Threats to a Colorado river provisioning basin under coupled future climate and societal scenarios

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Abstract

Clean, reliable supplies of water are critical to the sustainability and resilience of communities, including water needed for energy and food production, industry, drinking water, and other human and ecological needs. However, water infrastructure and management in the United States are largely optimized for historic conditions—designed and operated to respond to social needs, and past mean and extreme streamflow, which may no longer apply in the future. Temperature, precipitation, ecosystem dynamics, energy and food production, and social systems are all experiencing changes, which cumulatively affect the security of water supply. Here, we examine the impact of these changes in a provisioning basin in the arid Southwest, the San Juan River, which supplies water, food, and energy to the Colorado River and the Rio Grande. Our analysis applies a multi-model framework to examine future climate and water use scenarios. Results demonstrate that the San Juan River basin could experience significant disruptions to water deliveries (−12% to −48% for the drier models) and shortages that exceed manageable thresholds (53% to 73% of water in shorted years), potentially affecting both the local basin as well as other regions that receive water and energy from the San Juan. While water stress metrics vary across the scenarios, results indicate the need for government, industry, and communities to consider options for adapting to water supply shifts. These results raise important questions regarding the resilience of water resources in basins across the West under future scenarios and implications for energy, food, and other water supply needs.

1. Introduction

The management and operation of water resources in the US is largely optimized for historic mean supplies and is designed to be resilient to past natural extremes and social needs. Future mean and extreme behaviour of natural systems is projected to be significantly different from past observations, as noted by numerous research studies [1–5], with significant implications for water security. However, a major gap exists in our understanding of the intersection between changing natural systems and societal demands arising from rapidly growing and changing populations [6], technology development [7], and expanding environmental needs [8], which may rival or exceed the impacts of climate change alone [9, 10]. Addressing this knowledge gap and planning for a more resilient future is therefore one of the greatest challenges in 21st century water resource management, requiring interdisciplinary approaches that apply process- and information-based models to understand complex and geographically extensive water resource challenges.
Projected changes to natural systems, particularly from climate, include shifts in temperature distributions, changes in the timing of streamflow extremes, and intensifying drought [11, 12]. All of these impacts have significant consequences for large, managed river systems such as the Colorado River Basin (CRB). For instance, streamflow in the CRB headwaters is projected to decrease by up to 40% by some Earth System Models [13]. Changes such as these have cascading impacts resulting in ecosystem disturbances [14], impaired water quality [15], reduced agricultural productivity, vegetation mortality [16], wildfires [17, 18], and infestations of insects and pathogens [19, 20].

Societal changes resulting from increasing urbanization and demographic and economic change are also placing increasing pressures on provisioning basins that sustain both local and regional municipal, commercial, agricultural and industrial centers [21]. Such basin are typically headwater systems with limited population density, but which export much of their local production of food, energy and water to more urban areas [22, 23], acting as provisioning basins to these regions. Changing climatic and societal conditions could threaten the resilience of coupled food-energy-water systems in such provisioning basins [21, 24, 25], with far reaching, i.e. local and non-local, implications.

This study analyzes the challenges posed by changing climatic conditions and water usages on a major provisioning basin in the CRB, the San Juan River (SJR), which is a critical source of water, energy, and food for tens of millions of people in neighboring states. We chose to examine the CRB because it is one of the most important rivers in the US, contributing an estimated 1.4 trillion to the US economy [26], with the SJR being one of the CRB’s largest tributaries (supplying ∼15% of incoming water) and highly sensitive to climate impacts owing to its high elevation and snow-dominant headwaters. To carry out this study, we have taken an interdisciplinary approach to analyze potential changes in the system and have included consideration of a mosaic of natural and human factors that could impact water security outcomes including: water management agencies, regulators, operators, water users, contractors, and ecosystems components that depend upon SJR water.

The primary goals of this study are to:

1. Demonstrate a coupled human- natural-science and engineered systems model framework, formulated at the basin scale, including consideration of energy, food, and water features (only a handful of studies have undertaken this task at the asset or basin scale, owing to the challenges of coupling models, and understanding the complexities of river operations and water rights).

2. Examine how physical and social changes in a major provisioning basin in the West could affect water and thus energy and food security in the region, and how water resource management strategies of the past may feedback on these affects.

3. Consider the combined impacts of climate, social, and legal factors, and the complexity and the scope of these inter-related variables, which are projected to be significantly different in the future, both in terms of means and extremes, from historical conditions.

4. Explore variability in results across multiple scenarios- both climate and water metrics, contextualizing implications of this variability for decision making.

