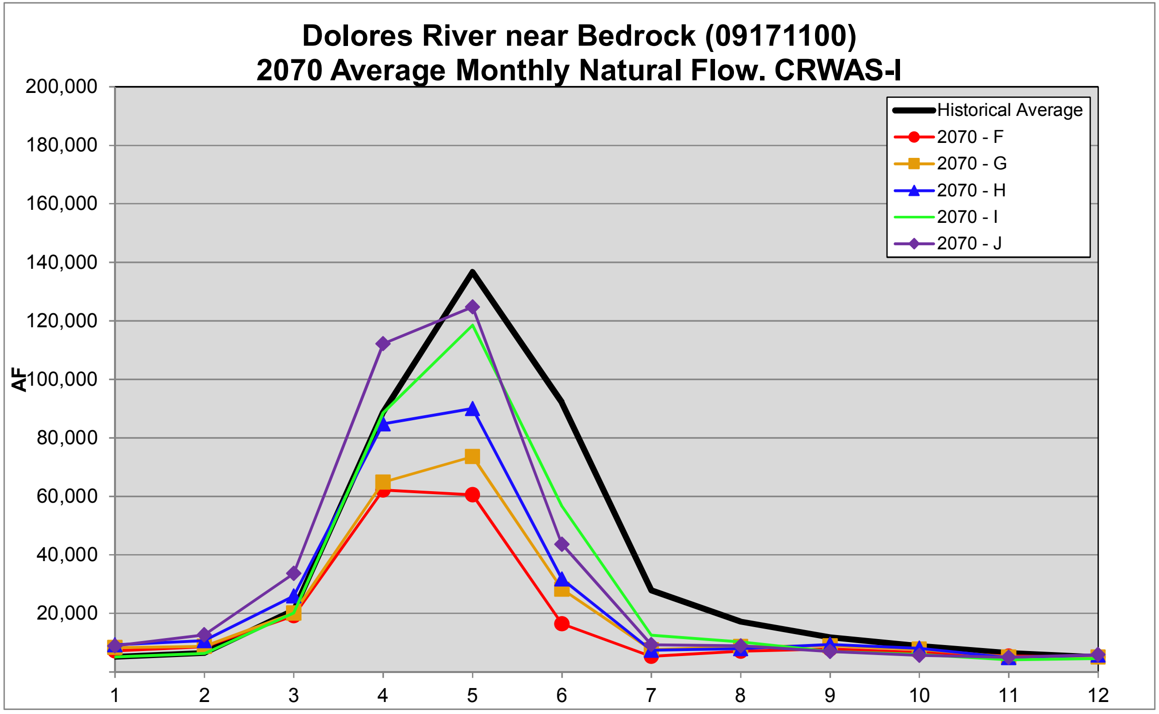


Figure 3. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, Dolores River near Bedrock, 09171100.



