The Hydrology of the Colorado River Basin: Present Conditions and Future Trends

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1 Introduction

The Colorado River basin (CRB) is a critical resource to the Western United States. Ranging over seven states and providing water to numerous cities and municipalities outside of the basin, the river is a water source to over 25 million people and 3 million acres of irrigated agriculture (Bruce 2012). The CRB is typically spilt into two regions: the upper basin and the lower basin, with the dividing point at Lees Ferry. The large scale of the CRB produces many heterogeneous attributes. Elevation ranges from sea level at the Gulf of California to close to 4,400 m in the Rocky Mountain peaks of Colorado. Additionally, temperatures vary widely both spatially and seasonally. Thus, precipitation varies as well. The lower basin receives most of its rain in the summer as intense, short duration storms. Whereas in the upper basin, precipitation falls in the winter and spring as either rain or snow depending on elevation and temperature (Webb et al. 2004). These characteristics come together to create climate variability, with zones varying from desert to alpine forests (National Research Council et al. 2007).

The natural hydrologic conditions of the CRB produce peak discharges from May to July, supplied by snowmelt in upper basin headwaters (Webb et al. 1999). Into the summer, flows reach their minimum, except during the occasional flash flooding events that occur. However, much of the flow variability was eliminated with the completion of Glen Canyon Dam in 1964. With the reservoir being used for storage and hydropower, the discharges are now fairly uniform and past flooding peaks are no longer observed. The yearly peak flows now occur in either December/January or July/August, when power production is highest. Additionally, the magnitude of the peak has been cut by over one third of historical peak flows. While these flow changes have produced a variety of environmental changes and problems and are necessary to understand, the natural flows are advantageous when analyzing climate change impacts. The basin's response to alterations in climatic patterns can be understand by using the river's full natural flow (FNF), a value that can be calculated from reservoir inflows and outflow. Thus, for the remainder of this analysis, full natural flow of the Colorado River will be used.

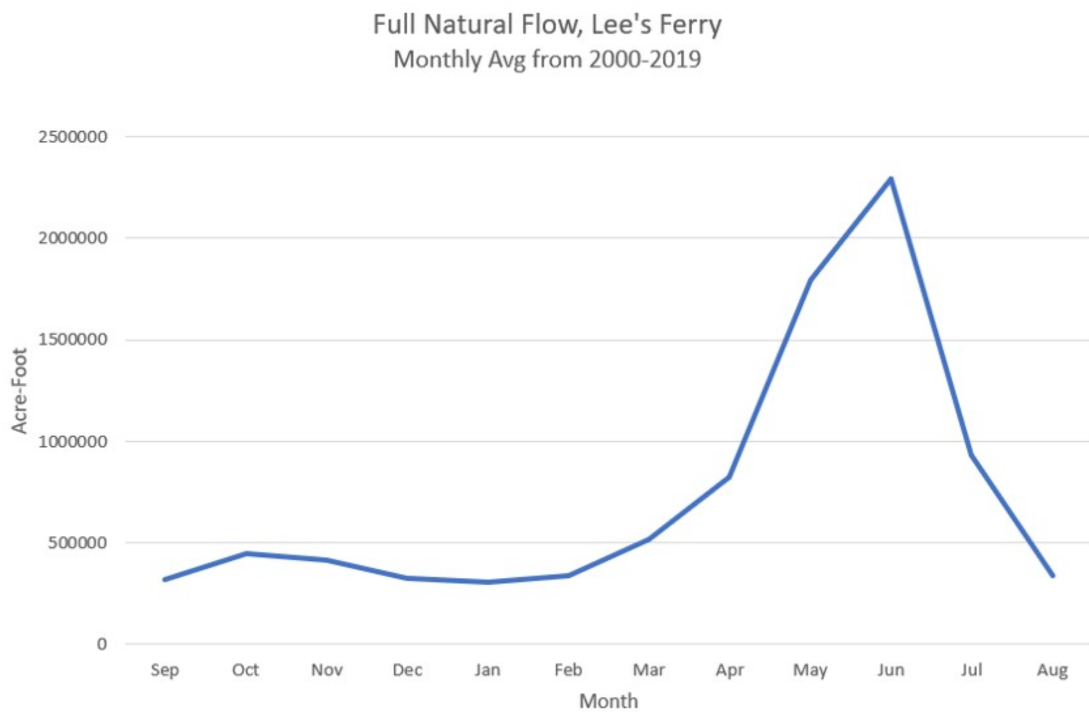

Figure 1: Monthly averaged full natural flow at Lee's Ferry (CLD Station, from 2000-2019 (California Data Exchange Center 2019).

