Model Sensitivity Analysis

An Overview of CBRFC's Hydrologic Model Sensitivity to Changes in Precipitation, Temperature, Soil Moisture, and Evapotranspiration Perturbations

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National Oceanic and Atmospheric Administration (NOAA)

National Weather Service (NWS)

Colorado Basin River Forecast Center (CBRFC)

1. Introduction

This report is the final product of Project #1, Part 2 identified by the Colorado River Climate and Hydrology Work Group (Work Group). This report summarizes the findings from a sensitivity analysis conducted by the Colorado Basin River Forecast Center (CBRFC), which intends to quantify the magnitude of impact (i.e., sensitivity) of key parameters within the CBRFC's hydrologic modeling paradigm. The results summarized here are intended to provide decision support for stakeholders within the Colorado River Basin when prioritizing investment decisions; for example, the results of this study indicate that precipitation data has the most influence on seasonal (April through July) volumetric streamflow and therefore may be most important to invest resources into improving precipitation monitoring and forecasts to improve forecasts of seasonal volumetric streamflow. The original Scope of Work (SOW) for this project is included as Appendix A to this report.

For this study, four hydrologic model input parameters describing precipitation, temperature, evapotranspiration, and soil moisture were perturbed from historical values to quantify their impact to model streamflow output. Precipitation, evapotranspiration, and soil moisture values were perturbed at ±2.5%, ±5.0%, and ±10% of historical values. Temperature values were perturbed at ±0.5 degrees Fahrenheit (°F), ±1.0 °F, and ±2.0 °F. It is important to note that these perturbation values were not selected to be representative of any future climate conditions, and that these results are not intended to be used to quantify impacts to streamflow as the impacts of climate change are realized. These levels were selected solely to produce a departure from historical modeled values that could be quantified and attributed to the parameter of interest. Further, this study does not incorporate forecast lead time since perturbations to the parameters presented here are not intended to improve the skill or accuracy of CBRFC forecasts; the parameter perturbations are intended only to illustrate responses from the CBRFC's hydrologic model.

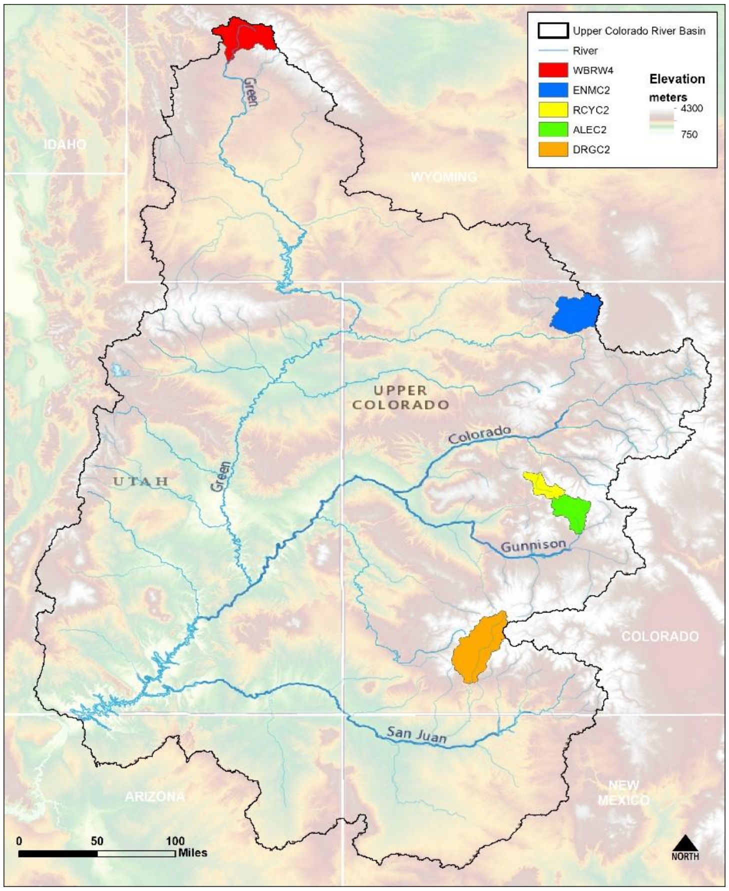


Figure 1: The five basins used in this study are highlighted here. WBRW4 (red), ALEC2 (green), RCYC2 (yellow), DRGC2 (orange), and ENMC2 (blue) cover a broad range of the Upper Colorado River Basin.

Five forecast locations were chosen by the CBRFC to be studied over the course of this research. The Animas River at Durango (DRGC2), East River at Almont (ALEC2), Crystal River above Avalanche Creek near Redstone (RCYC2), Elk River near Milner (ENMC2), and Green River at Warren Bridge near Daniel (WBRW4) were selected due to their nature as headwater locations with no regulation from reservoirs or diversions from water users which span much of the Upper Colorado River Basin.

As headwater locations modeled with no anthropogenic influence, any impacts to streamflow from parameter perturbation can be solely attributed to the perturbed parameter and not other anthropogenic influences such as a change to reservoir operation. In the SOW, the Colorado River at Glen Canyon Dam (GLDA3) was considered for inclusion in this study due to its importance to CBRFC stakeholders and general Colorado River management; however, due to limited computational resources and level of anthropogenic influence at that location, it was removed from the study. Historical years spanning almost the entirety of the CBRFC's calibration period, water year 1981 through 2015, were considered in this study, which is a departure from the original SOW. Initially, 6 years representing "wet", "dry", and "average" conditions were to be selected, but innovative programming at the CBRFC allowed for all water years from 1982 through 2015 to be considered; 1981 was excluded from this study as it served as a spin up year for the CBRFC's hydrologic model. Streamflow sensitivity to perturbed model parameters was considered on a monthly timescale, and aggregated to include impacts to the April through July runoff volume, October through September (i.e. Water Year) runoff volume, and October through December runoff volume.

2. Methodology

Using the CBRFC's Community Hydrologic Prediction System (CHPS), historical, mean areal temperature and precipitation forcings over the five selected study areas were perturbed independently at 6-hourly increments over the course of each water year spanning 1981 through 2015. Temperature data was perturbed by ±0.5 degrees °F, ±1.0 °F, and ±2.0 °F. Precipitation data was perturbed by ±2.5%, ±5.0%, and ±10%. Historical mean areal temperature and precipitation data is derived using weighted observed (i.e., gaged measurements) precipitation and temperature information. Monthly evapotranspiration coefficients developed through the CBRFC's calibration efforts were also perturbed independently by ±2.5%, ±5.0%, and ±10% of the calibrated values. It is important to note that evapotranspiration is not a function of temperature within the CBRFC's hydrologic modeling framework. Evapotranspiration is only impacted by the coefficients that have been derived during the calibration process, which are not affected by temperature. Historical, initial (i.e., October 1st) modelled lower zone soil moisture states derived by the CBRFC were also perturbed independently at ±2.5%, ±5.0%, and ±10% of the historical derived values. It is important to note that in some instances where historically wet conditions were present, perturbing the soil moisture state exceeded the capacity of the hydrologic model's soil moisture parameter. In these instances, initial soil moisture states were set to fully saturated levels, but may not technically represent the full increase prescribed by the perturbation level. For example, consider a hypothetical soil moisture parameter with a maximum depth of 6 inches, where at some historical instance is at 5.75 inches. Any perturbation in excess of approximately

5.0% will exceed the maximum value of this parameter; as such, all perturbations above 5.0% would be equivalently set to the maximum value of 6 inches.

Each water year considered spanning the CBRFC's calibration period (1982 through 2015) was run perturbing each parameter of interest by the predefined perturbation levels. As such, for each of the five locations considered in this study, there are 816 scenarios (4 parameters x 6 perturbations x 34 years), or 204 traces (6 perturbations x 34 years) considering each parameter at each of the basins in this study. This report summarizes the 4,080 overall traces considered (4 parameters x 6 perturbations x 34 years x 5 locations), but does not show every individual result. Figures in this report are representative of results at all locations, unless otherwise specified, but equivalent figures are available at all sites and timeframes included in this study. All data is available upon request from the CBRFC, or can be reached at the following link[1].

3. Results

3.1. General Results

As anticipated in the SOW, changes to precipitation had the most impact to annual and seasonal runoff volumes. In general, for each 1% increase or decrease in precipitation, there was an approximate 1.6% increase or decrease, respectively, to annual and seasonal streamflow at each of the basins studied here. Precipitation was also the most impactful driver of monthly streamflow volumes from May through September, though temperature was occasionally more impactful during these months. Precipitation was typically least impactful to monthly streamflow from November through March, likely due to precipitation events more likely being characterized by snowfall rather than rainfall. For example, precipitation that was added in January and February did not result in higher streamflow during those months; rather, higher streamflow was observed later in the runoff season (April through July). It is important to note

[1] For those unable to access the link from the text, the full address is: https://www.cbrfc.noaa.gov/report/Sensitivity_Analysis_Supplemental_Information.zip

that comparisons of any parameter to temperature are not exactly congruent in this study, as precipitation, soil moisture, and evapotranspiration were perturbed by percentages, and temperature was perturbed by degrees Fahrenheit. Figure 2 summarizes the average impacts of each perturbation at DRGC2, which are typical for the locations included in this study.

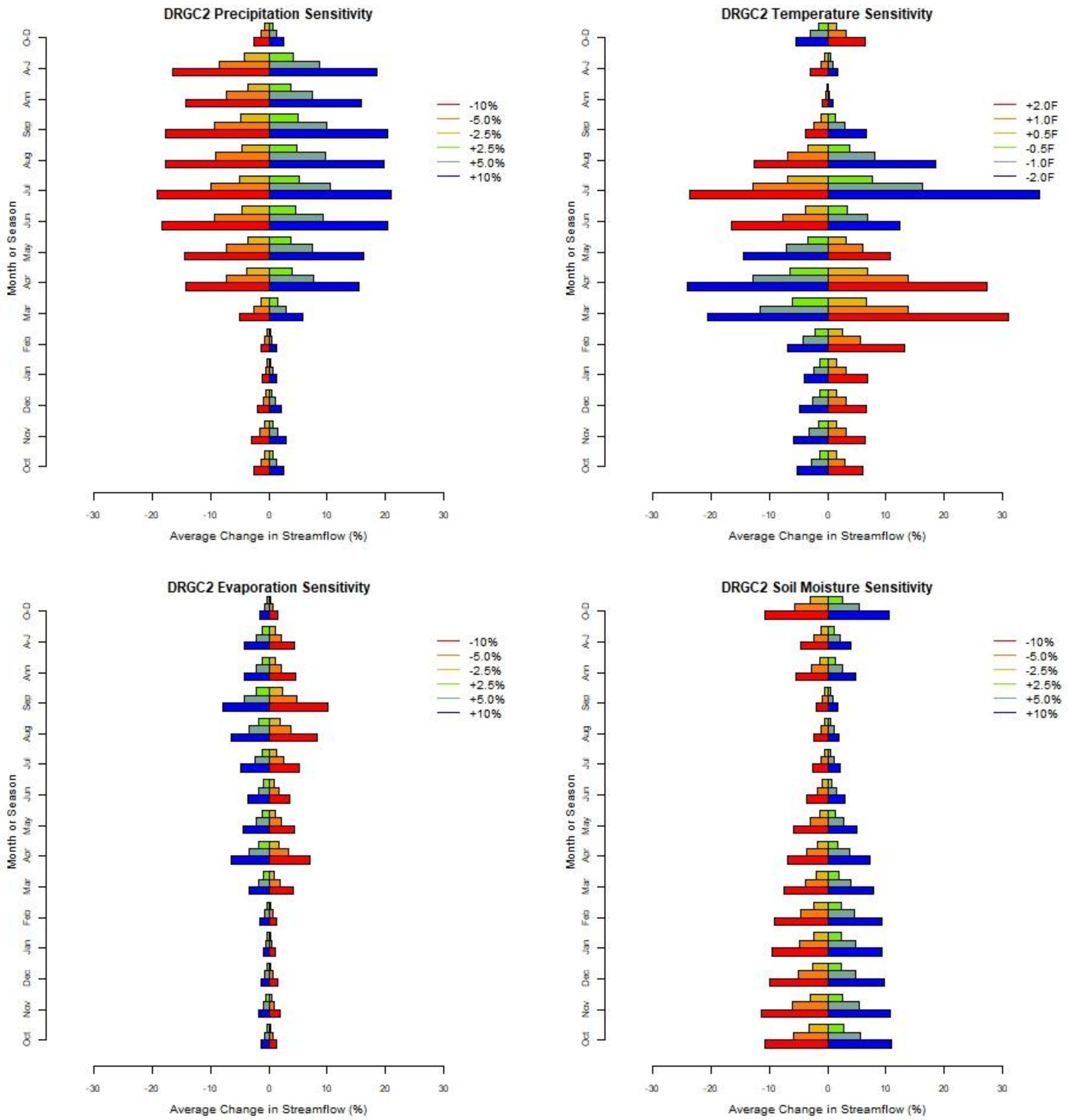


Figure 2: This sensitivity plot summarizes the impacts of each perturbation at DRGC2. Note that the color scheme is associated with the perturbation level and not streamflow. So cooler colors correspond with increased percent change or decreased temperature and warmer colors correspond with decreased percent change and increased temperatures

October through December seasonal volumes were predominantly impacted by initial soil moisture conditions, having nearly 2 to 4 times the impact of temperature and precipitation considerations. Over the October through December timeframe, a 1% increase or decrease in initial soil moisture conditions generally resulted in an approximate 0.8% to 1.2% increase or decrease in streamflow, respectively. Temperature impacts over October through December were also significant over this timeframe, resulting in roughly a 1.5% to 3% increase or decrease in streamflow volume per degree Fahrenheit increase or decrease, respectively. Increased temperatures over this timeframe increased streamflow due to increased snowmelt and rainfall events.