Achieving these goals will aid in identifying potential future impacts to the SJR due to changing climate and societal conditions. From here we wish to take the analysis an additional step by considering the implications of such stresses on water management; specifically:

- Is the current management structure flexible enough to accommodate projected changes?
- Can current management policies, practices, and infrastructure effectively meet current needs and respond to change if the basin’s water rights are fully utilized?
- How can water management policies and practices in the basin be adapted to better meet water needs in the future and minimize shortage and operational disruptions?
- What types of additional analysis (modelling efforts, case study analysis) are needed to inform changing or altering current water management practices?, and,
- How will the shortages of water, and resulting decreases in energy production that occur within the San Juan Basin reverberate throughout the portions of the southwestern US that receive water and energy from this provisioning basins.
These questions must be addressed for SJR and similar provisioning basins across the Western US to continue to operate sustainably in the future.

The paper begins with a description of the study site, and methods, which explains water use and operations scenarios in the SJR and modelling methods used in the study. Results are presented with an analysis of the implications for the SJR basin and beyond. Finally, the broader impacts of this work are presented with a discussion of potential mechanisms for decision makers and water resource managers to consider in mitigating impacts to water and energy systems.

2. San Juan river basin

2.1. Study site

The SJR is an important headwater tributary in the CRB, located near the intersection of Colorado, New Mexico, Arizona and Utah, known as the Four Corners region (figure 1). Originating as snowmelt in the San Juan Mountains (part of the southern Rocky Mountains) of Colorado, the SJR flows 616 km through northern New Mexico and southeastern Utah to join the Colorado River at Glen Canyon in Lake Powell. The basin spans 65,000 km² and contributes between 11 and 20% (15% on average) to the flow volume of the Upper CRB at Lees Ferry; after the Green River, SJR closely follows the Gunnison River in terms of flow contributions to the Upper CRB. Monthly average temperatures in the SJR range from −2.5 °C in January to +22.7 °C in July [based on 2001–2010 gridded observations of climate, [27]]. Precipitation follows a bi-modal pattern, with the highest precipitation falling during the summer months when monsoonal weather arrives from the Gulf of Mexico and Gulf of California and delivers precipitation in the form of short-duration, intense rainfall events. Winter also has high precipitation, largely falling as snow in the upper headwaters of the SJR. Freshet, or melt out of snow, has historically occurred in the SJR basin in May and June.

2.2. Water use, operations and administration

Like many river systems in the West, management and operations of the SJR basin are governed by a complex set of jurisdictions, laws, infrastructure, and water allocation regimes which intersect with changes in natural
For the purposes of this study, water use is defined as water in the SJR system that is depleted due to consumption, or loss due to atmospheric conditions. Figure 1 shows a map of the SJR water systems, and figure 2 shows water use and operations under current and future scenarios. Diversions are structures used to transport, carry or channel water. Water deliveries refer to water that is moved throughout the basin or interbasin transfers (i.e. SJR basin to the Rio Grande) to meet required or agreed to allocations.

Among the most significant water users in the SJR basin is the Navajo Nation, which is the largest tribal nation in the US, covering 71,000 km² of land in New Mexico, Arizona, and Utah. After years of litigation and negotiation, the Navajo Nation entered into a settlement agreement with the US government and State of New Mexico regarding the tribe’s water rights in the basin in 2005, which was signed into federal law in 2009. The Navajo Nation’s allocation of water in the basin is currently being utilized (current use) largely for agriculture in the Navajo Indian Irrigation Project, Environmental Flows = natural flow reserved for environmental, Simulated Flows = simulated VIC natural flow available to water users.

The largest non-tribal water use in the SJR basin is the irrigated agricultural sector (figure 2). The next largest non-tribal water use is for electric power generation at two coal-fired power plants operating in the basin. The Four Corners Generating Station is a coal-fired power plant located near Farmington and run by the Arizona Public Service Company, to largely supply the electricity needs of the Phoenix metropolitan area. The San Juan Generating Station is a coal-fired plant operated by the Public Service Company of New Mexico (PNM), and provides approximately one-third of the power supplied to the state of New Mexico. Both power plants utilize water from the SJR basin for cooling. Additionally, several municipalities (including the cities of Farmington and Durango, and smaller towns, such as Pagosa Springs, Bloomfield, Waterflow and Shiprock), and self-supplied industries also depend on water supplies from the river (figures 1, 2). SJR water is also transported via tunnel through the continental divide into the Rio Grande basin via the US Bureau of Reclamation’s (Reclamation) San Juan-Chama Project. Water that is supplied by the San Juan-Chama Project is utilized by the cities of Albuquerque and Santa Fe, NM, numerous tribes and Pueblos, agricultural users, and to meet endangered species requirements in the Rio Grande.