2 Current Conditions and Atmospheric Phenomena

The monthly averaged FNF at Lee's Ferry from 2000 to 2019 can be seen in Figure 1. By looking at the averaged monthly values of two decades, a typical hydrograph for the river can be analyzed. In this hydrograph, only the upper basin is considered. The precipitation produced by summer flash floods is not taken into consideration, but over 70% of annual streamflow originates as snowpack in the upper elevation of the Rocky Mountains of Colorado, Utah, and Wyoming (Ficklin et al. 2013). Thus, the basin's hydrologic response can be understood from the upper basin precipitation patterns.

2.1 Current precipitation patterns

From Figure 1 and Figure 2, the CRB hydrologic response to the existing precipitation patterns can be analyzed. First considering rainfall (Figure 2 a, c, e, g), it is observed that precipitation is fairly uniform across seasons in the upper basin, contributing to the base flow of the Colorado River. The slight increase in upper basin rainfall in the spring (March, April, May) contributes to the rising limb of the hydrograph for that time period (Figure 1). Secondly, the contributions by snowfall can be considered, from Figure 2 (b, d, f, h). As expected, snow falls in the highest elevations of the Rocky Mountains during winter (December, January, February) and melts into the spring and summer. The spring snowmelt additionally contributes to the rising limb of the hydrograph. With higher temperatures, snowmelt begins and the soil is recharged, eventually entering the Colorado River and its tributaries (National Research Council et al. 2007). The peak flow that occurs in July is due to the snow being completely melted. By summer, the higher temperatures will melt all of the remaining snow cover and the saturated soil will allow the snowmelt to quickly enter the waterways.

The lower basin precipitation patterns differ significantly since with a lower elevation, snow does not occur. Thus, the system is rainfall driven instead of snow driven. In the fall and winter (Figure 2 a and c), a moderate amount of rainfall is expected. Into the spring (Figure 2 e), rainfall rates decrease. Finally, during the summer (Figure 2 g), intense, localized rainfall is observed. This is often in the form of convective thunderstorms (National Research Council et al. 2007). While this rate of rainfall is high, most of the water will not enter the river system due to the short duration of the storms and general dry conditions. As it rains, water will be lost to evapotranspiration, as it infiltrates in to the dry, warm soil. This rainfall is incredibly important to vegetation and small tributaries, but it will not contribute significantly to the mainstem and larger tributaries of the lower basin.

2.2 Atmospheric phenomena

The two precipitation regimes within the CRB are the winter snow season in the upper basin and the summer monsoon season in the lower basin (Webb et al. 2004). Beginning with the winter season, the atmospheric phenomena that produces precipitation are frontal systems coming from the Pacific (Webb et al. 2004). When the Rocky Mountains are encountered, the orographic effects cause moisture to be transported at high levels of the atmosphere, producing an increase in precipitation. The systems can either be warm or cold, depending on the air temperatures and where the frontal system originated. Cold fronts, typically originating in the Northern Pacific, bring cold air into the region. The precipitation enters the higher elevations of the CRB as snow and lower elevations as rain. Ultimately, cold fronts are responsible for building snowpack. Warm fronts on the other hand, originate in the tropical Pacific, bringing warmer air and moisture into the CRB. Precipitation will fall as rain at all elevations, as it is not cold enough to form snow. This warmer rain has the potential effect of melting snow, and typically produces flooding and high runoff events.