Evapotranspiration impacts over the course of the year and seasonal runoff were consistently the second or third most impactful parameter, although it tended to be relatively minor at monthly intervals or over the October through December timeframe. In this study, evapotranspiration generally increased or reduced annual streamflow volume by about 0.5% per 1.0% decrease or increase, respectively, over the course of the water year. Comparatively, evapotranspiration impacts over the October through December resulted in only about a 0.1% change per 1.0% decrease or increase, respectively, over the season. Monthly impacts between October and March were typically on the order of a 0.1% to 0.2% increase in monthly streamflow volumes per 1.0% decrease or increase, respectively; however, these impacts rose to between 0.4% and 0.6% in each month spanning April through September. Table 1 ranks the relative impact of the four parameters used in this study over monthly, annual, and seasonal timeframes. Table 2 shows the average percent change in streamflow per 1% perturbation (or 1 ^{o}F in the case of temperature) for DRGC2.

Table 1: This table ranks the relative impact of each parameter to streamflow volumes at various time frames at ALEC2. These results are representative of those observed at other basins in this study.

Timeframe/Parameter	Evapotranspiration	Precipitation	Soil Moisture	Temperature
October	4	3	1	2
November	4	3	1	2
December	4	3	1	2
January	3	4	1	2
February	3	4	1	2
March	4	3	2	1
April	3	2	4	1
May	3	2	4	1
June	3	1	4	2
July	3	2	4	1
August	3	2	4	1
September	3	1	4	2
Water Year	2	1	3	4
April - July	2	1	3	4
October - December	4	3	1	2

Table 2: The table summarizes the average percent change in streamflow per increased percent or °F perturbation for each parameter at DRGC2.

Timeframe/Parameter	Evapotranspiration	Precipitation	Soil Moisture	Temperature
October	-0.13	0.26	1.13	2.84
November	-0.18	0.30	1.12	3.13
December	-0.14	0.20	0.98	2.92
January	-0.10	0.12	0.94	2.74
February	-0.14	0.13	0.91	4.85
March	-0.38	0.54	0.77	12.71
April	-0.67	1.50	0.71	13.14
May	-0.44	1.49	0.55	6.45
June	-0.36	1.88	0.33	-7.22
July	-0.50	2.02	0.23	-14.70
August	-0.73	1.88	0.21	-7.50
September	-0.91	1.93	0.19	-2.56
Water Year	-0.44	1.48	0.51	-0.37
April - July	-0.44	1.72	0.44	-1.05
October - December	-0.15	0.26	1.09	2.98

3.2. Annual

Annual streamflow volumes were most impacted by precipitation, by far, in this study. Precipitation impacts were often 3 to 5 times greater than the second most impactful parameter (usually soil moisture) at the annual scale. At the annual timeframe, a 1% increase or decrease in precipitation resulted in about a 1.5% increase or decrease, respectively. Figure 3 shows the variability associated with precipitation perturbations compared with the other parameters considered in this study at DRGC2. The results shown in Figure 3 are representative of those at other sites considered in this study.

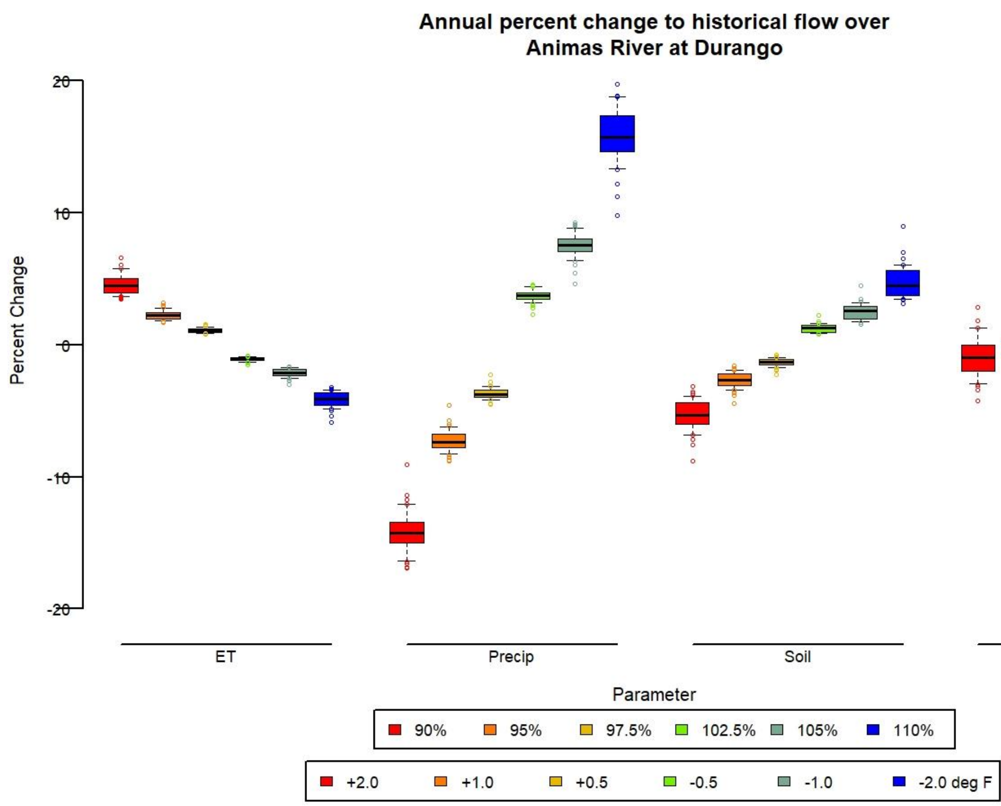


Figure 3: Percent change of annual streamflow as it relates to each parameter and perturbation over the water year at DRGC2. Results are representative of those at other basins considered in this study.

At the annual timeframe, evapotranspiration and soil moisture conditions are more impactful than temperature; however, while annual runoff is not greatly impacted by the temperature perturbations considered in this study, the timing of runoff is affected by temperature. Figures 4, 5, and 6 show the monthly distribution of streamflow for all parameter perturbations over water years 1984, 2002, and 2005 which were very wet, very dry, and near average, respectively. Temperature is the only parameter which significantly shifts the timing of the annual hydrograph, though the shift is not particularly apparent during the historically dry water year of 2002. Over the course of the year, a 1 ºF temperature increase (decrease) resulted in a 0.3% to 0.8% decrease (increase) in annual streamflow volumes.

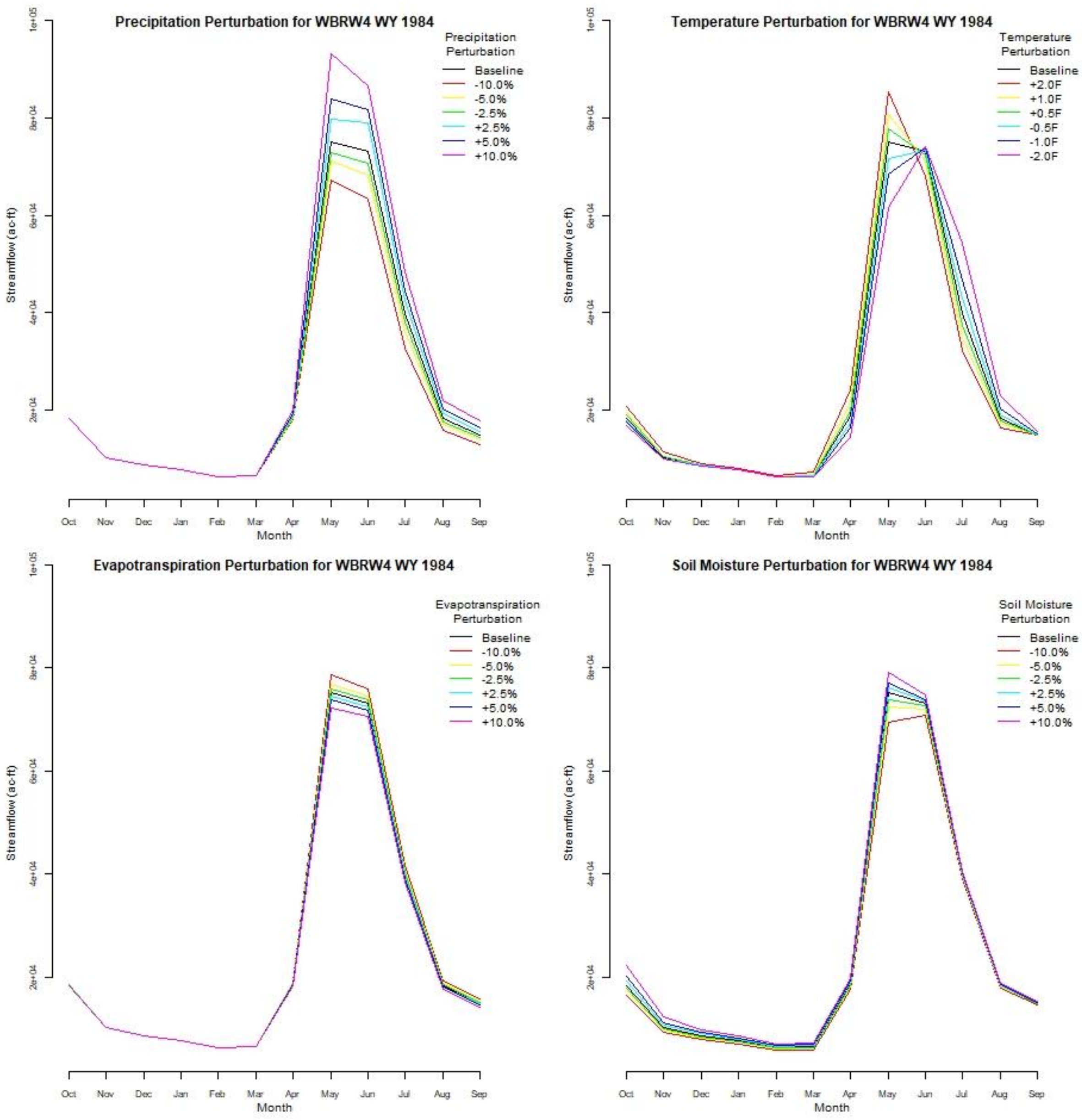


Figure 4: Change in streamflow under each perturbation condition for each parameter using historical information from 1984 at WBRW4.

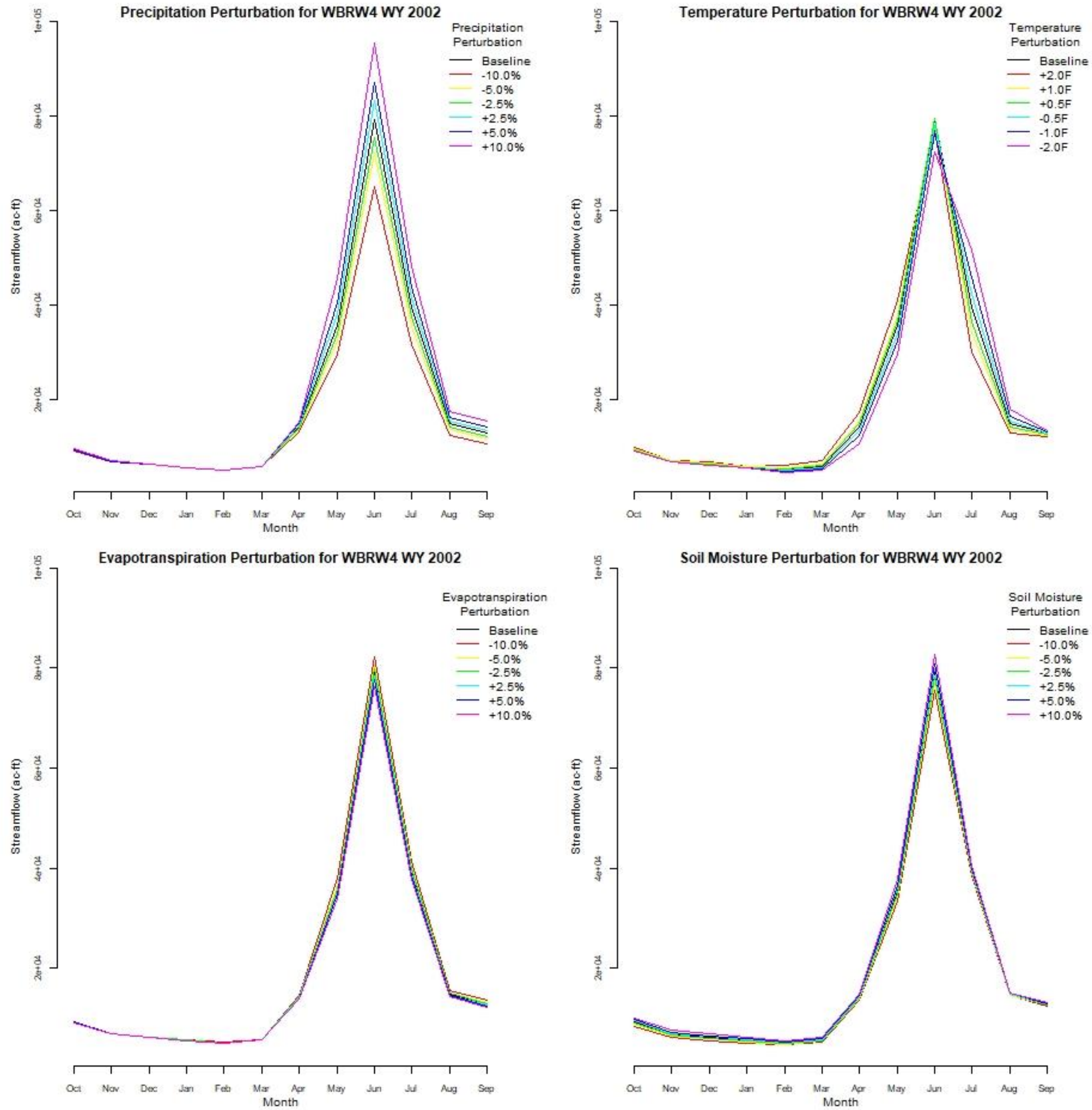


Figure 5: Change in streamflow under each perturbation condition for each parameter using historical information from 2002 at WBRW4.