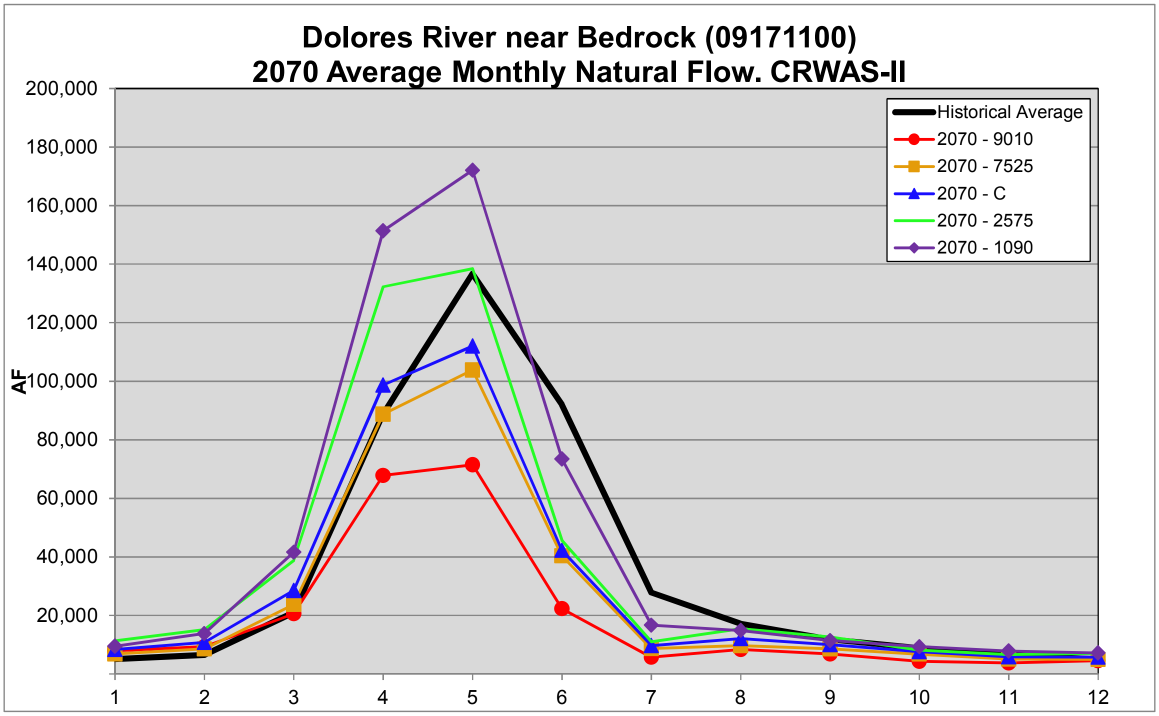


Figure 4. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, Gunnison River near Grand Junction, 09152500.