It is important to note that frontal systems are greatly influenced by global circulation patterns and the sea surface temperature of the Pacific Ocean. This has lead some researchers to investigate the links between global oscillation patterns and flooding within the CRB (Webb et al. 2004). Specifically, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have been considered. However, none of the results produced strong correlation between CRB flooding and either ENSO or PDO. Warm frontal systems common with El Niño occurrence, generally produced above average flooding for the CRB but not for all cases. Cold frontal systems common with La Niña, generally produced below average flooding for the CRB but again, this was not always the case. For PDO occurrence, direct effects were not found, but it is thought that the oscillation may influence atmospheric phenomena at a much longer time scale. In either case, additional research will need to be done to fully understand the effects of global oscillations on the CRB.

The summer monsoon season that is associated with high intensity, short duration thunderstorms is typically refered to as the North American Monsoon (National Research Council et al. 2007, Webb et al. 2004). Moisture is transported from the Gulf of Mexico, Gulf of California, and the subtropical Pacific at lower levels of the atmosphere. The intense land heating associated with the lower basin summers and up slope atmospheric flows interact with the moist air to produce

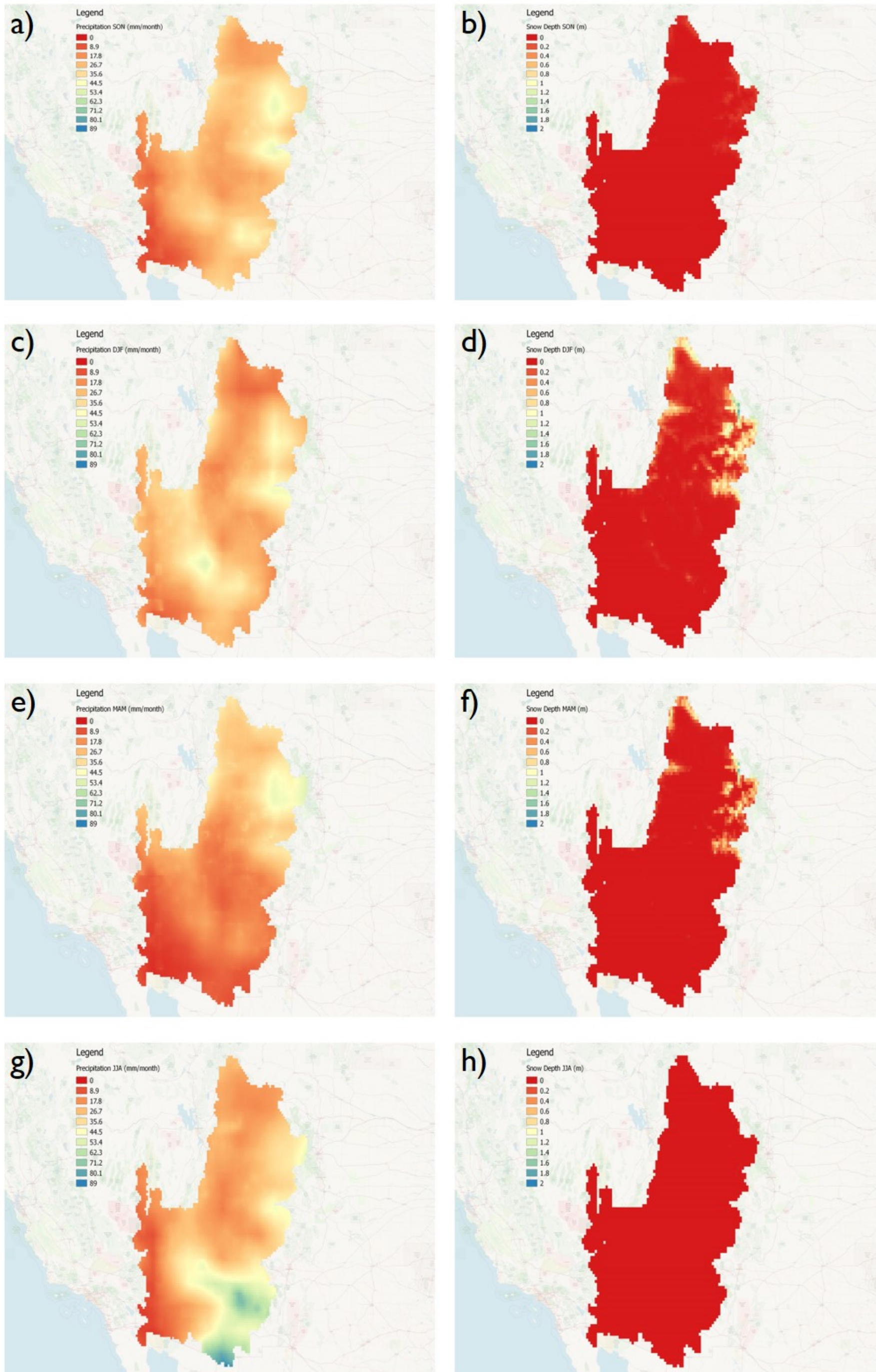

Figure 2: CRB seasonal averages from 2000-2019 of precipitation (mm/month) and snow depth (m). a) Seasonal Precipitation September-October-November. b) Seasonal snow depth September-October-November. c) Seasonal Precipitation December-January-February. d) Seasonal snow depth December-January-February. e) Seasonal Precipitation March-April-May. f) Seasonal snow depth March-April May. g) Seasonal Precipitation June-July-August. h) Seasonal snow depth June-July-August. Precipitation data provided by NASA IMERG (Huffman et al. 2014) and snow depth data provided by NASA NLDAS (NASA/GSFC/HSL & Mocko 2012).

convective thunderstorms as the moist air rises. As explained previously, flash floods may be produced but the effects are generally not seen on the larger stems of the river as the rain falls over a relatively small spatial scale with a high intensity and a short duration. The atmospheric phenomena that produce the hydrologic response within the CRB are important to understand, as the effects of climate change will be seen in the near future. It is expected that precipitation patterns may change, and understanding the underlying causes of precipitation is helpful to predict how the CRB hydrology will respond.