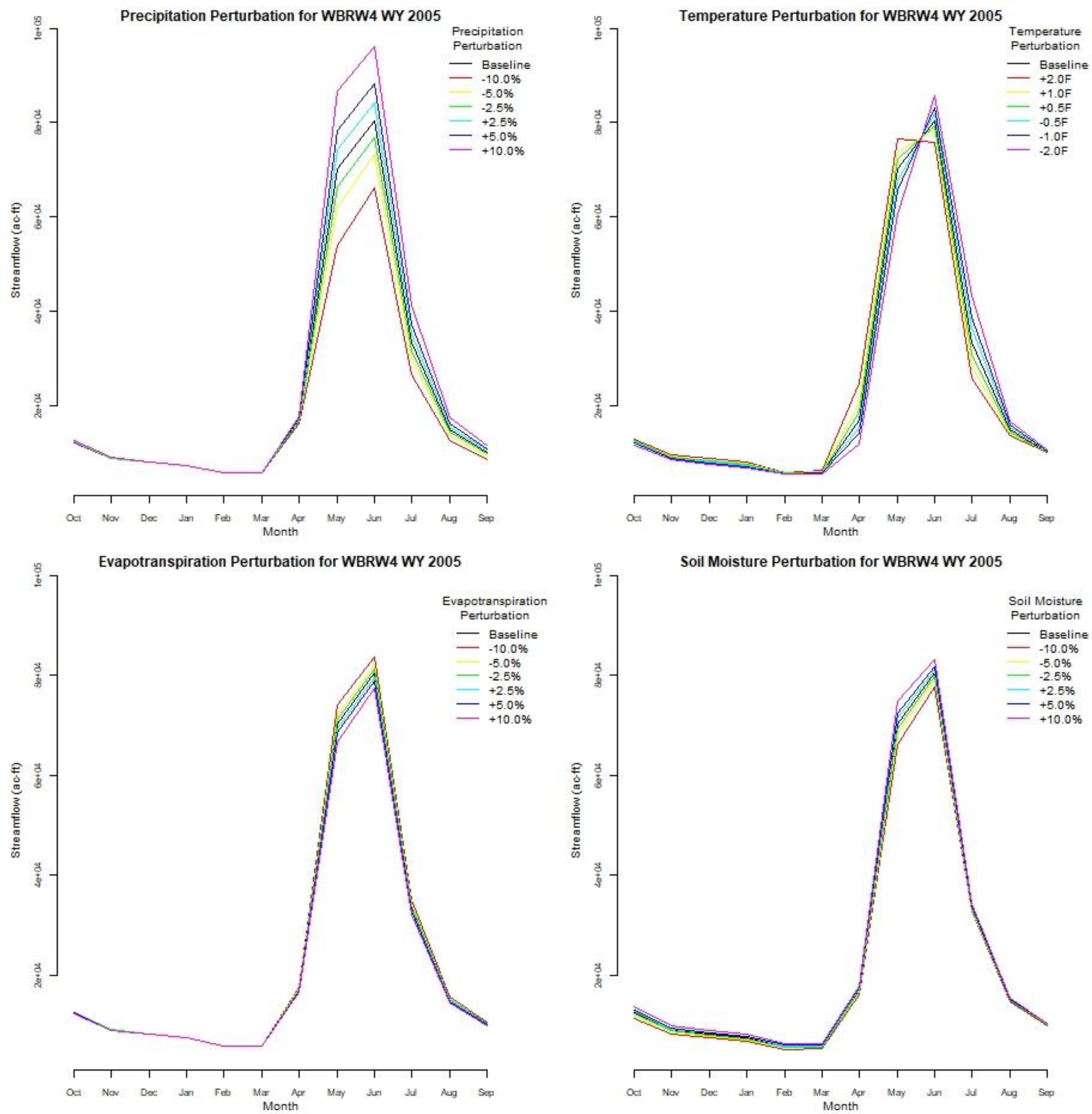


Figure 6: Change in streamflow under each perturbation condition for each parameter using historical information from 2005 at WBRW4.

Numerous studies indicate that under warming conditions in the Colorado River Basin, streamflow will significantly decrease (e.g., Vano et al., 2012[2]; Udall and Overpeck, 2017[3]; Milly and Dunne, 2020[4]). Notably, over the course of the year, changes to temperature do not significantly impact annual streamflow volumes in this study, though temperature does have a significant impact on the timing of streamflow runoff. In the current CBRFC's hydrologic modeling paradigm, other parameters such as evapotranspiration and soil moisture are not functions of temperature. This is a limitation of the CBRFC's current modelling framework in that these variables, and others, are not functions of temperature, but it is also beneficial for the framework of this study as it isolates the effects of these variables on streamflow.

Evapotranspiration and soil moisture impacts were significant over the course of the year, though not on the same order as precipitation. Evapotranspiration and soil moisture impacted each site similarly but had opposite directions of effect, and were typically separated by less than 0.5% per percent change.

3.3. Seasonal Runoff (April - July)

Seasonal runoff occurring in April through July was most impacted by precipitation and shared many of the characteristics described in the section discussing parameter sensitivity over the annual timeframe. This is expected, as most of the runoff over the course of the water year is the result of snowmelt during the spring and summer. Figure 7 shows the variability associated with precipitation perturbations compared with the other parameters considered in this study at DRGC2 over the seasonal timeframe.

[2] Vano, J., et al. "Hydrologic Sensitivities of Colorado River Runoff to Changes in Precipitation and Temperature." *Journal of Hydrometeorology*, vol. 13, Jun. 2012, pp 932-949.
[3] Udall, B. and Overpeck, J. "The twenty-first century Colorado River hot drought and implications for the future." *Water Resources Research*, vol. 53, Mar. 2017, pp 2404-2418.
[4] Milly, P. C. D. and Dunne, K. A. "Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation." *Science*, vol. 367, Mar. 2020, pp 1252-1255

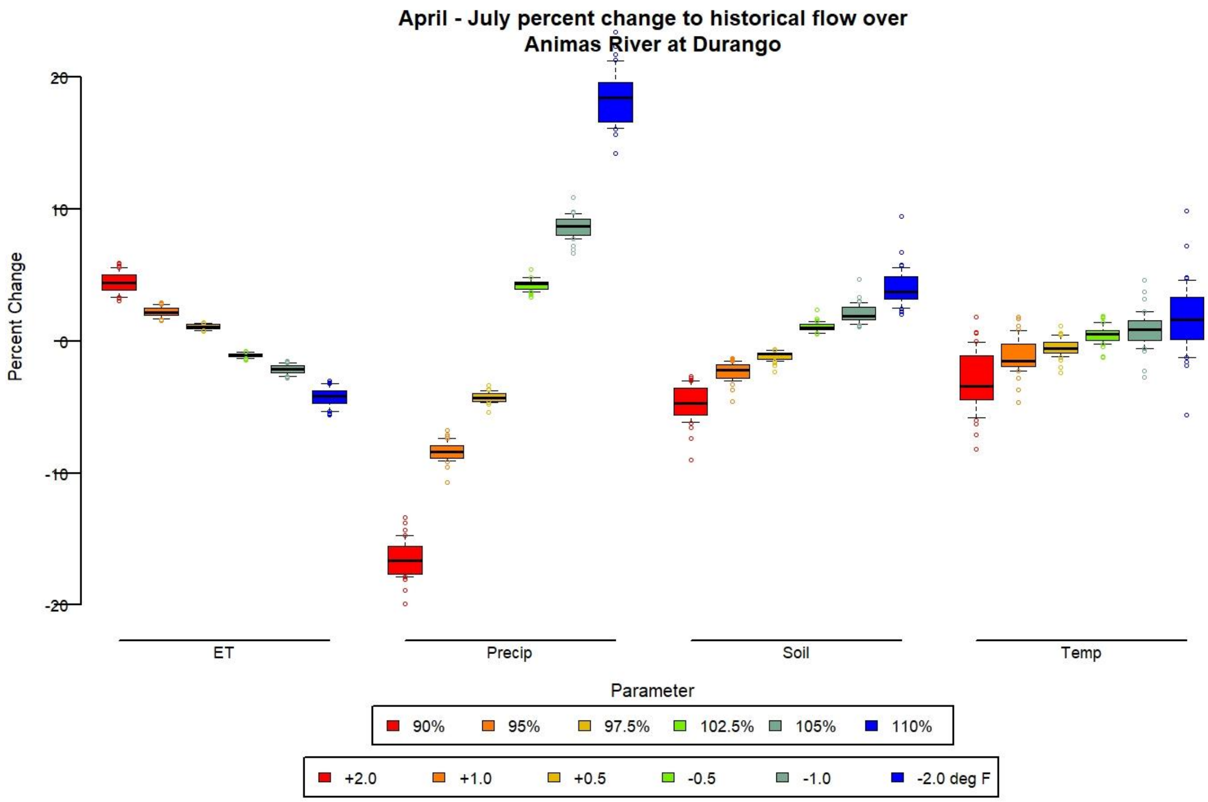


Figure 7: Percent change of annual streamflow as it relates to each parameter and perturbation over the seasonal runoff period (April through July) at DRGC2. Results are representative of those at other basins considered in this study.

Results over the seasonal runoff period are very similar to those observed over the annual timeframe. Precipitation impacts were slightly more impactful at the seasonal timeframe as a 1% increase or decrease in precipitation resulted in a 1.5% to 2.0% increase or decrease, respectively, in season runoff volumes. Evapotranspiration and soil moisture impacts at the seasonal timeframe were nearly identical to those observed over the annual timeframe.

3.4. Fall Season (October - December)

Over the fall season, soil moisture conditions became the dominant driving parameter. Soil moisture impacts were typically 2 to 4 times greater than the second most impactful parameter, temperature, over this timeframe. Precipitation, despite being the dominant parameter at the annual and seasonal timeframes, was only the third most impactful parameter (evaporation is the least significant parameter over the fall season). It is not unexpected that precipitation would have a less significant impact on streamflow during the fall season, since precipitation events between October and December are more likely to occur as snowfall events rather than rainfall events (Figure 8).

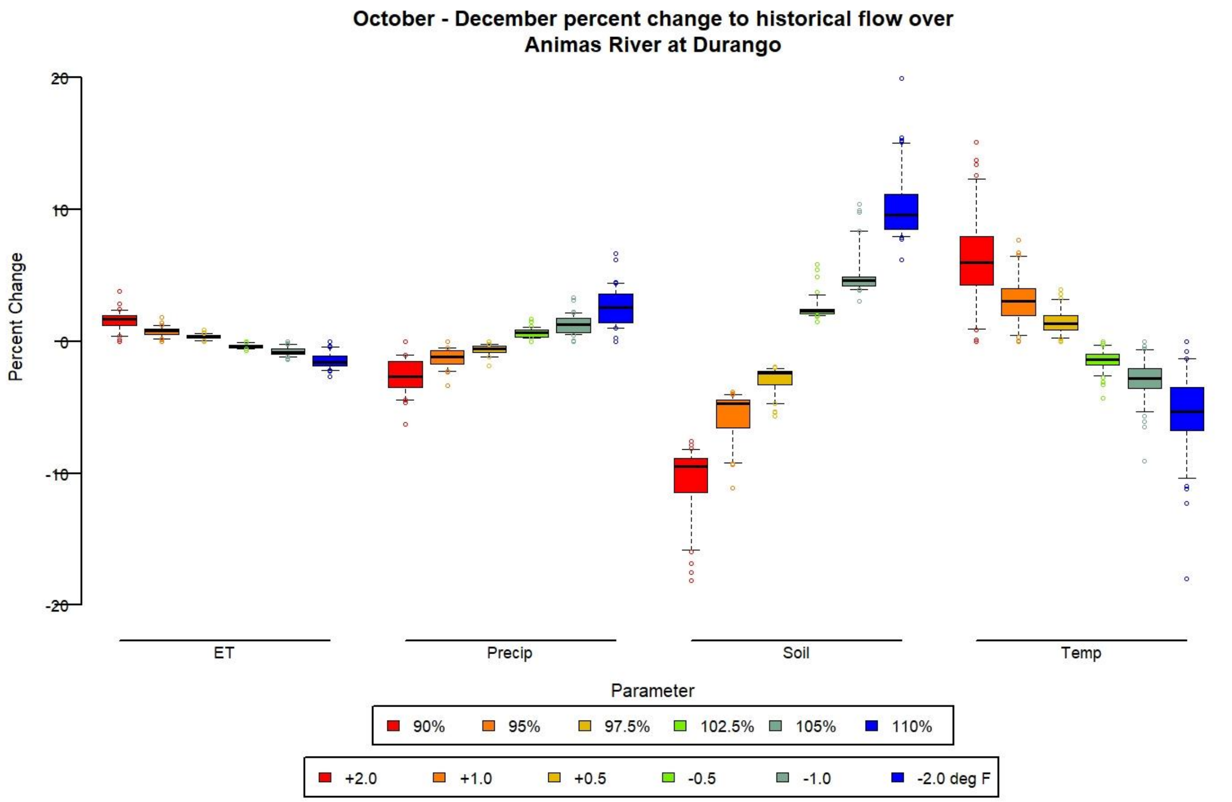


Figure 8: Percent change of annual streamflow as it relates to each parameter and perturbation over the October through December timeframe at DRGC2. Results are representative of those at other basins considered in this study

Soil moisture impacts over the fall Season were approximately 4 times more impactful than during the annual or seasonal runoff timeframe. Increasing (Decreasing) soil moisture by 1.0% typically resulted in an increase (decrease) of fall streamflow between 0.8% and 1.0%. Modelled soil moisture during the fall months drives streamflow conditions within a basin. A 1 ^{o}F increase (decrease) results in approximately a 2.5% to 3.5% increase (decrease) in fall season streamflow volumes; again, the increased impact of temperature over the fall season supports how the character of precipitation events (i.e. rainfall or snowfall events) impacts the volume of streamflow observed over this timeframe.