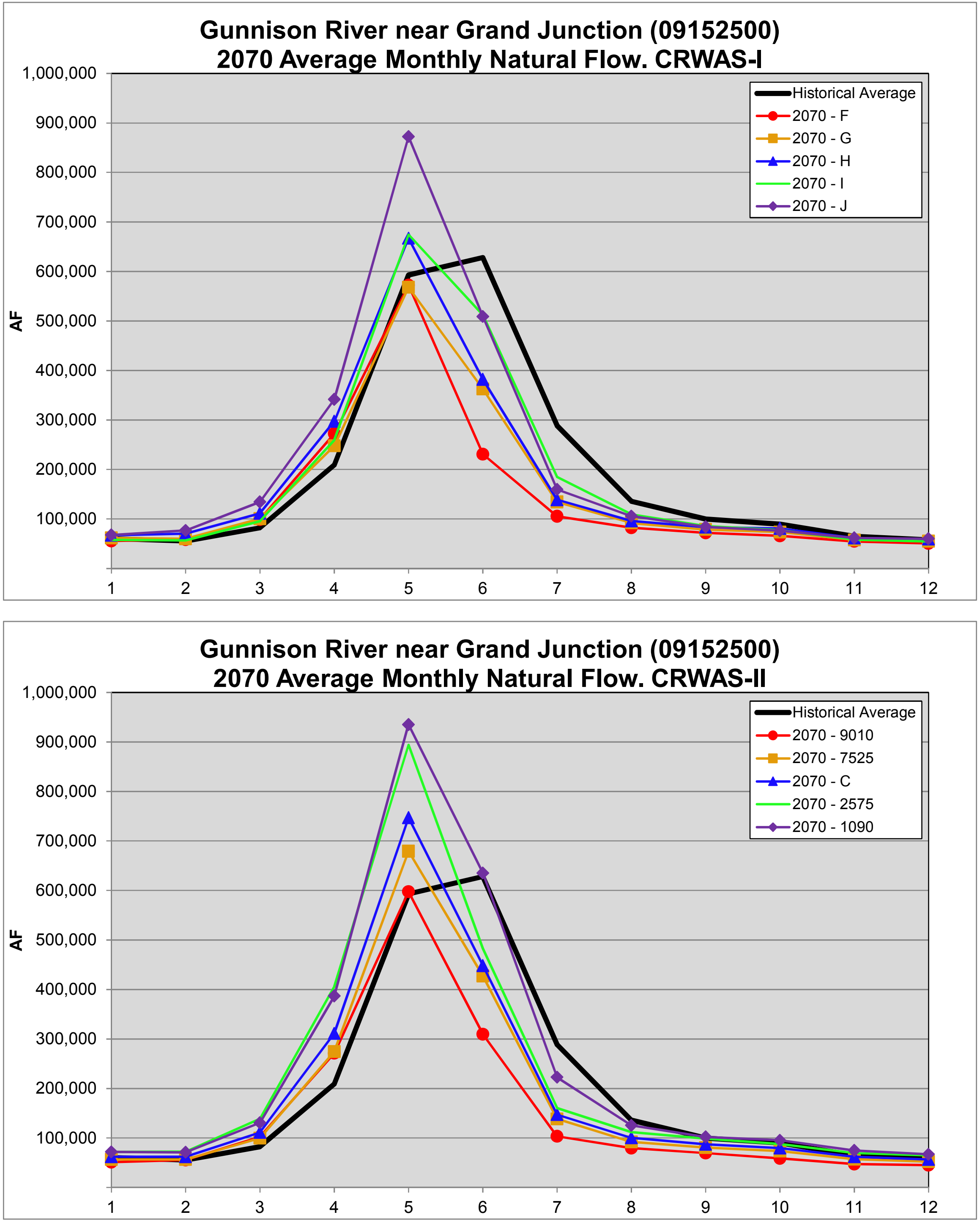
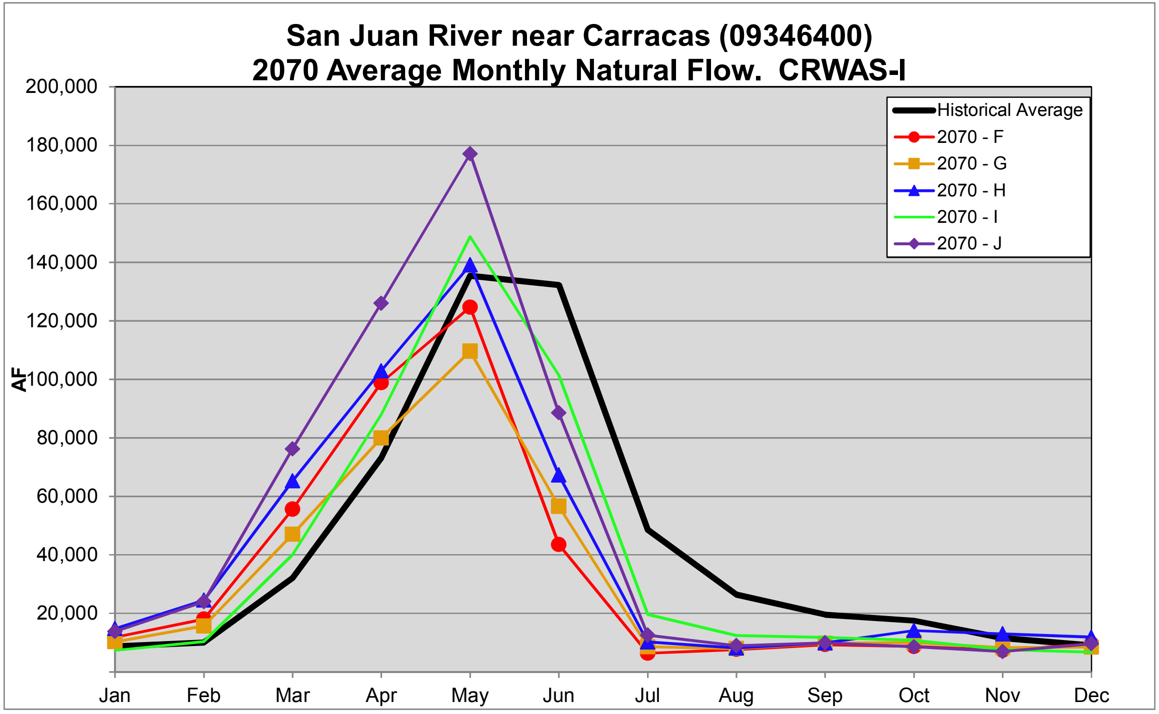


Figure 5. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, San Juan River near Carracas, 09346400.