The Navajo Reservoir, which is a large earth- and rock-filled dam, is the primary water management feature in the SJR basin, aside from the infrastructure associated with the San Juan-Chama Project. Navajo Reservoir is operated to meet storage and irrigation needs in the SJR basin and well as maintaining target base flows (500 cfs) for critical fish habitat, as set forth by the San Juan River Recovery Implementation Program (SJRIP).
As discussed above, a portion of New Mexico’s allocation of CRB water (pursuant to the Colorado River Compact), is delivered via interbasin transfer to the Rio Grande by the San Juan–Chama Project. Water is transported via the Azotea tunnel into Willow Creek, which then carries the water to Heron Reservoir and on to the Rio Chama, which is the largest tributary to the Rio Grande in New Mexico. Reclamation allocates water from Heron Reservoir to San Juan–Chama Project contractors at the beginning of each year. If storage in Heron Reservoir is insufficient to meet contracted allocations, a shortage is declared and contractors share proportionally in the deficit.

In New Mexico, the SJR basin has not been fully adjudicated to determine the priorities for water allocation under state law. To address the lack of adjudication, ten of the largest water users have cooperated to develop a shortage sharing agreement for the purposes of keeping Navajo Reservoir from drawing down the reservoir pool below 5990 ft elevation (which equals 661,800 AF), the elevation required for NIIP diversions. To manage the shortage sharing agreement, Reclamation’s develops operational plans twice monthly, based on a range of inflow forecasts provided by the Colorado River Basin Forecast Center (CBRFC). Further details of water use and operations, including the Navajo Nation settlement agreement, are provided in the Supplemental Information (SI).

3. Methods

In this study, models of the physical and engineered system are coupled to explore potential impacts of climate and water use change at the individual asset level (e.g., power plant, irrigation ditch, municipality). Historical climate along with six different future climate projections (including associated vegetation change) exogenously force the modelling along with two alternative water use regimes. Climate impacts on tributary inflows are simulated using the Variable Infiltration Capacity (VIC) surface hydrology model. In turn, VIC-calculated flows inform the river and reservoir routing model (RiverWare™) developed for the SJR and San Juan–Chama project. Impacts are quantified with three metrics specific to the SJR basin, Navajo Reservoir Storage, SJR Water Deliveries (shortages as dictated by the shortage sharing agreement), and Instream Flows, plus two additional metrics tracking deliveries outside the SJR basin, San Juan–Chama and Colorado Basin deliveries.

3.1. Model simulations of the climate and water systems

In this study, a total of nineteen simulations analysing various climatic, hydrologic, vegetation, and water management factors were performed. Specifically, four scenarios were modelled to examine climate disturbances and water supply outcomes as follows:

- Historical climate conditions with current water uses, which we term Historical (1 simulation),
- Historical climate conditions with full utilization of existing water rights (once full build–out of NIIP and the Navajo-Gallup Pipeline are completed), termed Full Use (6 simulations),
- Future climate and vegetation change with current water use, termed Future Climate (6 simulations), and,
- Future climate and vegetation change with full utilization of water rights, termed Future Climate and Full Use (6 simulations).

Simulations were run on a daily timestep from 1950–2099. For purposes of analysis, Historical climate conditions considered the period from 1970–1999 (1980–2009 for Heron Reservoir) and Future Climate considered the years 2070–2099.

3.2. Models and data

To examine the impacts of climate and landscape change in the SJR basin, we used the Variable Infiltration Capacity (VIC) hydrologic model (version 4.2) to simulate natural streamflow for the CRB [14]. VIC was newly calibrated for the entire CRB to develop revised parameters for soils, vegetation, elevation bands to better capture flow within the sub-watersheds of the basin, under recently released historical climate data. SJR basin upstream of Bluff, UT using Reclamation’s naturalized flow dataset [28]. We estimated climate-driven vegetation changes within the SJR basin using vegetation data from historical remote sensing [29]. To understand vegetation change, potential shifts in forest cover were modelled based on a recent research results for southwestern US forests [5].