3.5. Monthly Breakdown

The impact of various parameters varied from month to month, though trends were consistent between basins. At the monthly timescale, soil moisture conditions were the most significant from October through March. Interestingly enough, while the least impactful parameter over the course of the year, temperature is consistently the first or second most impactful parameter for any given month. While not intuitive, this illustrates temperature's important role in the timing of seasonal runoff and determination of whether a precipitation event is expressed as snowfall or rainfall. Figure 9 illustrates the sensitivity of streamflow to parameter perturbations over October and January. The impacts of parameter perturbations over the fall and winter months typically resulted in relatively small change; this is representative of less weather variability in fall and precipitation events typically occurring as snowfall.

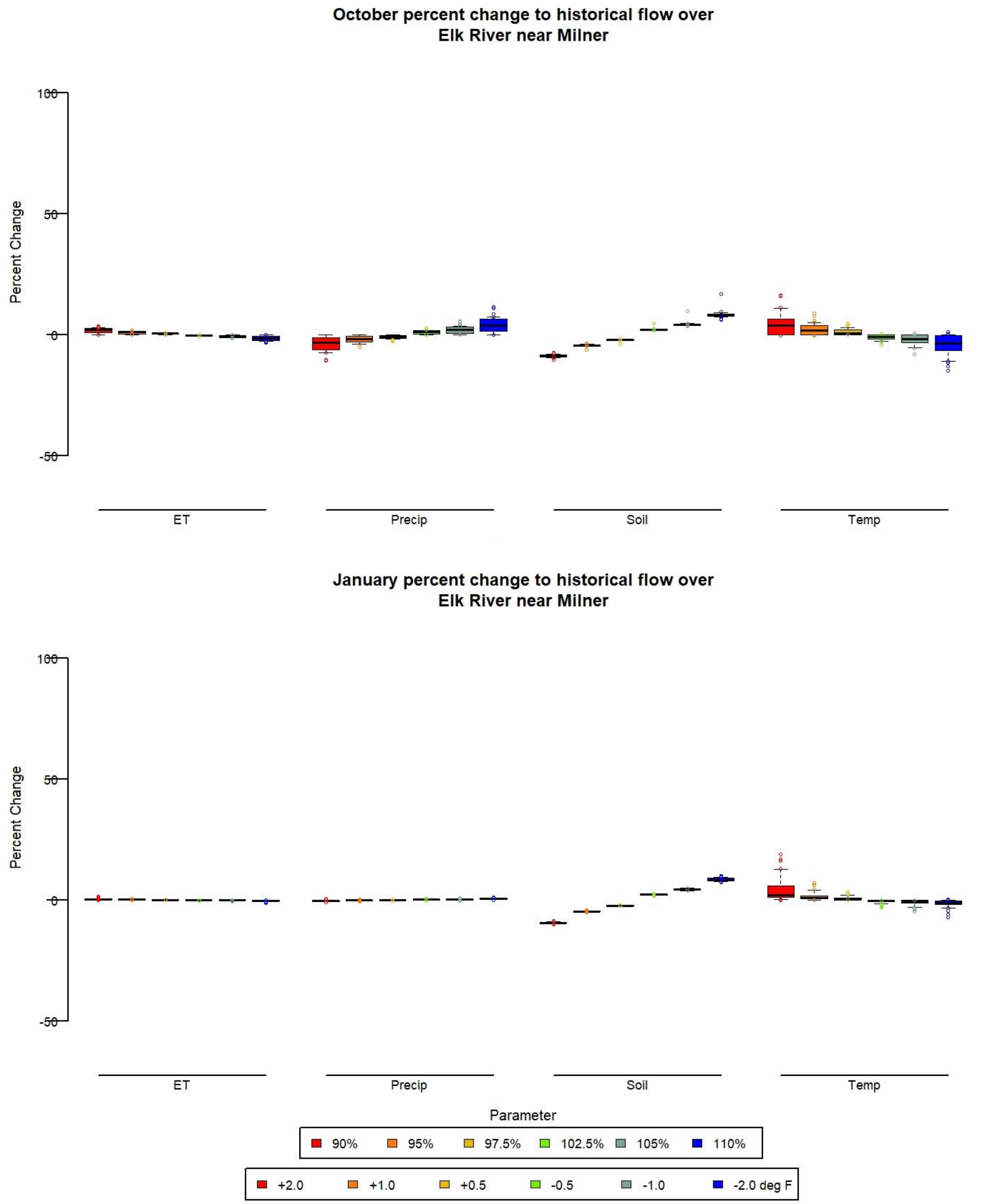


Figure 9: Percent change of monthly streamflow as it relates to each parameter and perturbation over the months of October (top) and January (bottom) at ENMC2. Results are representative of those at other basins considered in this study

From April through September, precipitation is typically the most significant parameter, though temperature is consistently the second most impactful parameter. In general, from October through May, increasing temperatures result in increased monthly streamflow, and from June through September, the inverse is true, with increasing temperatures resulting in decreased monthly streamflow. Figure 10 illustrates the sensitivity of streamflow to parameter perturbations over April and August. April is the month with the most variability associated with monthly streamflow, primarily driven by temperature impacts. Again, this illustrates the important role that temperature plays in the timing of spring runoff, particularly in early spring. The monthly impacts of each of the parameters included in this study is presented in Appendix B for DRGC2.

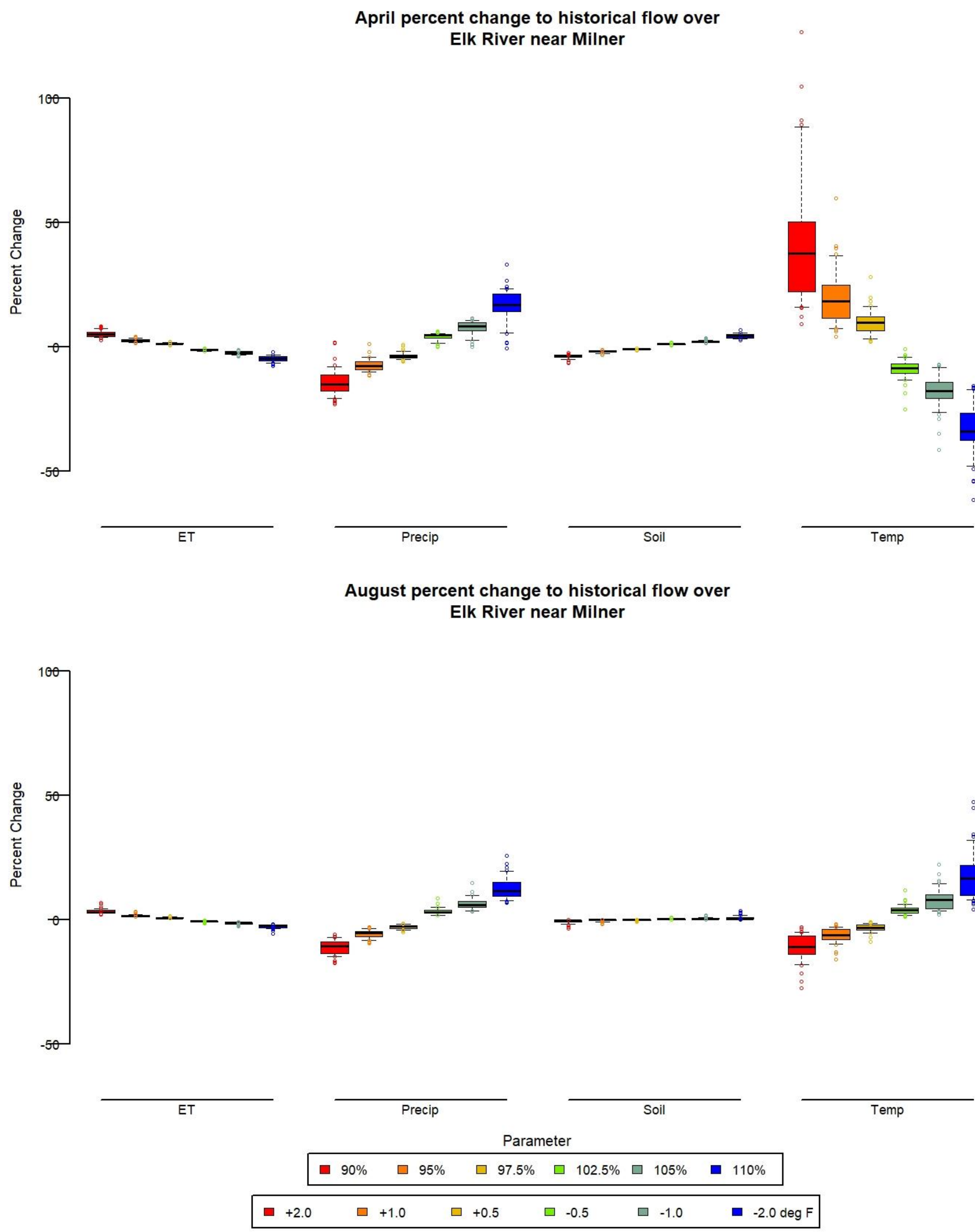


Figure 10: Percent change of annual streamflow as it relates to each parameter and perturbation over the months of April (top) and August (bottom) at ENMC2. Results are representative of those at other basins considered in this study

4. Summary of Results

4.1. Precipitation

As expected, precipitation had the largest impact to April through July seasonal runoff and annual runoff. At the annual and seasonal timeframe, a 1% increase in precipitation resulted in approximately a 1.5% increase in streamflow. Precipitation impacts were not as impactful over the October through December timeframe, as a 1% increase in precipitation only yielded a 0.25% increase in streamflow. In general, precipitation impacts from October through February are relatively small, since it is likely that most precipitation events during this time occur as snowfall events; in contrast, precipitation in August and September still have significant impacts on streamflow volumes, where a 1% increase in precipitation results in nearly a 2% increase in monthly streamflow. Water resource managers may consider this variability in their decision making process, as decisions made at the end of the runoff season (i.e. July and August) are still subject to increased uncertainty attributable to precipitation in August and September. Investing in efforts to improve long-term precipitation forecasts at the seasonal timescale could mitigate the uncertainty associated with precipitation and possibly improve streamflow forecasts.

4.2. Temperature

Temperature did not have the impact to annual and seasonal runoff volumes that may have been expected in light of other studies examining the impact of temperature on Colorado River Basin streamflows. Many of the parameters (e.g., evapotranspiration and soil moisture) in the CBRFC's current modelling paradigm are not functions of temperature, despite the fact that these parameters are physically very dependent on temperature conditions. This is a primary reason that the CBRFC's hydrologic model is not easily utilized for climate change analysis. However, temperature is still a vital consideration within the CBRFC's modelling framework in that it significantly impacts the timing of seasonal runoff, particularly in March and April. Further, temperature impacts can be significant in the fall and early winter, when temperature is critically important for determining the character of precipitation events (i.e. rainfall or snowfall events). Again, as water resource managers prepare annual operating plans, temperature variability and the resultant impact on early water year streamflow should be considered, and research efforts into accurate long-term temperature forecasts could be beneficial.

4.3. Evapotranspiration

Evapotranspiration was the only parameter considered in this study whose impacts to streamflow are consistently inversely proportional. This result is not unexpected, as increasing model evapotranspiration coefficients directly affects the amount of modelled water available for surface runoff. It is important to understand that evapotranspiration within the CBRFC's hydrologic model is developed using a monthly coefficient derived during the calibration process of the model. As currently implemented, evapotranspiration is not a function of temperature nor is it dynamic in response to changing hydroclimatological conditions from year to year. While evapotranspiration impacts to streamflow are not seen as impactful as precipitation in this study, possible future work could investigate whether implementing a dynamic evapotranspiration term that is a function of temperature or using an entirely different hydrologic model that represents evapotranspiration differently could improve forecasts or illustrate more significant impacts from evapotranspiration.