San Juan River near Carracas (09346400)
2070 Average Monthly Natural Flow. CRWAS-I

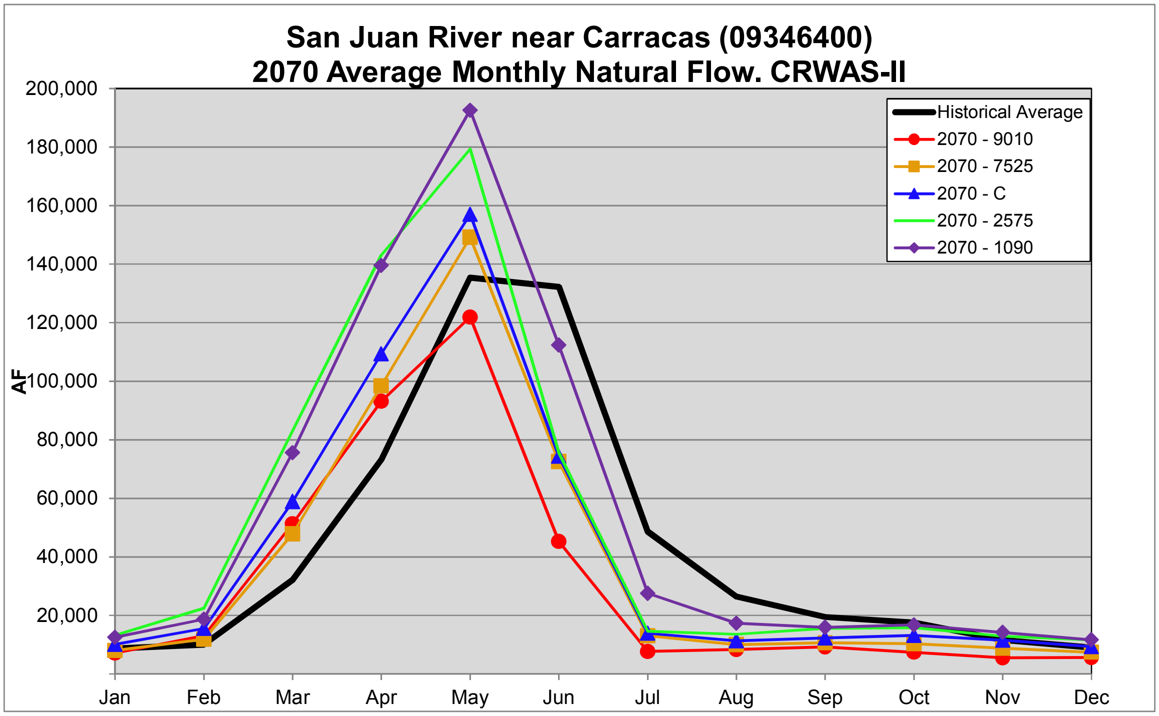
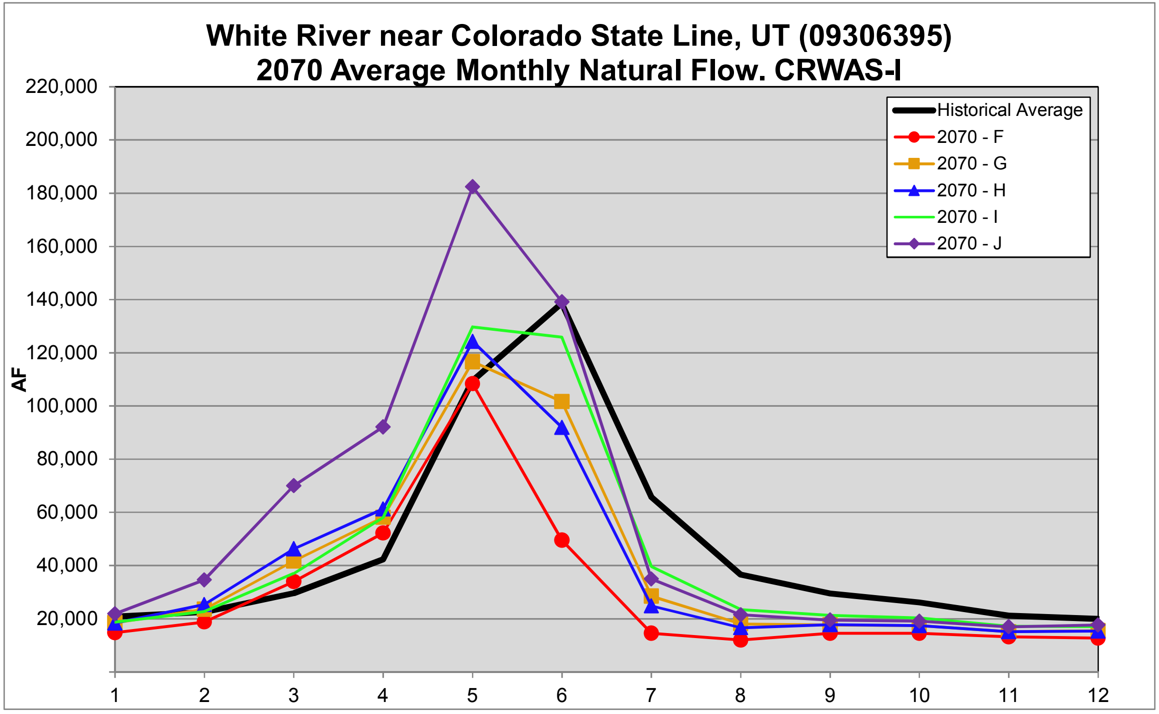