3 Future Conditions Under Climate Change

Over the past century, temperature data has exhibited consistent warming over the CRB (Dawadi & Ahmad 2012). Additionally, there is a general consensus that the Earth will experience warming of $2-6^{\circ}$ C by 2100 (Ficklin et al. 2013). This warming trend is expected to shift peak flows earlier in the year as snowpack begins to decline earlier into the winter and spring months (Dawadi & Ahmad 2012). This result may produce additional winter runoff, shortages in summer inflows and a potential for extreme events, such as flooding or drought, to increase in severity and frequency. Already changes in the storage of Lake Mead and Lake Powell have been seen due to flow changes and this trend is expected to only increase. While temperature trends are agreed upon, changes in precipitation patterns are associated to an important uncertainty. There is great debate over how precipitation will respond to a warmer temperature and ultimately alter the river's volume and timing. One theory indicates that the warmer atmosphere will increase the amount of rain compared to snow, decreasing snowpack and increasing melting rates (Ficklin et al. 2013). Additionally, the warmer temperatures may increase the rates of evapotranspiration, increasing the water losses from Lake Mead and Powell. However, this theory greatly depends on the assumptions and scale used in analysis. For example, at a subbasin scale, variations in land characteristics (elevation, soil, vegetation, etc.) will produce varied responses. The heterogeneity within the basin needs to be addressed before considering how the larger CRB will respond. The global climate model (GCM) and emission scenario used in the analysis will also alter results. Therefore, adding all these variables, only projections with high degrees of uncertainty can be generated using an ensemble of climate projections. As climate change effects start to be intensified, it is increasingly important for water managers to have an understanding of how streamflow may change and what uncertainties are involved. To further investigate how the CRB will respond to climate change, two research studies will be examined: Ficklin et al. (2013) and Dawadi & Ahmad (2012).