To model potential future climate scenarios and impacts to water supplies, six different Earth System Model (ESM) simulations were selected to sample a range of warm to warmer, and wet to dry to wet climate scenarios in the Coupled Model Intercomparison Project, Phase 5 CMIP5, [30] archive; we also selected ESMs for which...
vegetation processes were included. ESMs are similar to global climate models, but also include explicit representations of biogeochemical processes that interact with the climate system and alter its response to greenhouse gas emissions [31]. We utilized only one emission scenario in this work—Representative Concentration Pathway (RCP) 8.5—which governs a release of emissions causing an 8.5 W m\(^{-2}\) rate of greenhouse gas warming within the atmosphere [32]. RCP 8.5 is the concentration pathway trajectory the Earth is currently experiencing [33]. We used the Multivariate Adaptive Constructed Analogues (MACA) [34] dataset of downscaled ESM simulations, as MACA captures extremes with improved precision over other downscaling approaches, and the dataset was publicly available and easily accessible for download. More details on the VIC model setup, calibration, and ESM selection and simulations are included in the SI.

Two RiverWare\textsuperscript{TM} models were used to project the impacts of climate change and disturbances on river system operations—Reclamation’s San Juan River Basin Daily Operations Model and the San Juan-Chama Project Model. The San Juan River Basin Daily Operations Model simulates system operations, including reservoir operations, water allocations, and other rules that determine water deliveries for forecasting and operations of Navajo Reservoir on a day-to-day basis. The rules applied in the model for the Navajo Reservoir adhere to the 2006 Record of Decision, as well as the 2013–2016 San Juan River shortage sharing agreement. Releases are made to satisfy the minimum downstream target baseflow of 500 cfs, assuming normal irrigation is taking place. Losses in the reaches between the SJR gages are used to represent collective losses due to diversions, evapotranspiration, and groundwater loss, as well as gains from minor tributary inflows and return flows. The losses and gains between each reach are based on historical statistics and the time of year.

Water availability, or shortages, to the San Juan-Chama Project were determined using the San Juan-Chama Project model, a model based the Upper Rio Grande Water Operational Model (URGWOM). Computed deliveries consider annual water allotments made from the San Juan River system, available supply at Heron Reservoir and water allotments made to the downstream San Juan-Chama Project contractors. Shortages to San Juan-Chama contractors were analysed at the beginning of each calendar year, starting in 1976, when Heron reservoir was initially filled. Additional details for both RiverWare\textsuperscript{TM} models are included in the SI.

3.3. Water metrics

Five different water metrics were tracked as a means of comparing water supply impacts across different scenarios: storage in Navajo Reservoir, SJR water shortages, SJR basin discharge, instream flows, SJR discharge to the Colorado River, and San Juan-Chama Project deliveries. Average annual storage in Navajo Reservoir provides a general measure of water available to the basin for use. SJR water shortages are calculated according to the shortage sharing agreement and measure the reduction in deliveries to basin water users. Impacts on environmental or instream flows were measured at the Arizona-New Mexico border. Current operations have a target of 21 days above 5000 cfs during spring and summer to maintain critical habitat as defined in the SJRIP Flow Recommendations. To calculate instream flows, we sum the days in the year where average spring/summer (March to July) flow is above 5000 cfs and calculate the total days that do not meet the flow target, (i.e. less than or greater than 21 days), as a percentage of the target. When the value shown is negative, fewer than 21 days met the flow target, with −1 being no days meeting the flow target. Impacts beyond the SJR Basin are also tracked. Specifically, annual shortages to deliveries to the San Juan-Chama project (water exported to the Rio Grande), as well as annual average discharge downstream to the Colorado River (at Lake Powell) are also tracked.

4. Results

4.1. Model calibration and validation

VIC calibration and validation statistics are provided for the gages at Archuleta, NM and San Juan at Bluff, UT in the Supplemental (table S1). Results from the calibration, validation, and the entire period of record indicate that flow peaks match well in the simulated flows compared to the naturalized flows, however low flow (baseflow) matching and overall volume accounting is less skillful. Volume bias is low for the validation time period for the San Juan at Bluff, UT gage, although volume biases are good on average over the time period. The RiverWare\textsuperscript{TM} operational models were not calibrated.

4.2. Climate change and streamflow projections

Climate change projections for the SJR basin illustrate a pattern of warming, with variations in projected precipitation (figure S1 is available online at stacks.iop.org/ERC/1/095001/mmedia). All models project warming (with an average change of +5.4 °C), while precipitation projections vary between models and geographically across the basin, ranging from approximately +/−20% (CanESM2, +25%; IPSL-CM5A-LR, −22%), with average ESM change for precipitation of 8%.
The SJR basin has a flow regime that is dominated by snowmelt runoff in the spring (figure 3). Flow recession typically occurs in July, with low flows dominating in late summer, winter, and early spring (March). The Navajo Dam has altered this basic hydrograph, so that downstream of the dam the volume of the spring peak is diminished, but higher flows are maintained in the other seasons as water is moved downstream from reservoirs to meet the needs of water users, which causes a secondary streamflow peak in September to early October (figure 3).