4.4. Soil Moisture

Soil moisture is an important consideration, particularly in fall and continuing to early spring. As river gages freeze in the winter, it is important to the CBRFC's modelling efforts to represent soil moisture as accurately as possible after irrigation operations end and prior to river gages freezing; this allows for the model to track as well as possible when observed gage data is not available. The CBRFC's initial fall soil moisture states are not based on physical measurements such as those recorded at some SNOTEL sites and are developed using baseflow conditions; this is done because soil moisture measurements made at SNOTEL sites are not deep enough to correlate well with the CBRFC's soil moisture parameters. Future research efforts may look into funding a network of deep soil moisture sensors, or exploring the use of remote sensing to make soil moisture assessments that could be used within the CBRFC's hydrologic modeling framework, or the next generation of hydrologic models. As soil moisture impacts are most significant during the early months of the water year, water resource managers may look to them as an indicator of how efficient snowmelt driven runoff may be in the upcoming season.

5. Conclusions

A sensitivity analysis of the CBRFC's hydrologic model was addressed in the study presented here. Four parameters were perturbed to assess their impact on monthly, seasonal, and annual streamflow volumes. Over the course of the year and April through July runoff season, precipitation had the greatest impact, with soil moisture and evapotranspiration also having a significant impact. Over the October through December timeframe, soil moisture held the greatest influence; temperature was consistently the most or second most impactful parameter from month to month, but these affects resulted in no more than 1% change in the annual streamflow.

The results of this study underscore the importance of understanding how hydroclimatological factors influence streamflow forecasts and the hydrology of the Colorado River Basin. Improving the accuracy of weather forecasts, both in skill and lead time, can significantly improve streamflow forecasts at the annual, seasonal, and monthly timeframes. Beyond the obvious controlling influence of precipitation, it is additionally important to accurately reflect evapotranspiration and soil moisture conditions in the basin to develop and produce accurate forecasts of streamflow conditions. This study also brings awareness to how the CBRFC's modelling paradigm incorporates temperature and its impact on other parameters (i.e., the effect of temperature on evapotranspiration and soil moisture); future research efforts could examine a different modeling paradigm or incorporate the use of a dynamic evapotranspiration term. Ultimately, this study reinforces that resources to improve weather forecasting and assessment of evapotranspirative and soil moisture conditions within the

Colorado River Basin will benefit hydrologic forecasting. Moreover, within a decision support context, this study helps point to specific parameters and time of year where additional investigation could be informative.

The implications of this study as it relates to water resource management decisions can not be fully determined from the results in this study; however, there are some important inferences that can be arrived at from these results. The variability of streamflow in response to precipitation and temperature is particularly high in August and September; therefore, decisions made based on expected end-of-year hydrologic conditions during that timeframe can be significantly impacted by changes in weather and climate. Beginning in October and through January, monthly streamflow variability is reduced and dependent much more soil moisture conditions. Similarly, beginning in March and becoming even more exaggerated in April, temperature and precipitation begin to significantly impact monthly streamflow volumes, and streamflow variability increases in response to increased variability in the precipitation and temperature record. It is reasonable to assume that end-of-year or end-of-water year forecasts made between April and September are subject to increased uncertainty due to the variability in temperature and precipitation events.

6. Opportunities

Based on the results of this study, there are several opportunities that could be pursued in the future to improve CBRFC's streamflow forecast and its utility for basin water users. As a reminder, CBRFC's forecasts are integral to the operational decisions that are made across the entire Colorado River Basin, so even relatively minor forecast improvements can lead to significantly improved decision-making outcomes. CBRFC is driven by a continuous improvement philosophy and this study reveals some specific opportunities, not necessarily in priority order, that could be pursued:

1. Annual and April-July streamflow volumes are most sensitive to the precipitation time series, therefore, improvements to this input is an obvious opportunity for future

exploration. The CBRFC and Climate Prediction Center (CPC) are currently evaluating the CPC's sub-seasonal to seasonal prediction tools with the goal of providing a more skillful precipitation (and temperature) time series than climatology for Week 2-4 that can be used in CBRFC's water supply forecast. Continuing to track progress on this effort and evaluating any improvements in skill from using data streams that result from this effort are important opportunities.

2. Under current Lake Powell and Lake Mead reservoir operations determination procedures, August and April are key months for decision-making. For example, the Bureau of Reclamation's (Reclamation) August 2020 24-Month Study projections of the January 1, 2021 system storage and reservoir water surface elevations will set the operational tier for the coordinated operation of Lake Powell and Lake Mead during 2021. Similarly, Reclamation's April 2021 24-Month Study projection of end of water year (i.e., September 30, 2021) elevations at Lake Powell and Lake Mead may adjust operations at Lake Powell and affect the volume of water released. Reclamation uses the CBRFC water supply forecast (among other data sources) in these 24-Month Studies, so there is an opportunity for careful examination of the parameters that are most sensitive in the August-December and April-September periods. Setting aside precipitation as the most sensitive parameter that influences streamflow, this study identified the opportunity to examine temperature sensitivity in August, ET sensitivity in August-September, and soil moisture sensitivity in October-December. These parameters and timeframes were identified since they offer the opportunity to improve general understanding of the hydrologic model and associated parameter sensitivities during times that are among the most critical for decision making by stakeholders in the Colorado River Basin.
3. The previous opportunity references the present timing of important decisions to reservoir operations made by the Bureau of Reclamation that are, at least partly,

contingent on forecasts developed by the CBRFC. The timeframe for making these decisions may change in the future as operational guidelines are reconsidered; also, there are many operational decisions and agencies that rely on CBRFC forecasts to make decisions throughout the year. The results of this study provide information to resource managers to assess the impact of weather and climate variability on CBRFC forecasts and possible subsequent impacts to decisions made based on these forecasts. Using the example of decisions made by Reclamation affecting Glen Canyon Dam and Hoover Dam in April and August under current operating guidelines, the results of this study suggest that decisions made in August regarding end of calendar year conditions are susceptible to forecast uncertainties in precipitation and temperature conditions in August and September. Resource managers should recognize that a forecast made in October regarding end of calendar year conditions would be less susceptible to changing precipitation and temperature conditions since changes to these drivers have less impact on forecasts from October through at least February. Similarly, forecasts made in April are more susceptible to change if precipitation and/or temperatures deviate significantly from median climatological conditions.

In this particular study, model sensitivity was not correlated with forecast lead time; the impacts from parameter perturbations to streamflow at monthly and seasonal timeframes are not compared to forecast skill since the perturbations considered in this study are not intended to improve forecast skill or accuracy and are used to illustrate model response to changes in forecast drivers. Generally, CBRFC forecasts made between October and February for short lead times will be less likely to be affected by variability in weather conditions.

It is important to note that uncertainty due to climate variability in CBRFC forecasts is not (and should not be) the only consideration when developing resource management policy; however, understanding when forecasts can be most affected by climatic variability is important information for resource managers when crafting policy.

4. The temperature perturbations explored in this study had the greatest impact on monthly streamflow volumes of all perturbed parameters but had the smallest impact on annual streamflow volume, since other model parameters (e.g. ET) are not a function of temperature and therefore lessen the impact of temperature changes over the annual timeframe. Tracking CPC's effort to improve the Week 2-4 temperature outlook, as described above, and adopting these improvements for times when streamflow is highly sensitive to temperature (such as April through August) is an important opportunity.
5. This study clearly revealed ET is not influenced by temperature inputs in CBRFC's modeling approach despite the physical relationship between temperature and ET. Instead, ET is represented through elevation specific monthly demand curves that are established through model calibration. CBRFC has plans to re-calibrate their model in the near future so there is an opportunity to re-examine and potentially improve representation of ET, temperature, and the relationship between the two parameters, which could impact the most sensitive months of April, August, and September. The model calibration manual[5] offers pathways for improvement and CBRFC has identified the following specific opportunities to explore:
    a. The impacts of temperature and ET are physically linked, even if the current hydrologic modelling paradigm does not explicitly connect the parameters. As such, identifying and incorporating trends in temperature over the historical record is essential to better understanding impacts of ET. The historical record could be detrended to better reflect contemporary temperature characteristics that could then be used to generate an ensemble of streamflow traces adjusted

[5] Anderson, E. 2002. "Calibration of Conceptual Hydrologic Models for Use in River Forecasting." https://www.nws.noaa.gov/oh/hrl/modelcalibration/1.%20Calibration%20Process/1_Anderson_CalbManual.pdf

to account for recent temperature trends. This may be an opportunity to understand how temperature has affected runoff timing.

b. Spring temperature trends should be studied to evaluate the impact of high elevation temperature changes independently of precipitation impacts. Using SNOTEL stations, trends in temperature can be separated by the amount of precipitation observed to provide the opportunity to identify temperature trends that are independent of changes to precipitation (e.g., identifying a warming trend rather than a drying trend). Subsequent study may focus on trends in the changing character of precipitation; that is, trends in the frequency and magnitude of both snowfall and rainfall events.

c. The CBRFC's hydrologic model currently utilizes static monthly coefficients to account for evapotranspiration. A dynamic time series of evapotranspiration data can be developed, utilized, and compared; however, based on the results of this study, this approach, and subsequent impact to response from the hydrologic model, is highly contingent on the degree to which dynamic ET deviates from ET derived using the current static ET coefficients. . The benefit to using a dynamic ET dataset is that it would be more representative of the physical relationship between ET and temperature.

d. There is an abundance of new ET research and datasets becoming available. In particular, gridded datasets may help inform the CBRFC's hydrologic model in a similar way that gridded precipitation datasets currently do.

e. Remotely sensed and other gage-based soil moisture datasets are becoming more prevalent and widely available. Semi-quantitative techniques are currently used to develop soil moisture states within the CBRFC's hydrologic model, but additional or improved soil moisture datasets could improve upon these techniques. By improving the accuracy of the soil moisture parameter, the development of the ET parameter would additionally benefit.

6. The CBRFC utilizes historical temperature information to develop water supply forecasts. As the impacts of climate change continue to be realized in the Colorado River Basin and warmer temperatures impact streamflow conditions, there may be an opportunity to assess current temperature trends and apply that information to historical temperature traces. By shifting past data to reflect current warming trends, the impacts of current warming trends may be more readily accounted for in the current water supply forecasting paradigm. As this opportunity is considered, the results of this study suggest that forecasted annual runoff volumes would not change significantly; however, adjusting historical temperatures to better reflect current temperature trends would likely yield more pronounced changes to runoff timing. Combining changes to temperature with, for instance, dynamic ET may yield significant changes to both runoff magnitudes and timing.
7. Unlike the temperature and precipitation time series parameters, where perturbations were applied at each timestep, soil moisture is a state variable and was perturbed on only a single date (i.e., October 1). Given the importance of the October soil moisture state in influencing the high streamflow sensitivity detected in October-December, improvements to the October soil moisture state is an important opportunity to explore. Partnering with the U.S. Geological Survey in their Next Generation Water Observing System work is an opportunity that could result in an improved estimate of the October 1 soil moisture state. Moreover, focusing on low elevation areas where soil moisture may be less affected by frozen ground is an opportunity to explore.
8. The CBRFC has said the lack of real-time deep soil moisture information causes the biggest uncertainty in estimating the soil moisture state variable. Placing sensors at the depths to collect deep soil moisture data (approximately 4 meters) is often very difficult

when considering the terrain and underlying geology. Additionally, in the mountainous West, the profile of a soil column can change significantly over small spatial scales. There's an opportunity to explore new technique to measure deep soil moisture using NASA's GRACE Tellus satellites, or other emerging technology.

Appendix A

Scope of Work

Project: Accuracy Assessment and Sensitivity Analysis of Hydroclimatic Parameters within the Colorado Basin River Forecast Center's (CBRFC) Modeling Framework

Background: The long-term goal of this work is to improve the accuracy of CBRFC's water supply forecast and to achieve this goal, the project is split into two parts.

Part 1 – The first part of this project is to document the existing process that CBRFC uses to improve the water supply forecast and to identify opportunities for improving the process or making the process or its products more accessible. CBRFC already uses a robust and on-going accuracy improvement process which includes both inward and outward facing components. For example, CBRFC organizes an annual Water Supply Review/Verification Webinar for stakeholders to describe: what actually occurred; what went well and why; and what can be improved and how. Few stakeholders know, however, that this relatively short webinar is preceded by rigorous internal deliberations.

Part 2 – The second part of this project does not directly investigate the accuracy of the seasonal water supply forecasts per se; rather, it intends to gain an understanding of the magnitude of impact (also referred to as "sensitivity") that changing key components has on water supply forecasts developed using the latest CBRFC methodology and data. This part of the work is referred to as the sensitivity analysis; an evaluation of the effects of changes in input values or assumptions on a model's results. The intent of this work is to lay the foundation for future adjustments to model parameters leading to improvements in model accuracy. For example, knowing the magnitude of impacts and their rank order should help provide direction on which components of the forecast should be examined further. Moreover, this information should help with making investment decisions, i.e., what work may lead to the greatest improvement in accuracy.

In response to stakeholder comments stemming from a drought resiliency meeting, the Bureau of Reclamation (Reclamation) and the CBRFC partnered to identify sources of uncertainty within the water supply forecasts that drive Reclamation's 24-Month Study and its resulting reservoir elevation projections. During initial efforts, sources of uncertainty were identified and presented qualitatively, with little quantitative analysis. Part 2 of this scope is designed to further a portion of Reclamation's and CBRFC's past effort by quantitatively assessing the sensitivity of uncertainties associated with the water supply forecast specifically, which fall into three categories[6]: model parameters, initial model conditions, and model forcings.