San Juan River near Carracas (09346400)
2070 Average Monthly Natural Flow. CRWAS-II

Figure 6. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, White River near Colorado-Utah State Line, 09306395.



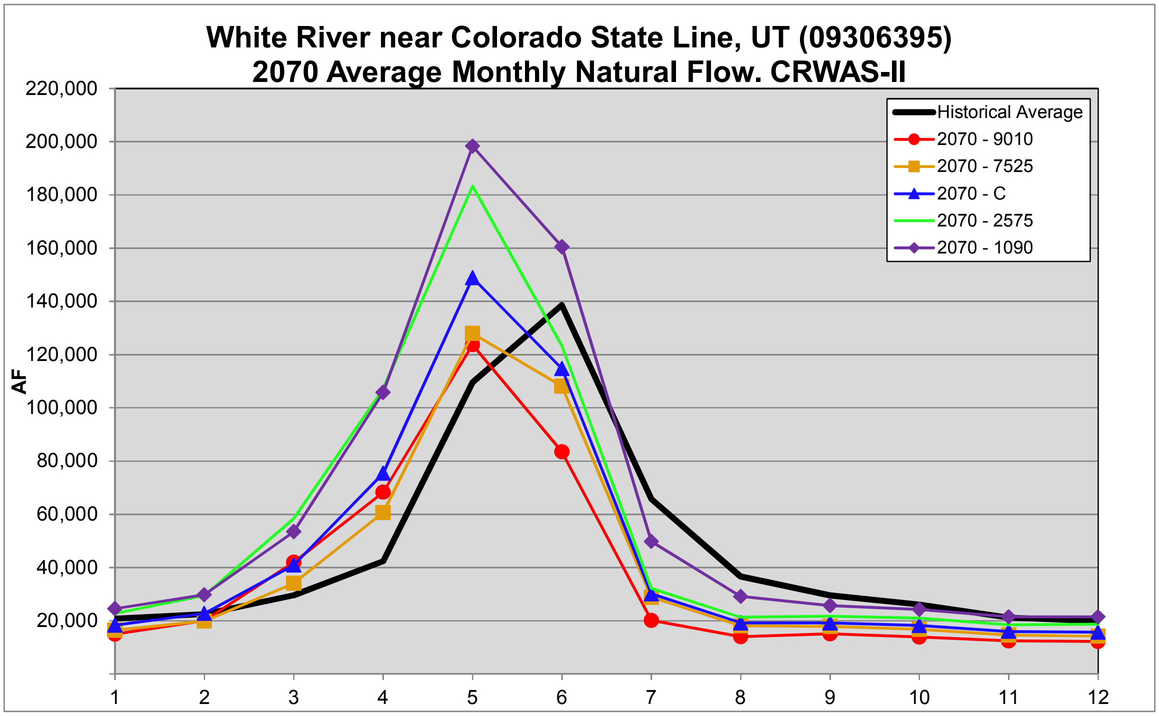
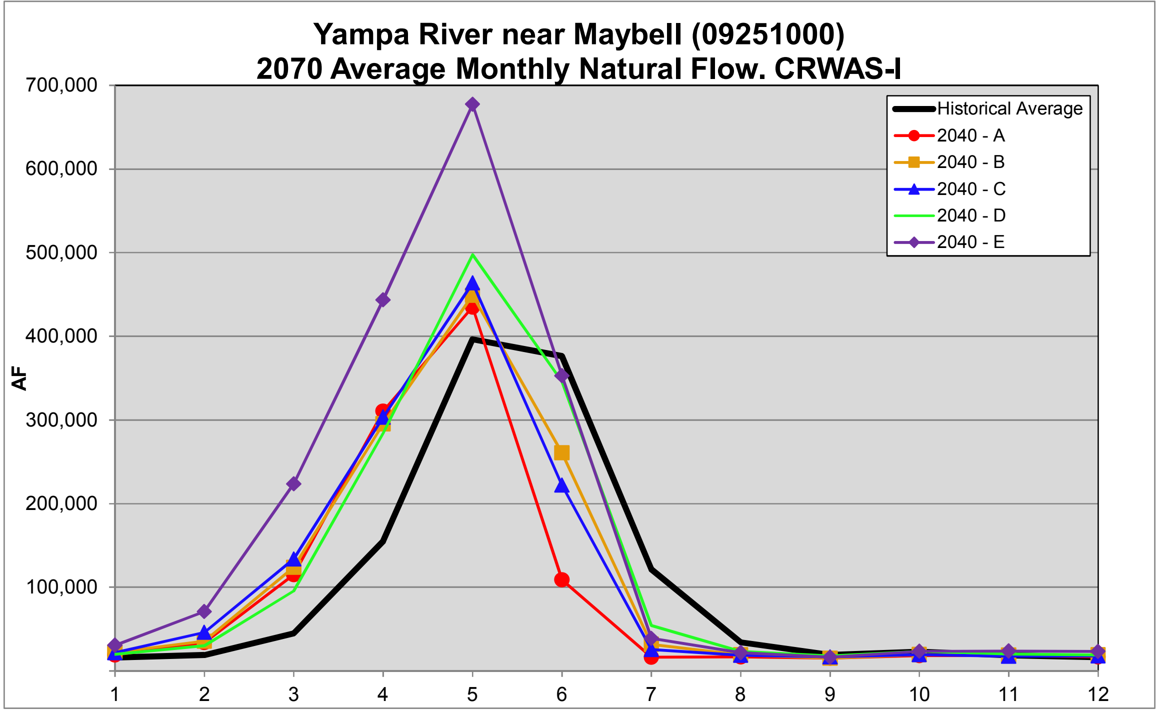
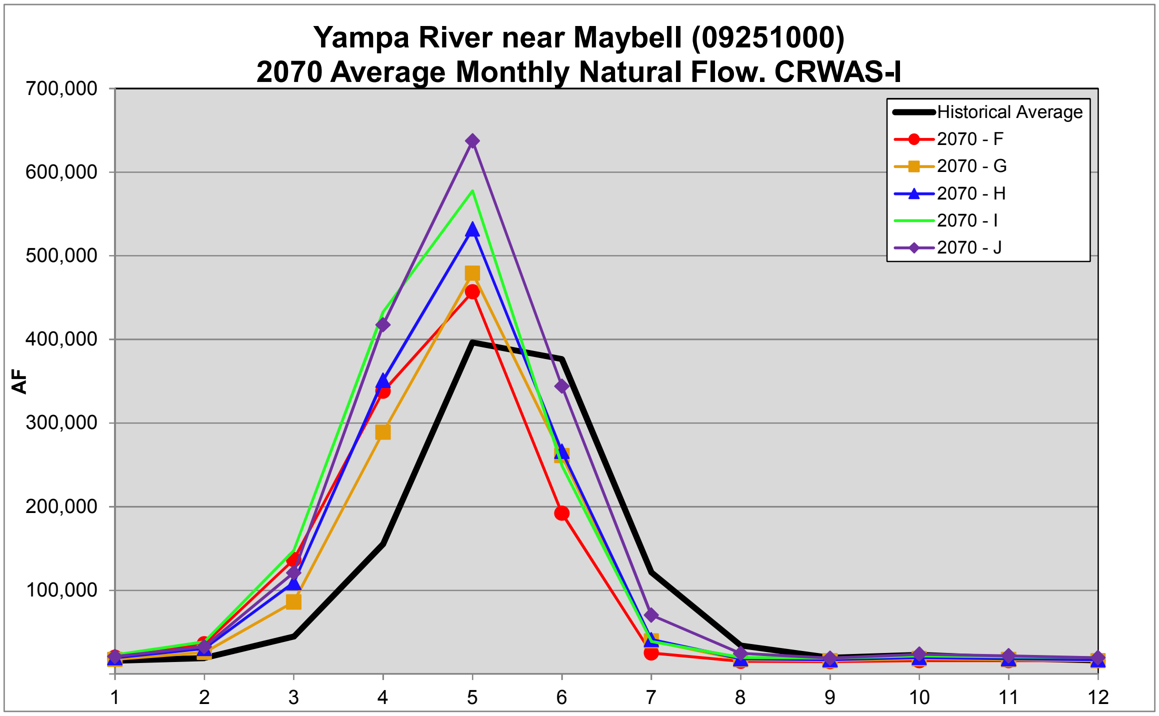