Flow projections developed from ESM simulations (Future Climate) suggest that in the future, spring melt will occur approximately two weeks to one month early, with peak flow occurring in May instead of early June (figure 3), and projected annual flow volumes that are 14% lower than historical means. However, future flows in the late fall through early spring (November-March) may be higher than they were historically, due to more precipitation falling as rain rather than snow and earlier runoff of low-elevation snowpack (figure 3). The range of responses for Future Climate is greater than all other scenarios, emphasizing the uncertainty across different ESMs.

Due to water rights that are not currently being fully utilized, historical scenarios that include full utilization of current water rights (Full Use) yield a volumetric reduction in flows that is equal to ~30% less water in the river annually, with the largest percentage differences occurring in the spring, summer and early fall (figure 3). Under pressure from future climate and water use (Future Climate and Full Use), annual flows volumes are projected to be 33% lower than historical values, but with a dramatically different hydrograph than the Full Use scenario (figure 3). The 2018 water year (October 1st, 2017 to September 30th, 2018) illustrates the impact of flow retention and release at Navajo Reservoir during low water years on the SJR basin hydrograph.

4.3. Water metrics
4.3.1. Navajo reservoir storage
Navajo Reservoir is critical in managing year-to-year variability in basin water supplied (figure 4(a)). Under the Future Climate scenario, ESMs project stable storage at Navajo Reservoir until the 2030s, after which a marked increase in variability is evident. However, the Full Use scenario is sufficient alone to drive change where average minimum storage volumes are just 26% higher than the shortage sharing cutoff. This is exacerbated under the Future Climate and Full Use scenario, particularly after 2050s, where variability increases and minimum storage volumes fall below the average minimum storage volume in 29 out of the 50 years.
4.3.2. Basin discharge
The SJR basin discharges to the Colorado River at Lake Powell (figure 4(b)). Water releases from Navajo Dam are managed to meet the minimum average flow requirement of 500 cfs throughout the critical habitat reach; however, historically, average annual flows have been well above the limit at 2000 cfs (not shown). The Full Use scenario illustrates lower minimum flows to Lake Powell, punctuated by higher flow events, with several low flow events (9) where the flow goes below the 2018 mean (figure 4(b)). Future Climate and the Future Climate and Full Use scenarios for the ESMs track closely until about the 2050s, when they start to diverge. Both scenarios include two large peak flow events, with low flow events for which the average minimum flow requirements (500 cfs). The black vertical lines highlight the 2030, and the 2050s, which are discussed in the text.

Figure 4. Results for all ESMs from 1970–2099 for (a) Navajo Storage (1000s of AFY) and for (b) Flow to Powell (cfs). The Full Use scenario is shown in red, the Future Climate scenario is shown in blue, and the Future Climate and Full Use is shown in purple. Dotted lines shown the mean of all models, with the envelope around the mean representing the full range of all ESMs. The dashed horizontal lines illustrate the 2080s mean for Future Climate and Future Climate and Full Use scenarios. The solid horizontal line shows the 1980s mean for the Full Use scenario. The black horizontal lines illustrate the a) shortage sharing cutoff for Navajo reservoir, and the (b) 2018 water year mean. The orange line in (b) is the minimum flow requirement (500 cfs). The black vertical lines highlight the 2030, and the 2050s, which are discussed in the text.

4.3.3. Water shortages
Of particular concern is the frequency and extent to which SJR basin water users are shorted water deliveries under potential future scenarios. Historically, there has never been a declared shortage in the SJR basin, but under the Full Use scenario numerous shortages occur, often shorting deliveries by 25%–50% (figure 5(a)). However, climate change alone (the Future Climate scenario) only results in a few instances of water shortages, and only under the driest ESMs, suggesting that operations of Navajo Reservoir smooth intensifying interannual variability driven by climate change relative to the chronic depletions associated with full utilization of water rights (figure 5(b)). As expected, shortages intensify under the Future Climate and Use scenario (figure 5(c)). Changing climate and water use regimes within the SJR basin impact water resources beyond the basin via water deliveries to the Rio Grande basin through the San Juan-Chama Project. In contrast to SJR shortages, the
Full Use (figure 5(d)) scenario yields few contractor shortage events, while numerous shortage events are recorded for the Future Climate scenario (figure 5(e)). As expected, the Future Climate and Full Use scenario (figure 5(f)) yields the highest potential for contractor shortages. This difference in shortages for the SJR versus San Juan-Chama reflects the fact that the San-Juan Chama flow volume is based on the legislated average annual diversion, thus the projected volume that is withdrawn after meeting bypass requirements is always allocated for. Note that the legislated average annual diversion could change in the future, and whether the San Juan-Chama Project contractors should share in the shortages of the Navajo Reservoir Contractors downstream is still an open legal question.