Scope of Work – Part 1

[6] The three categories are defined as follows: "model parameters" are those parameters defined through the CBRFC's calibration process, such as those related to evapotranspiration; "initial conditions" are what are commonly referred to as the "states" of the model and represent the current modeled hydrologic state of the system. For this study, initial conditions are represented through soil moisture characterizations; and "forcings" are those model inputs that drive changes to the model such as precipitation and temperature inputs.

The first part of this work will focus on improving the visibility of CBRFC's accuracy assessment process or data products. CBRFC will document the components of their accuracy improvement process and will post this, and other helpful information, such as any accuracy improvement investigations conducted annually, on the cbrfc.noaa.gov website.

Scope of Work – Part 2

There are many different techniques for conducting sensitivity analyses and this work will use a one-at-a-time[7] (OAT) technique. The basic concept of the OAT approach is to perturb each factor by a given percentage or value while holding all other factors constant. While other techniques are more sophisticated, the OAT approach offers a computationally simple and readily implementable method for exploring sensitivities. The first step in the OAT approach is to identify the factors that will be changed one-at-a-time. This study will focus on temperature, precipitation, evapotranspiration, and soil moisture because, in CBRFC's best professional judgment, the water supply forecast is most sensitive to these factors[8].

- Temperature: Temperature is a model forcing and these point-sourced data are obtained from observation networks. Water supply forecasts are expected to decline with increasing temperature.

- Precipitation: Precipitation is a model forcing. There is no doubt that precipitation has a major influence on the water supply forecast. Minimal new knowledge is expected to be gained by investigating this factor but it is necessary to be included because it is the expected primary driver of water supply and will serve an important comparison role.

- Evapotranspiration (ET): ET rates are represented as a model parameter calculated through the model calibration process (every 5 years). This factor is not based on observed data. The sensitivity of ET rates and temperature are expected to covary.

- Soil Moisture: Soil moisture initial conditions are not based on observed soil moisture data or networks. Historical soil moisture information is estimated during the calibration process and relies mostly on historical baseflow observations.

The next step in the OAT process is to determine the magnitude of change (perturbation) to be evaluated. Selecting the right range of perturbations is important to develop an informative change-response curve and to avoid unnecessary analyses. Six perturbations will be evaluated for each factor: 1) the daily temperature record will be perturbed by ± 0.5 ºF, ± 1 ºF, ± 2 ºF; 2) the daily precipitation and ET record will be perturbed by ± 2.5%, ± 5%, ± 10%; and 3) the October 1 soil moisture condition will be perturbed by ± 2.5%, ± 5%, ± 10%. Based on preliminary trials, other perturbations may be explored. These

[7] More advanced sensitivity analysis techniques may be considered at a later date. For example, see http://www.andreasaltelli.eu/file/repository/A_Saltelli_Marco_Ratto_Terry_Andres_Francesca_Campolongo_Jessica_Cariboni_Debora_Gatelli_Michaela_Saisana_Stefano_Tarantola_Global_Sensitivity_Analysis_The_Primer_Wiley_Interscience_2008_.pdf

[8] A full list of the modeling factors that are used in the water supply forecast can be found at https://www.nws.noaa.gov/oh/hrl/general/indexdoc.htm#models

perturbations were initially selected because of their basis in physical reality, a desire to evaluate a range of effect sizes, and to maximize opportunities for making comparisons among the factors.

The spatial domain of the sensitivity analysis will focus on the Upper Colorado River Basin. Some headwater locations in the Upper Colorado River Basin are relatively unimpaired, which will better enable this analysis to isolate the impacts of the perturbations. Therefore, the CBRFC will examine sensitivities of the factors at five forecast locations: Animas River at Durango (DRGC2), East River at Almont (ALEC2), Crystal River above Avalanche Creek near Redstone (RCYC2), Elk River near Milner (ENMC2), and Green River at Warren Bridge near Daniel (WBRW4). The Colorado River at Glen Canyon Dam (GLDA3) forecast location will also be examined, not because this location will help this analysis isolate the impacts of the perturbations, but because of its importance in the Colorado River Basin.

CBRFC's calibration system will be used for the sensitivity analyses. Baseline years will be taken from a calibrated 35-year-long simulation of historical conditions for the period of 1981 to 2015. A year is defined as the October 1 to September 30 period. Sensitivity analyses will be performed by comparing a simulation of one perturbed year to its corresponding historical simulated (baseline) year. Sensitivities will be measured in thousands of acre-feet (kaf) and they will be determined by evaluating April – July runoff volume, October – September runoff volume, and October – December runoff volume for baseline vs. perturbed years. Each category and magnitude of perturbation will be applied to six individual years: two dry, two average, and two wet as determined by CBRFC.

A total of 864 single-year runs will be modeled consisting of 3 year types × 2 perturbed years × 6 basins × (6 temp. perturbations + 6 precip. perturbations + 6 ET perturbations + 6 soil moisture perturbations). The following table summarizes the analyses to be performed.

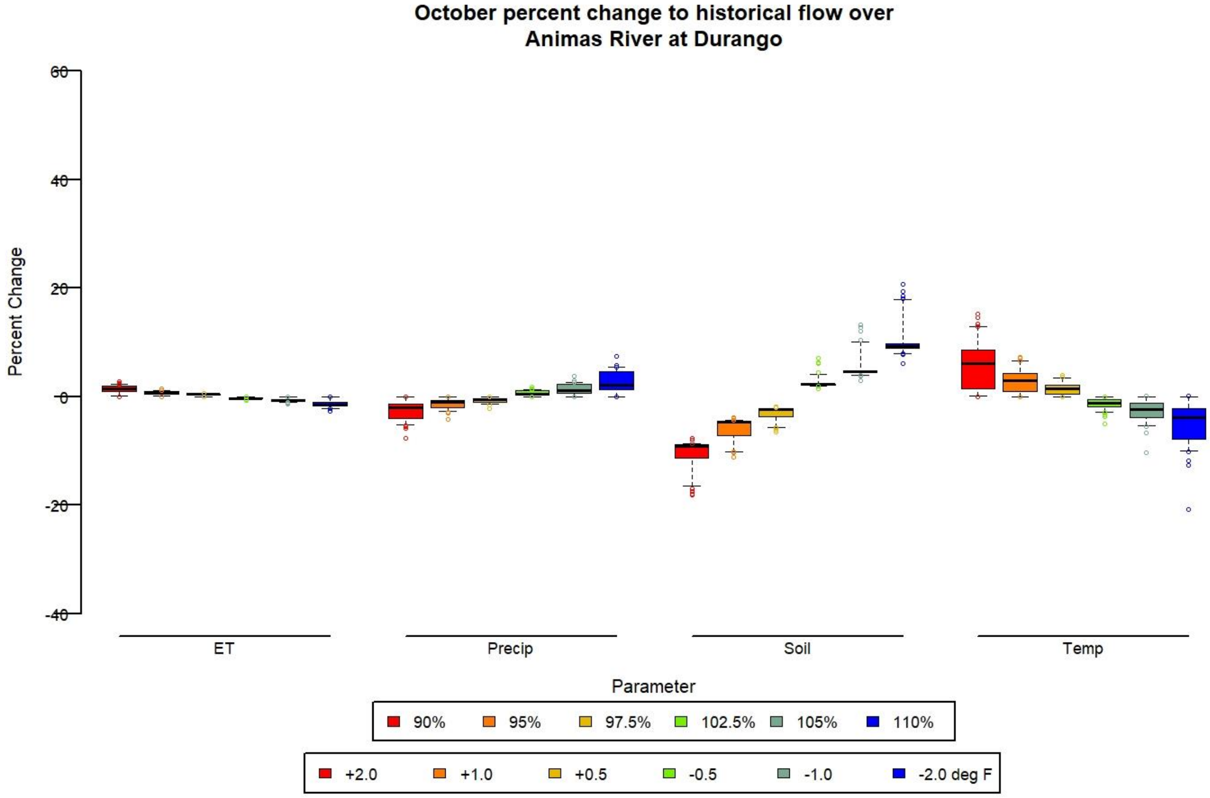
Year Type[9]	Perturbed Years[10]	Basins	Temp.	Precip.[11]	ET	Soil Moisture	Sensitivity Metrics
Dry Average Wet	Year #1 Year #2	DRGC2 ALEC2 RCYC2 ENMC2 WBRW4 GLDA3	± 0.5 °F ± 1.0 °F ± 2.0 °F	± 2.5% ± 5.0% ± 10.0 %	± 2.5% ± 5.0% ± 10.0 %	± 2.5% ± 5.0% ± 10.0 %	Apr-Jul runoff volume Oct-Sep runoff volume Oct-Dec runoff volume

Proposed Timeframe and Deliverables: The CBRFC estimates that Part 1 and Part 2 of this scope of work can be completed by August 2019, with summary presentations, an updated website, and a report to stakeholders of work performed over the past year to improve water supply forecasts available in the fall of 2019.

Estimated Cost: In-kind.

[9] The Oct-Sep runoff volume will be used to define the year type. Dry, wet, and normal years are to be determined.
[10] More perturbed years may be analyzed depending on preliminary trials
[11] Final percentage perturbations for Precip, ET, and Soil Moisture may change depending on preliminary trials