Figure 7. Mean 2070 Monthly Natural Flows for CRWAS-I and CRWAS-II scenarios, Yampa River near Maybell, 09251000.





References

Brekke, L., Thrasher, B.L., Maurer, E.P. and T. Pruitt. 2013. *Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.* U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Brekke, L., Wood, A.W. and T. Pruitt. 2014. *Downscaled CMIP3 and CMIP5 Hydrology Projections*. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado. July 3, 2014.

Bureau of Reclamation. 2012. Colorado River Basin Water Supply and Demand Study for the Western United States. Eos, Vol. 92, No. 48, 29 November 2011.

Colorado Water Conservation Board (CWCB). 2000. Colorado Decision Support System Overview. At http://cdss.state.co.us/.

Colorado Water Conservation Board (CWCB). 2012. Colorado River Water Availability Study. Final Report, March 2012, Denver, CO.

Colorado Water Conservation Board (CWCB). 2015. CDSS basin info. At http://cdss.state.co.us/basins/Pages/BasinsHome.aspx.

Gleckler, P. J., Taylor, K. E., and Doutraiaux, C. 2008. Performance metrics for climate models, J. Geophys. Res., 113, D06104, doi:10.1029/2007JD008972, 2008.

Harding, B. L., Wood, A. W. and Prairie, J. B.. 2012. The implications of climate change scenario selection for future streamflow projection in the upper Colorado River basin, Hyd. Earth Sys. Sci. http://www.hydrol-earth-syst-sci.net/16/3989/2012/.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lukas, J., Barsugli, J., Doesken, N., Rangwala, I., and K. Wolter. 2014. Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. A report by the Western Water Assessment, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder for the Colorado Water Conservation Board.

Meehl, G. A. Covey, K., Delworth, T., Latif, M., Mcavaney, B., Mitchell, J. F. B., Stouffer, R. J., and K. E. Taylor. 2007. The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research, Bull Am Met Soc. Volume 88, Issue 9 (September 2007)

Pierce, D.W., Barnett, T.P., Santer, B.D. and P. J. Gleckler. 2009. Selecting global climate models for regional climate change studies. P. Natl. Acad. Sci.,106, no. 21. 2009.

Program for Climate Model Diagnosis and Intercomparison (PCMDI). 2013. http://wwwpcmdi. llnl.gov/ipcc/about_ipcc.php, http://wwwpcmdi.llnl.gov/projects/cmip/index.php. Last accessed June 28, 2013.

Rupp, D.E., Abatzoglou, J.T., Hegewisch, K.C., and P.W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50843.

Stainforth, D. A., Downing, T. E., Washington, R., Lopez, A., and New, M.: Issues in the interpretation of climate model ensembles to inform decisions Philos. T. Roy. Soc. A, 365, 2163–2177, 2007.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012: An overview of CMIP5 and the experiment design. Bull. Amer. Meteor. Soc., 93, 485–498.

Tebaldi, C. and Knutti, R.: The use of the multi-model ensemble in probabilistic climate projections, Philos. T. Roy. Soc. A, 365, 2053–2075, doi:10.1098/rsta.2007.2076, 2007.

Wilby, R. L.: Evaluating climate model outputs for hydrological applications, Hydrolog. Sci. J., 55, 1090–1093, 2010.

Woodbury, M., Yates, D., Baldo, M. and L. Kaatz. 2012. Joint Front Range Climate Change Vulnerability Study. Water Research Foundation, Denver, Colorado