4.3.4. Instream flows
Central to SJR basin operations is the management of instream flows. For instream flows, the Full Use and the Future Climate scenarios both place significant downward pressure on spring releases (figures 5(g), (h)). When taken together, there are few years for all but the wettest models, with even one day above the target flow (figure 5(i)). This result is concerning as it will mean that meeting minimum flow requirements is likely to be a major challenge in the San Juan River basin. This finding also illustrates variability across metric indicators, with some metrics being of much greater concern over others.

Figure 5. Water shortages and instream flows for each scenario, with columns showing Full Use, Climate and Climate and Full Use and all ESMs. Water shorted are shown in panel a, b, c for the SJR, with each individual ESM response being represented by the bars and the height of the bars equalling percentage of water shorted in a given year for water users. Panel d-f represent water shortages to contractors on the San Juan-Chama project as described above for SJR. Bars in panels g-i illustrate the percentage of days above or below the target instream flow conditions (5000 cfs in spring season), where negative values show insufficient days met.
4.3.5. Combined impacts

Combined impacts are considered by looking at the average across all ESMs and all years, to consider the side-by-side impacts of all flow metrics analysed, relative to the Historical scenario (figure 6).

For Navajo Reservoir storage, the impacts are limited (figure 6(a)) for this high capacity reservoir. The Future Climate scenario projects increased storage for three wetter ESMs, while the three drier ESMs project a slight decrease in average storage. In contrast, the Full Use scenario projects all ESMs having reduced storage of roughly 10%–15% (figure 6(a)). Under the Future Climate and Full Use scenario, Navajo storage is consistently lower relative to Historical and Future Climate scenarios. However, responses are variable, reflecting nuances in reservoir operations and interannual variability across the ESMs (figure 6(a)).

SJR discharges to Powell are projected to be lower under the Full Use scenario for all ESMs (figure 6(b)). Under Future Climate, four ESMs show decreases on the order of −12% to −48%, while two ESMs show increases of +8% and +21%. Under Future Climate and Full Use, all models show decreased flows to Powell on the order of −0.5% to −57% (figure 5(b)).

For shortages in the SJR, few shortage events are generated by the Future Climate scenario, except in the case of the driest model (figure 5(c)). Shortages are more common under Full Use, where all ESMs except HadGEM2-ES indicate more than one shortage sharing event. Under Future Climate and Full Use, shortage

![Figure 6. Averages for each metric for all ESMs and each scenario, (a) Navajo Storage, (b) Flow to Powell, (c) Shortages on the SJR, (d) shortages on the San Juan-Chama, (e) days of when instream flow targets are met. For each metric, the average of all the ESMs is shown with a black line, with the exception of (d), where the black line represents the target number of flow releases (21).](image-url)
sharing is the norm, with models projecting shortage sharing in 4 to 26 of the 30 years, depending upon the ESM (figure 6(c)). The average shortages range from 3% to 52% throughout those years (not shown).

In figure 6(d), shortages on the San Juan-Chama are considered. The Full Use scenario yields only a few years and ESMs for which contractor shortage sharing would be implemented. For the Future Climate scenario, contractor shortages are apparent for both drier and wetter (e.g. CanESM2) ESMs. In fact, half of the six ESMs show shortage sharing in effect during 13 to 21 years out of 30, and average shortages ranging from 16% to 70% (not shown). For the Future Climate and Full Use scenario, this situation is exasperated with half of the ESMs indicating shortage sharing in 18 to 29 of the 30 years (figure 5(d)), and contractor shortages on average between 19 to 73% throughout those years (not shown).

For instream flows, under Future Climate, all but the driest two models yield average spring releases above the flow target (but generally well below Historical levels, figure 6(e)). Full Use averages fall even lower, with all ESMs yielding fewer than 15 days per year with spring releases. The combined Future Climate and Full Use scenario rebounds for wetter models, but indicates the least number of days for dry models, with more days for wetter models compared to the Full Use (figure 6(e)).