Appendix B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Percent Change
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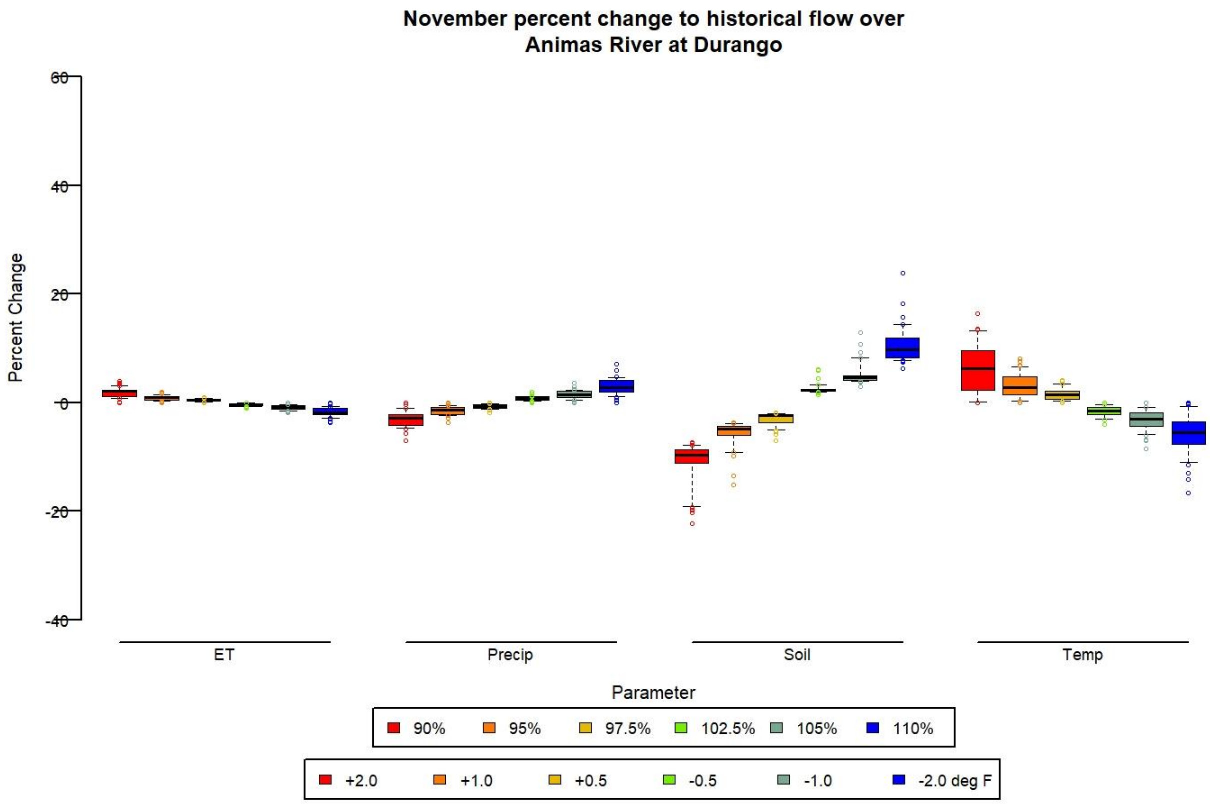
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Percent Change
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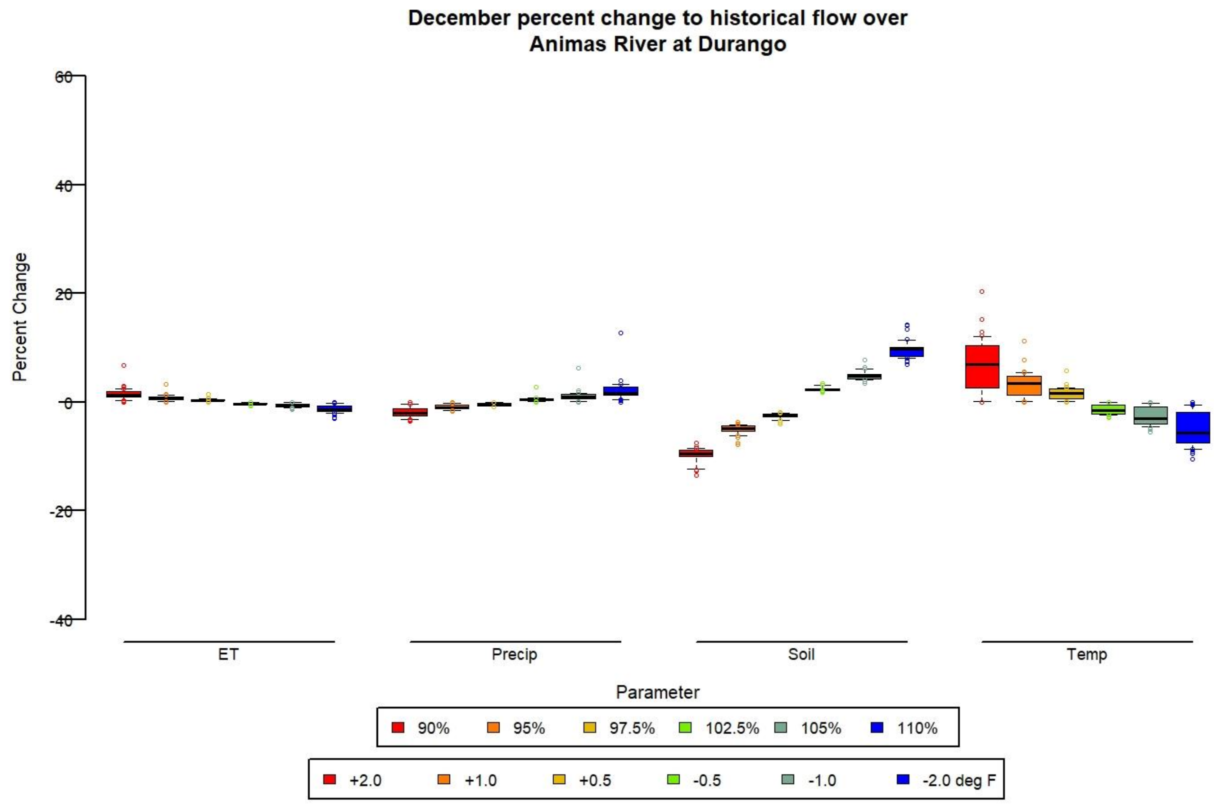
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Percent Change
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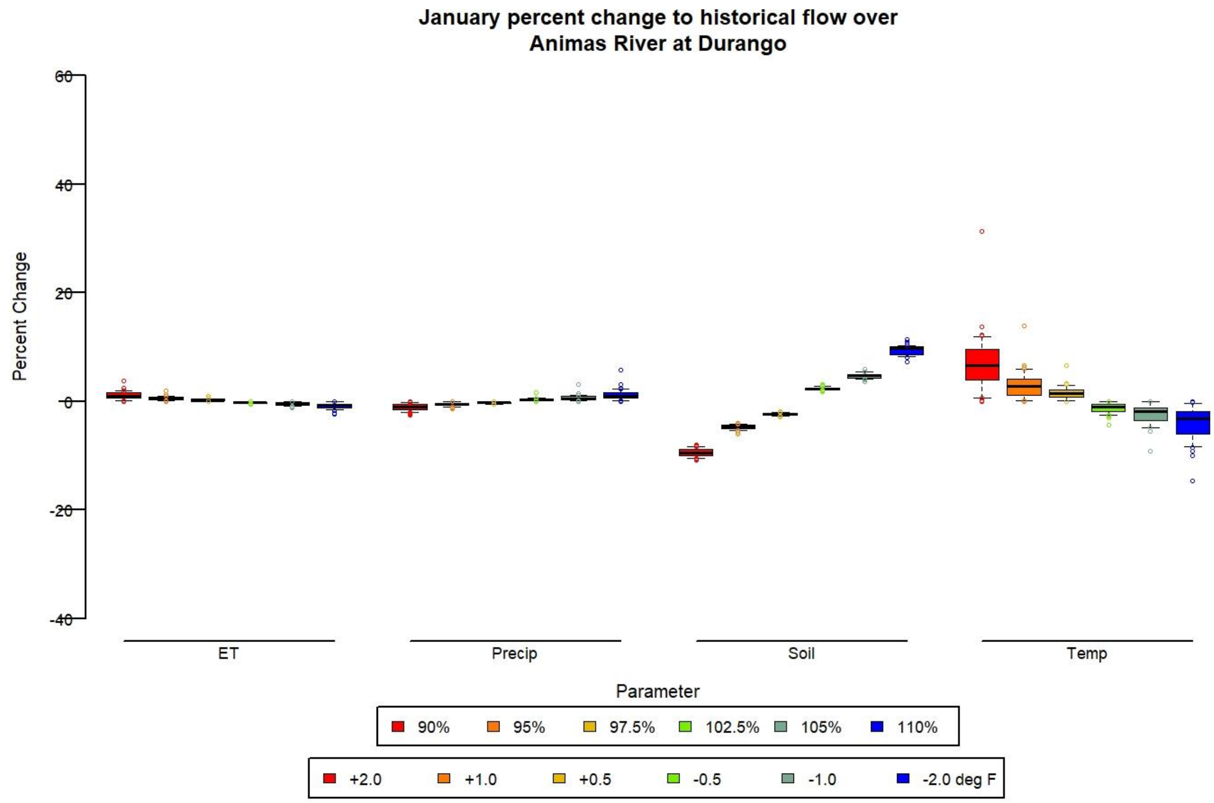
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Percent Change
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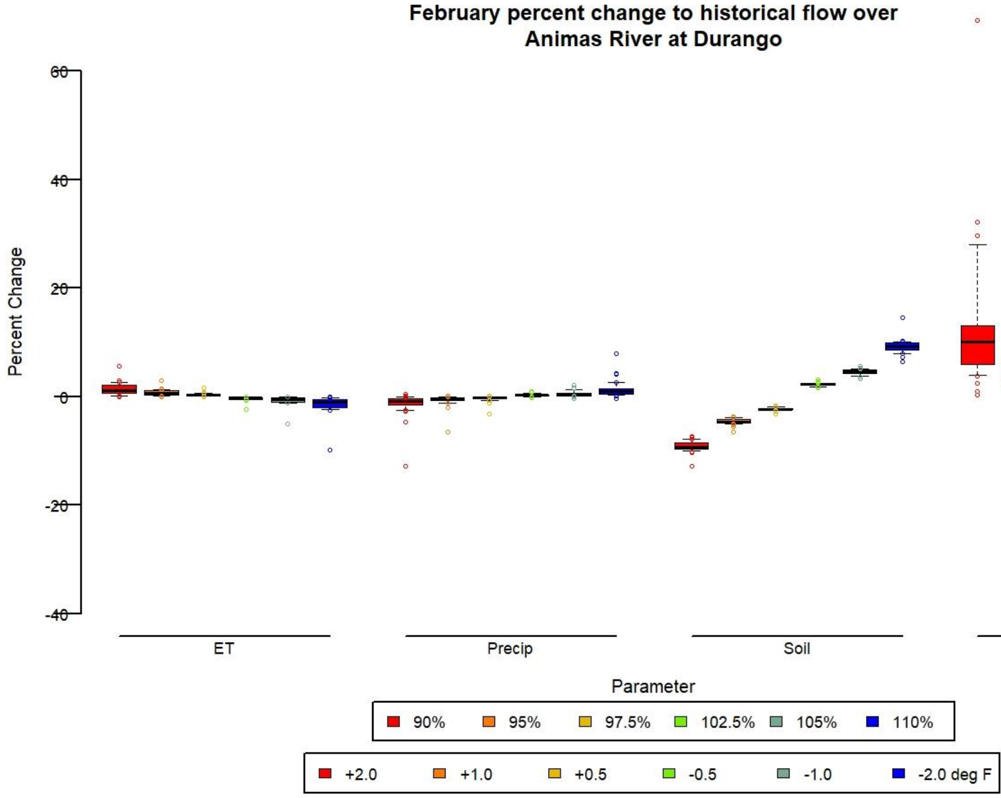
February percent change to historical flow over
Animas River at Durango
Percent Change