3.1 Ficklin et al. (2013)

In order to understand the CRB response to potential climate change scenarios, Ficklin et al. (2013) used the A2 emission scenario (IPCC 4^{th} Assessment), the average atmospheric conditions from an ensemble of 16 GCMs, and the Soil and Water Assessment Tool (SWAT) to compute the hydrologic response. They focused on the upper basin, since the majority of the water volumes in the CRB are originated in this area. The median results will be presented here but the authors also computed the first and third quartile responses to understand potential extreme conditions. To begin, temperature and precipitation changes were examined, as can be seen in 3. The temperature results indicate an uniform warming across the upper CRB of $4.7^{\circ}C$ by 2100; a result consistent with various studies

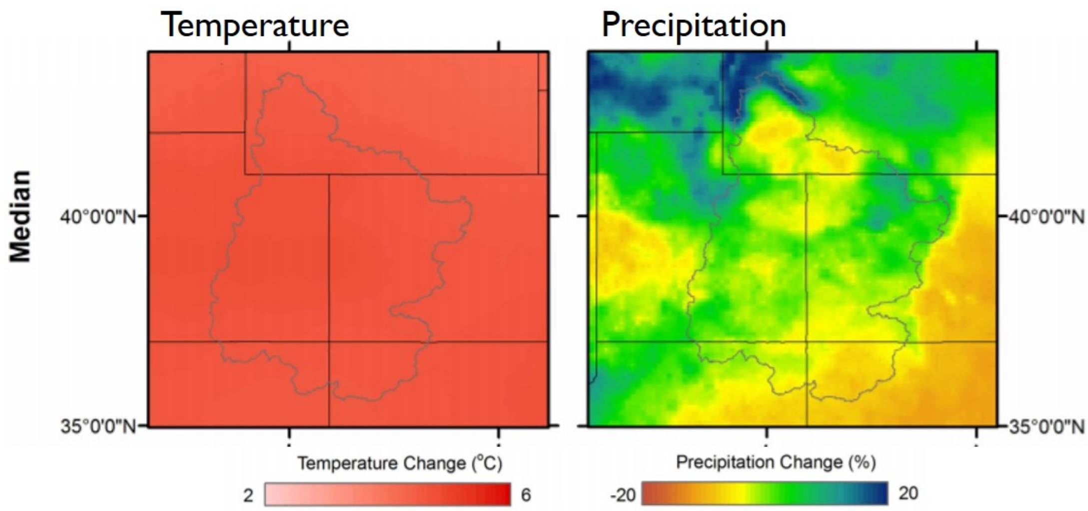

Figure 3: Median temperature and precipitation results from Ficklin et al. (2013). Percent changes were computed from the projection results and the 1960-1990 averages.

and the general scientific consensus. Precipitation, on the other hand, varied significantly in volume and distribution across the upper basin and across the various GCMs. The median results indicate smaller changes, less than 5%. The higher elevations exhibit precipitation increases, while the lower elevations exhibit precipitation losses. In the case of precipitation, the first and third quartile responses are significantly different. The first quartile exhibits extreme decreases in precipitation, specifically in the lower elevations, of over 15%. The third quartile, however, exhibits extreme increases, specifically in the upper elevations, of over 12%. The variability in precipitation change makes it difficult to predict how the entire basin will respond hydrologically, and corresponds to the expected increase in extremes associated to climate change.

To understand how the upper basin hydrologic response will be altered, the important tributaries are modeled individually before contributing to the mainstem of the river, to capture the heterogeneity of land conditions and precipitation changes. As can be seen in Figure 5, the volume and timing of streamflow will change. First considering volume at Lee's Ferry, streamflow is projected to decrease by 19% in 2050 and 23% in 2080, compared to historical streamflow volumes. Similarly to precipitation, streamflow volume also contained significant differences between the first and third quartiles. The first quartile showed large decreases (44% in 2050 and 50% in 2080) while the third quartile showed an increase in volume (15% in 2050 and in 2080). Now considering hydrograph timing, in the upper most tributaries (Fontenelle Creek and the Green River in Wyoming) the peak flow shifts one to two months earlier in the year and there is a slight increase in flow volume. This is likely due to the earlier snowmelt associated with warmer temperature in the highest elevations. Into the lower tributaries and mainstem of the river, streamflow volume is expected to decrease with a shift of peak flow earlier by one to two months, as well. This is likely due to the decreases in precipitation and the shift of the upper tributary peak flows. The seasonality of streamflow can also be assessed. Beginning in the winter, streamflow may increase slightly compared to historical flows. This may be due to precipitation falling as rain with warmer temperature instead of snow, increasing winter flows but decreasing snowpack. Into the spring, as explained previously, peak