5. Discussion

Climate impacts in the SJR illustrate a changing basin, with differences between impact scenarios comparing historical past mean to future mean and extreme, and with deviations when water usages are included. But there is also consistency between observed impacts. For example, all scenarios project changes in the timing of water flows during spring months. Uncertainties between the scenarios remain, but are not equal. For instance, there is certainty in the water utilization scenarios, versus higher uncertainty in the climate scenarios (figure 7). This difference in uncertainty between the climate and utilization scenarios points to the need to integrate across disciplines to understand both changing climate and water use regimes, which are projected to place nearly constant pressure on water users in future years for the SJR.

An ensemble of average future projections show wetter and warmer conditions compared to the historical under the Future Climate scenario, with punctuated extremes; a finding that is reflected in recent studies in the CRB [35, 36]. Across ESMs, a range of potential future hydroclimate conditions are projected, with the differences between ESMs occurring largely as a result of differences in precipitation projections. For example, some ESMs project almost no shortages to SJR basin water users, nor to the San Juan-Chama Project, while others result in persistent shortages. Likewise, some ESMs project increases in Navajo Reservoir storage and Colorado River deliveries, while other models show decreases in these metrics (figure 7). However, instream flows show dramatic reductions for almost all ESMs, with the exception of two wetter ESM projections (figure 7).
One important exception to the response to *Future Climate* scenario was noted in the contractor shortages on Reclamation’s San Juan-Chama Project, where impacts were consistently realized across models (based on a 2013–2016 SJR shortage sharing agreement). This response occurs due in part to the diversion point for the San Juan-Chama Project being above Navajo Dam or any other reservoir, thus there is no storage buffer to smooth out the intensifying interannual variability associated with climate change. Also, the operational rules of the San Juan-Chama Project combined with complexities of a 2013–2016 SJR shortage sharing agreement (relatively high allowable depletions) make the San Juan-Chama Project diversions insensitive to SJR shortages, except under extreme conditions. Here, we see the intersection of interannual variability, geography, infrastructure and policy dictating significant differences in impact in the SJR, which is likely to occur in many similar headwater systems throughout the US West.

Under the *Full Use* scenario, there is a clear and negative impact on four of the five metrics examined, and again, the intensity and direction of impacts is much more certain than in the case of *Future Climate* alone (figure 7). The driver is a consistent and expected change associated with currently under-utilized basin water rights.

In the intersection of the changing natural systems and changing societal demands is the scenario with the greatest impact, the combined *Future Climate and Use*, where consistent negative change was observed within all five metrics (figure 7). Interestingly, this scenario shows only a slight increase in impact over the *Future Use* scenario, pointing to the non-additive effects of climate and water utilization. These non-additive behaviors arise due to increases (decreases) in precipitation under future (historical) flows interacting with infrastructure and policy changes in water, as observed in the differences between SJR shortages and San Juan-Chama shortages.

Several models under the *Future Climate and Full Use* scenario yield impacts that could exceed manageable local and non-local thresholds in the basin. Severe impacts are most notable and consistently observed for the HadGEM-ES and IPSL-CM5B-LR models, but are also associated with other ESMs for specific metrics. Specifically, if impacts were realized as projected in this work, changes to operations, policies or water use practices may be required. However, because the current SJR shortage sharing agreement is written based on four-year intervals, the scenario we describe here may never be realized because of the ability to adjust the shortage sharing agreement accordingly.

The SJR basin is characteristic of other Western US headwater basins that play a key role as provisioning source basins of water and energy resources for neighboring urban centers [37]. These basins are vulnerable to the combined impacts of climate and accompanying vegetation change; however, the intensity and even the direction of these impacts, which decline under some ESMs and increase in others, is uncertain. However, as the 2018 water year has shown us, impacts such as very low flow years are possible even now, and have consequences for short term water, energy, food and other such usages including recreation, with the possibility to strongly impact the system if several of these low flow years occur concurrently. These basins are also subject to changing water use regimes not because of population and industrial growth (as most basins are closed to new freshwater appropriations, 14), but rather due to currently under-utilized or un adjudicated basin water rights. These factors, when taken together (*Future Climate and Full Use* scenario) show the potential for disruptive impacts to water deliveries and instream flows. For example, in the future it will be increasingly difficult to provide adequate flow volumes for fish and other instream flow needs.

### 5.1. Impacts to water, food and energy

Such disruptions have the potential for compounding local to non-local water and energy impacts. Consider the projected persistent and often intense shortages to water users locally in the SJR basin that suggested reduced water deliveries by 25% to 50% to municipalities, electric power plants and agriculturalists. While impacting the local economy, these shortages also mean that less electricity and food will be exported to non-local urban centers, for which most of the local electricity and food production is destined. For example, downstream water deliveries are significantly lower on average, but in some years the shortages exceed 75% or more. Because shorted water is not available to produce hydroelectric and thermoelectric power downstream, grow crops, or supply drinking water to cities, this effect produces a compounding local to non-local effect. Impacts are further compounded when considering tradeoffs, such as if communities are forced to expend more energy to increase groundwater use to fill the supply gap. Energy-for-water tradeoffs prove much more complex downstream in California and Arizona where elaborate interbasin water supply projects operate [37].