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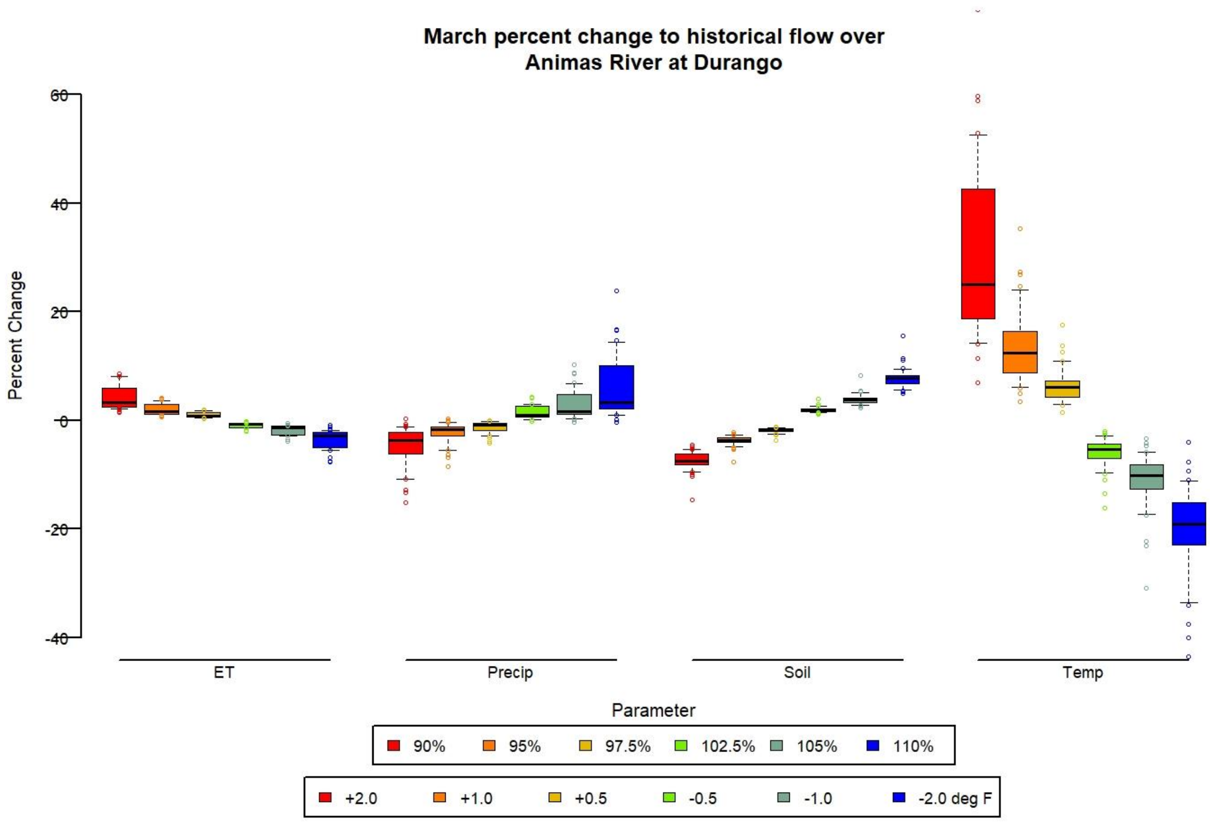
March percent change to historical flow over
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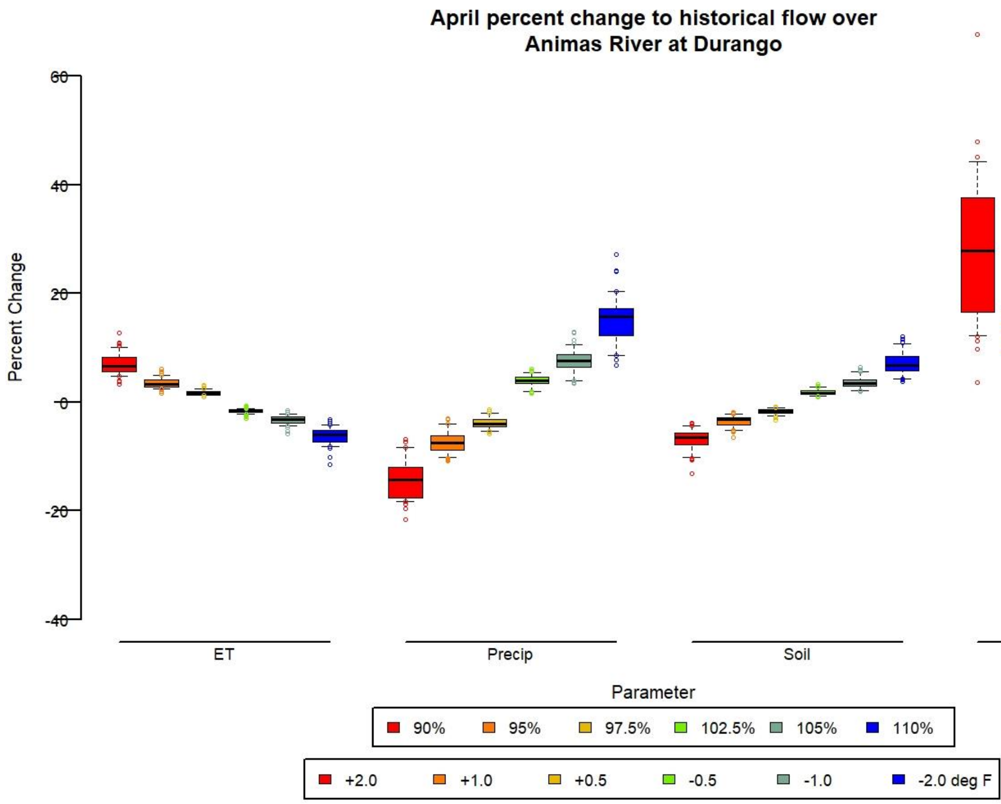
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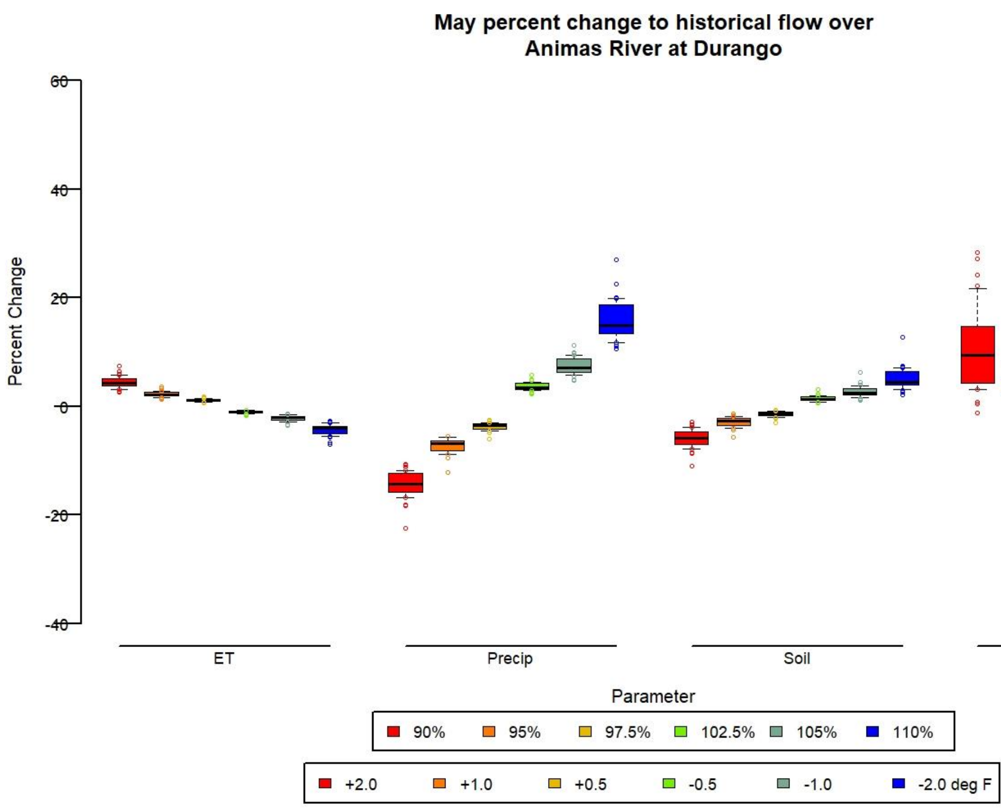
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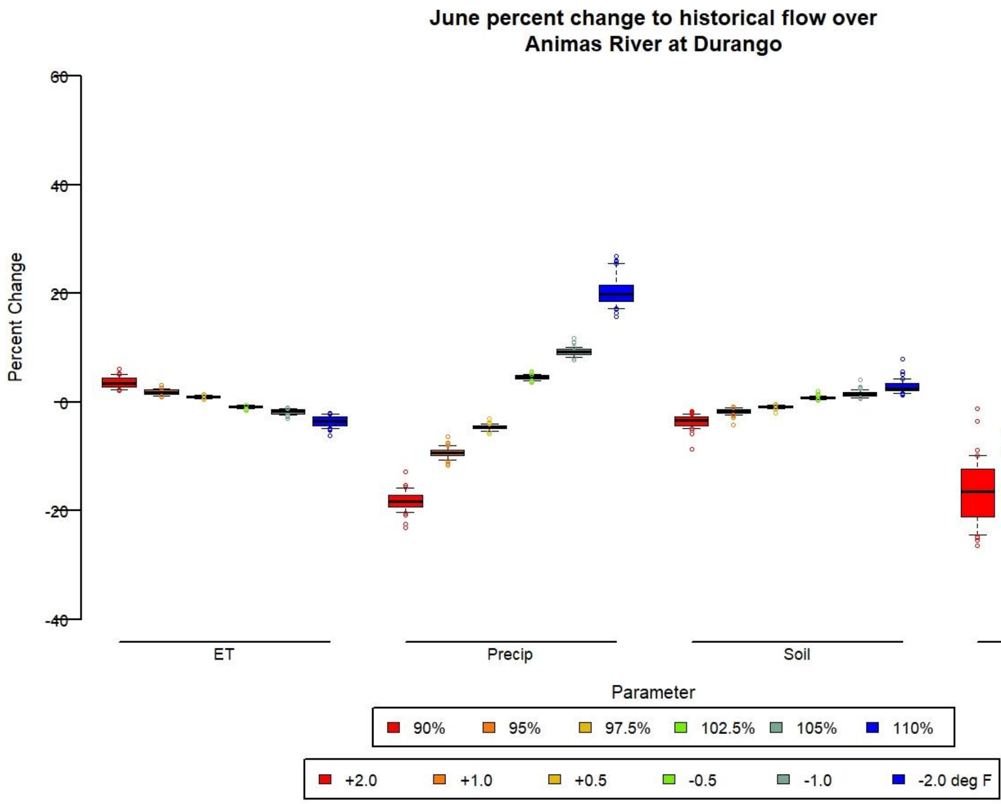
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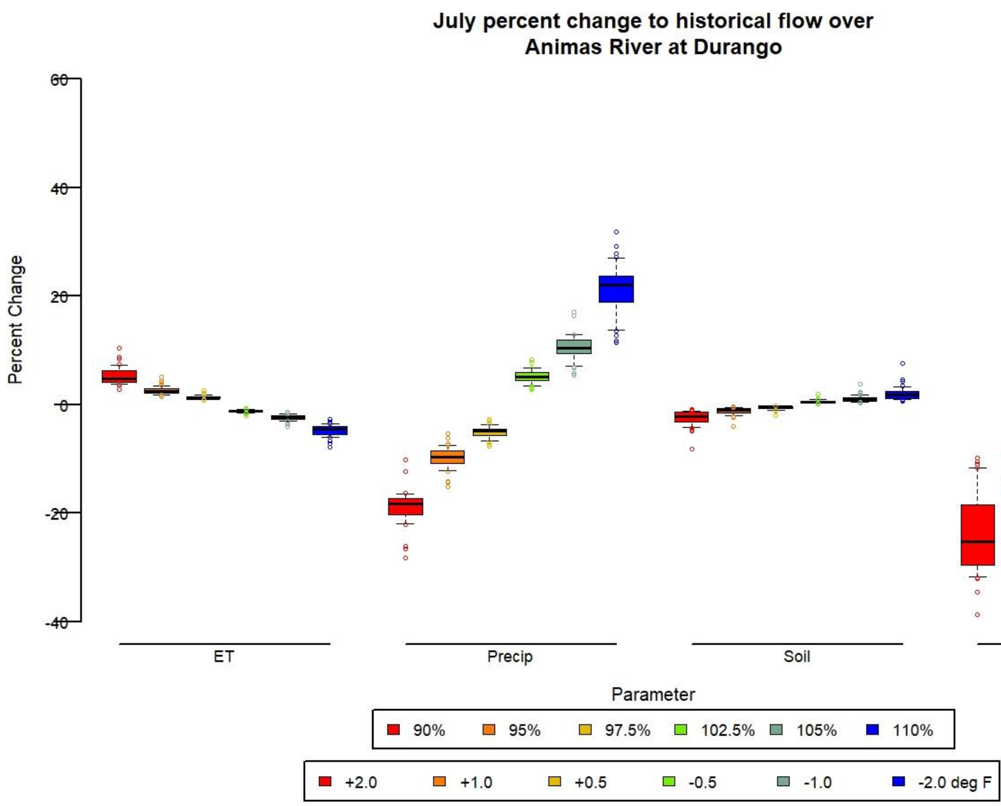
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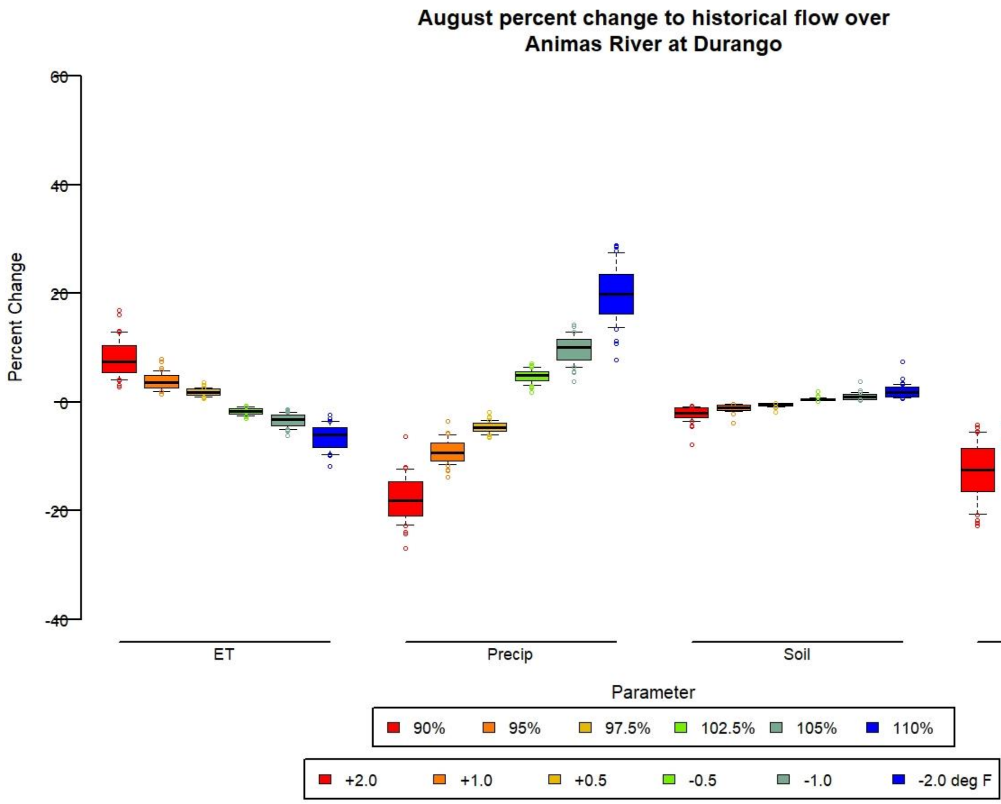
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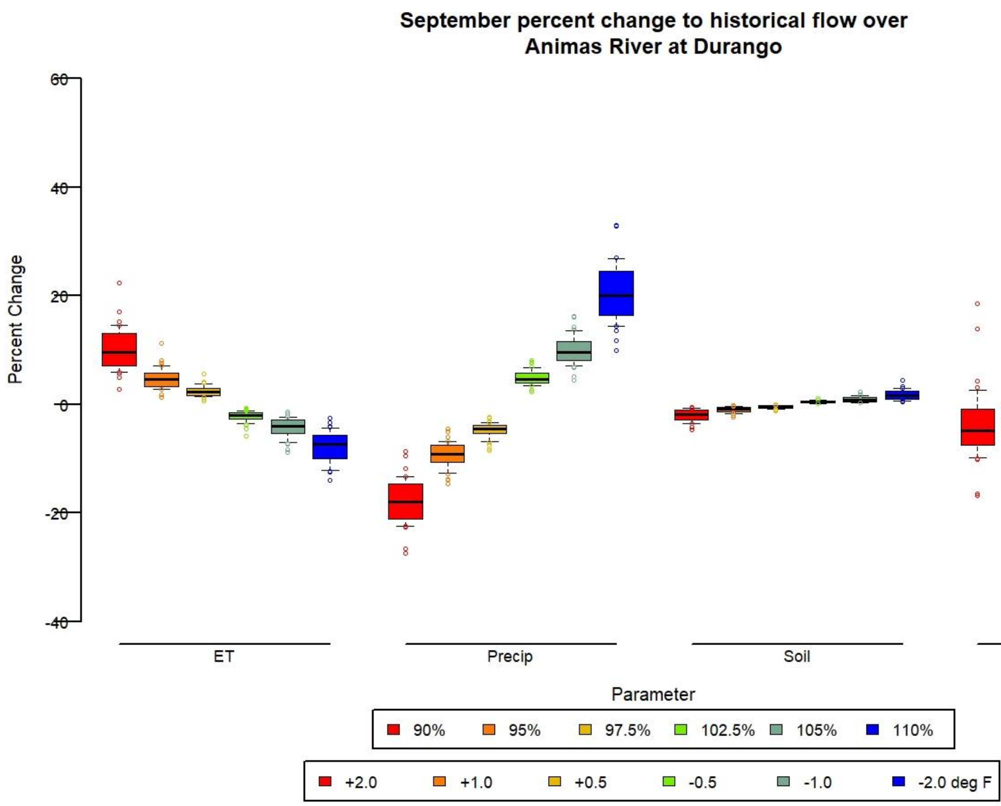
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