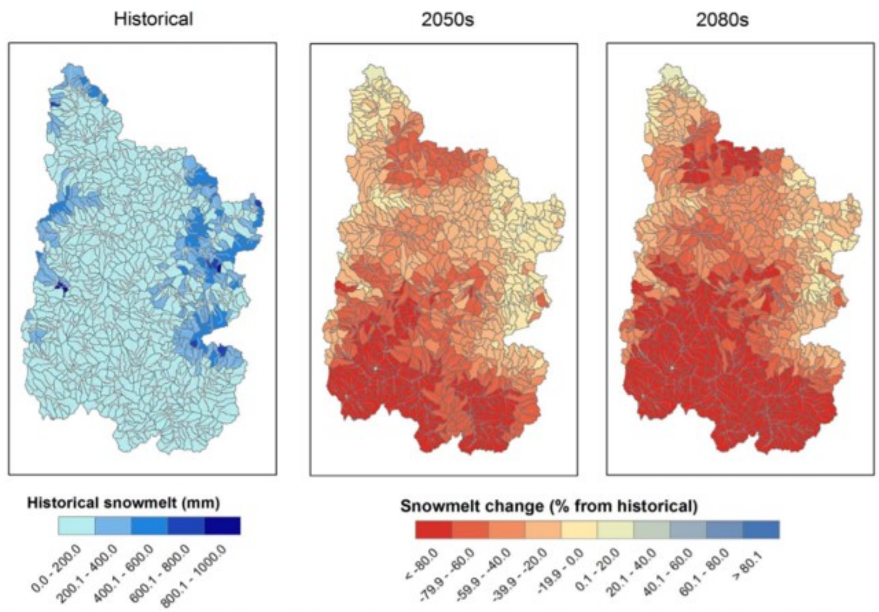

Figure 4: Snowmelt changes from Ficklin et al. (2013) compared to historical values. Across the upper basin, snowmelt is expected to decrease.

flows are decreasing with the loss of snowpack. The summer and fall are expected to exhibit significant declines in most subbasins. This is especially important as flows are typically low and a loss of water will greatly impact ecosystems. Again, it is important to note that the results vary widely depending on the GCM used. Using the ensemble average of numerous GCMs, however, will give a general idea of how the upper CRB may respond.

As can be seen in the expected streamflow changes, snowpack and snowmelt are critical to basin's hydrologic response. Figure 4 shows how snowmelt is projected to change into 2050 and 2080. Focusing on the higher elevations where snowpack is important, snowmelt is expected to decrease into the 2050s and continue into the 2080s across the upper basin. This will greatly affect streamflow peak timing and volume. Additionally, this will affect the timing of soil saturation. Historically, the soil would become saturated in May, with contributions from snowmelt infiltrating and precipitation. In the future, with snowmelt occuring earlier and reduced precipitation, the soil may become saturated as early as April. This will likely result in drier soil into the summer and fall when water demands are high from both vegetation and human demand. The combination of warmer temperatures, less snowpack, and earlier and smaller streamflows will be key interaction to understand for water managers. Into the 2080s, the lower regions of the CRB will likely become more arid and future changes to basin hydrology, such as increased groundwater pumping, will exacerbate these effects as the system shifts from being snowmelt driven to relying on subsurface and surface flows to maintain streamflow into the warmer months.

3.2 Dawadi & Ahmad (2012)

Similarly to Ficklin et al. (2013), Dawadi & Ahmad (2012) studied the hydrologic response of the CRB using the ensemble average of 16 GCMs. This study differed, however, by analyzing three emissions scenarios from 1970 to 2035. The emissions scenarios they considered were A1b,