### 5.2. Questions raised

The questions raised in the introduction can be partially answered by the results of this study. However, we feel that many questions still remain, questions that will be answered in part by future work being carried out in the SJR by the authors.
Is the current management structure flexible enough to accommodate projected changes?

We think that the answer to this question is yes. The advantage of the shortage sharing agreement is that it can be changed and adapted as the years continue and the uncertainties around climate impacts begin to narrow. As the direction of change becomes apparent, and the impacts from extremes is realized, the shortage sharing agreements may be shifted. Keeping this agreement flexible may be one of the main ways in which the basin can adapt and mitigate large shifts in climate. The most important factor here is adaptability and willingness of operators and contractors to be flexible rather than moving towards a more strict, regimented policies that may not be as useful under the flux, change and uncertainties projected for the future.

Can current management policies, practices, and infrastructure effectively meet current needs and respond to change if the basin’s water rights are fully utilized? How can water management policies and practices in the basin be adapted to better meet water needs in the future and minimize shortage and operational disruptions?

Management policies and practices in the basin that are flexible as opposed to rigid will serve the communities that rely upon the water resources better in the future. However, infrastructure is an important point where management strategies and structures could be improved in the face of future use of water rights and water needs. For example, releases of water from Navajo, Blue Mesa and Flaming Gorge Reservoirs under drought conditions in Lake Powell are being discussed under a December 2018 agreement between the Upper Colorado River Commission for Colorado, Utah, Wyoming and New Mexico, and the federal Bureau of Reclamation [38]. Such agreements may be necessary to allow for management of drought and to meet the needs of downstream users, and these agreements acknowledge the importance of the provisioning headwater systems across the Colorado. However, to carry out such as agreement, studies must be undertaken to plan for such water retention and release, and understand how both may affect the multitude of water contractors and users both in and out of the basin. If the 2018 drought year is an example of what is to come, this type of contingency planning will be fundamental.

What types of additional analysis (modelling efforts, case study analysis) are needed to inform changing or altering current water management practices?

Going forward, the types of analysis that needs to be done include modelling and case studies that focus on both the natural flow system and the operationalized flow system, incorporating the details such as water usages, water rights, operational schedules and more. Early results from forthcoming studies incorporating finer-scale water operations modelling indicates that these data play a significant role in the resulting impacts to the availability and timing of water resources across the system. Thus, if we are to understand and be able to flexibly manage the CRB under a changing climate and increased water stresses, these kinds of detailed studies are imperative.

How will the shortages of water, and resulting decreases in energy production that occur within the San Juan Basin reverberate throughout the portions of the southwestern US that receive water and energy from this provisioning basin?

Extending the results of this study by averaging across the models implies that approximately 7% of streamflow from the SJR will decline, and while approximately 8% of the water use will increase under full utilization of water rights. If we multiplied this across the Upper CRB, there could be a little more than 1 million AFY reduction in inflows to Lake Powell, which after ∼14 years would equal about half the capacity of reservoir. Carrying through these results into the energy sector, this would mean an approximate reduction in power of 678 gWH [39], which loss of energy to 65,560 households and an economic loss of about 98 billion dollars [26].

6. Conclusion

This paper presents a coupled science- and engineering-based modelling framework to examine potential implications of future climate, vegetation, and water supply changes in the San Juan River basin, which is a critical provisioning basin in the US Southwest. Results from this study suggest changes in the timing and duration of water supplies in the basin with climate change that could have significant implications for meeting water rights, endangered species, and storage needs and impacts to water supplies needed for energy and agricultural production and municipal use both locally and throughout the southwestern US.

These findings are important for those who manage and are impacted by water management to consider in planning for future water needs and mitigating the impacts of change. While results across all metrics indicate variability, there is significant certainty that instream flows will be strongly impacted, which is of particular relevance to ecological managers. With full utilization of water rights and potential impacts from climate change, it will likely become increasingly difficult to meet ecological water needs, requiring action and adaptation in advance to minimize impacts.
Next steps for this work include connecting our analysis to agent- and production-based modelling for an-depth study of the impacts to power generation, both within the SJR and externally within the Western US power generation grid.

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