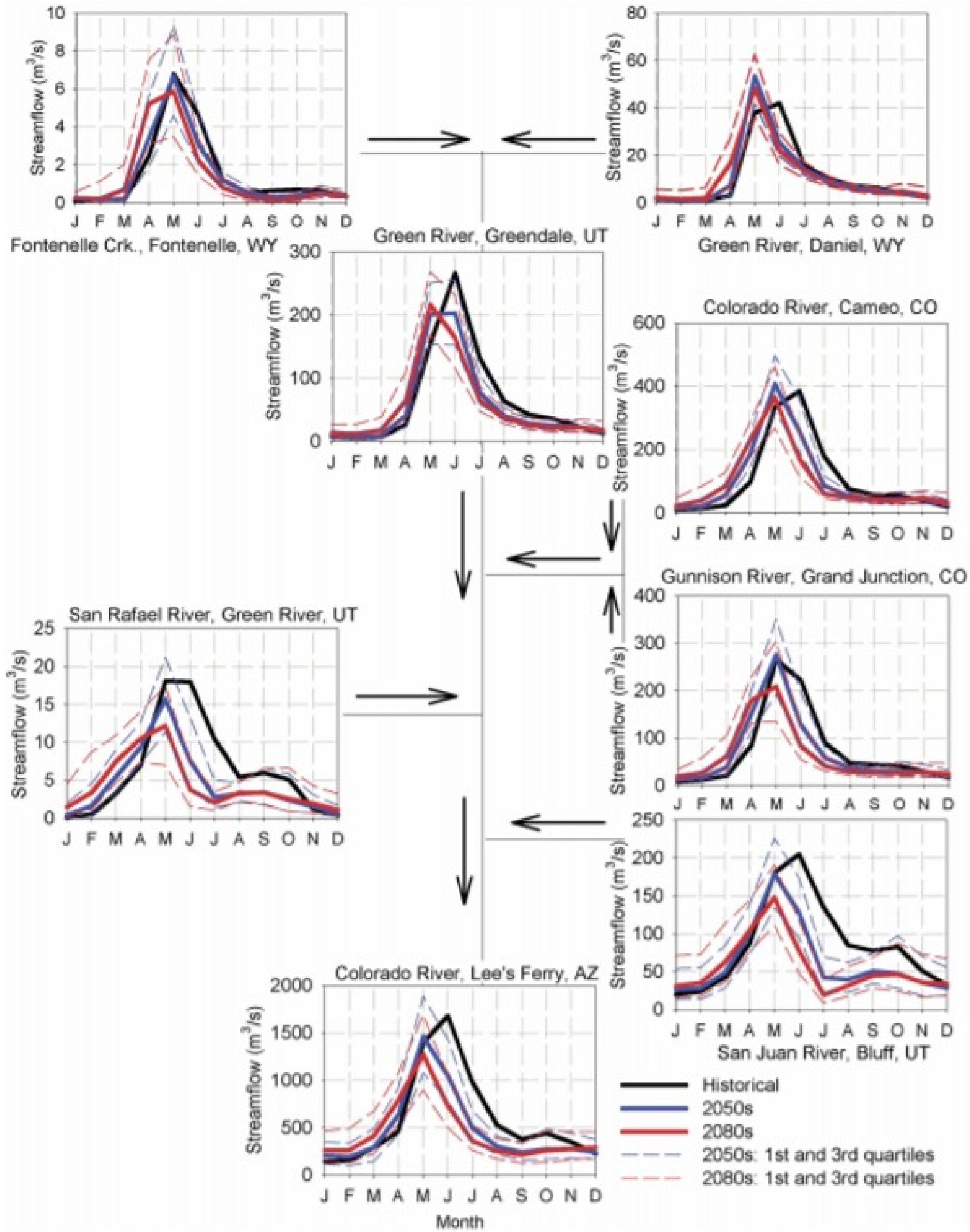

Figure 5: Monthly streamflow hydrograph changes from Ficklin et al. (2013). Historical hydrographs are compared to project hydrographs of 2050 and 2080. Important tributaries are modeled to understand the overall basin response at Lee's Ferry.

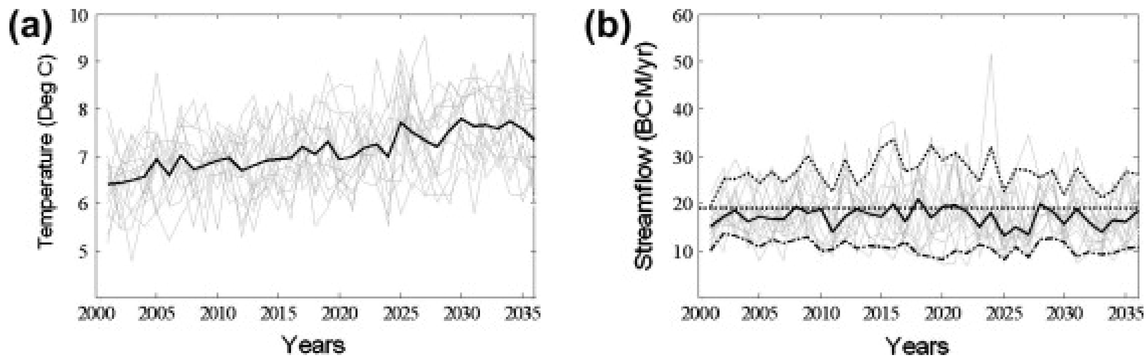

Figure 6: Project trends produced by Dawadi & Ahmad (2012) for the A1b emissions scenario. A) Ensemble average temperature projections. B) Ensemble average streamflow projections.

A2, and B1 (IPCC 4^{th} Assessment); representing the middle, higher, and lower emissions path respectively. In the analysis done, the authors computed Lee's Ferry streamflow, Lake Mead levels, probability of curtailments and risk evaluation to the lower basin, and future temperature and precipitation trends of individual GCM results. In general, results suggest similar projected trends as the Ficklin et al. (2013) study.

Projected temperature and streamflow trends can be seen in Figure 6. The ensemble temperature projections show an increasing trend into the future and a majority of the individual GCMs support this. Precipitation trends were computed as well and on average there was not a large change to the historic conditions. Again, this is greatly dependent on the GCM used and there was significant differences between independent results. With temperatures predicted to increase and precipitation predicted to remain similar, streamflow changes can be deducted. In Figure 6 B, it is observed that projected streamflow will be reduced to below the historical streamflow averages. This will have an enormous impact on the current system and future water management decisions need to plan for this potential future. If streamflow is reduced, reservoir storage will fall, decreasing hydropower production and reservoir outflows. If reservoir outflows are curtailed significantly, the Colorado River compact may be violated if lower basin states do not receive their full allocation. However, streamflow is difficult to be accurately predicted due to the nonlinear nature of the interactions with temperature and precipitation. For example, even with a slight increase in precipitation and an increase in temperature, evapotranspiration may increase enough to ultimately decrease streamflow. The CRB is a complex and interconnected system and it is difficult to predict how exactly the hydrology will respond to changing atmospheric conditions, but using ensemble averages it is possible to predict an average response the system may exhibit.

4 Conclusions

The CRB is a vital supply to a large portion of the American West. Numerous municipalities, industry, and agriculture depend on the water supplied through the CRB. As a snowmelt driven system, peak flows currently occur from May to June when temperatures are warming and melting the snowpack. Moisture is brought into the CRB by winter frontal systems, building snowpack in higher elevations or providing rain for lower elevations, or through summer monsoons, bringing brief flash flooding into the lower basin. This current precipitation pattern and resulting hydrologic response is likely to change, however, as climate change impacts begin to be seen. There is general agreement that the CRB will experience uniform warming, though there is still debates about how precipitation will be altered. However, various studies have shown that water managers should plan for at least a slightly drier system and a shift in streamflow characteristics. Warmer temperatures are likely to decrease snowpack, especially at mid-elevations and high elevations. This will cause snowmelt peaks, and streamflow peaks, to occur earlier in the year as less snow will melt faster, due to a loss in snow pack and additional temperature increases. An earlier peak flow will be problematic during the warmer summer months when vegetation demand and human demand are already high. Coupling this with a decrease in water availability is likely to increase tensions between water users. Additionally, changes in water use, such as with additional groundwater pumping, will alter the CRB hydrologic responses as the system begins to rely heavily on surface and subsurface flows instead of snowmelt. As water managers begin to plan future water uses, they should keep in mind that subbasin responses will vary over the CRB. It may be more productive to manage the basin at the subbasin scale where heterogeneity of the system can be considered, instead of at the scale of the CRB entirely. As we move further into the 21st century, demand requirements between human demand and ecological necessities will likely become strained as the CRB begins to exhibit warmer and drier conditions.

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