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CHANGING HYDROCLIMATE IN THE COLUMBIA RIVER BASIN: POTENTIAL IMPACTS ON THE SNAKE RIVER DAMS

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I. INTRODUCTION

Climate variability and climate change exert fundamental controls on the hydrology and management of the Columbia River System and the four lower Snake River dams.[1] Hydrologic infrastructure is typically designed with an assumption of stationary conditions; that is, streamflow and other hydrologic variables may be stochastic at various timescales, but ultimately follow a statistical distribution that does not change over time.[2] However, climate change renders this assumption invalid, fundamentally altering the practice of water management.[3] In this review, we discuss observations and projections of changing climate in the Columbia River Basin (CRB),[4] the hydrologic consequences of these changes, important unknown factors, and what these changes in hydrology might mean for management of the four lower Snake River dams.[5] Observed and projected changes for each are discussed in detail below. In many cases, research is available for the CRB as a whole, with varying levels of spatially explicit detail that illuminate observed or projected changes relevant to the Snake River specifically; we therefore discuss changes in both the CRB and the Snake, highlighting results that are specific to the Snake

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1. *See* Fig. 1, *infra*.
2. P.C.D. Milly et al., *Stationarity Is Dead: Whither Water Management?*, 319 SCIENCE 573–74 (2008).
3. *Id.*
4 *See* Fig. 2, *infra*.
5 *See* Fig. 1.

whenever possible. The aim of this article is to provide an overview and synthesis of the current state of the science regarding the impacts of climate change on the Snake River Basin (SRB) and the four lower Snake River dams. We do not explicitly support or oppose the removal of the dams nor the entirety of Rep. Simpson's proposal.

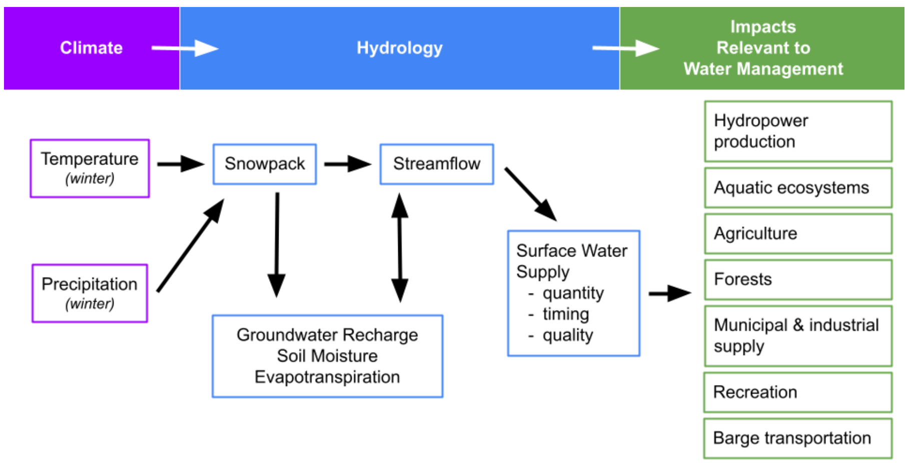

Figure 1. Primary pathways through which climate change affects water management in the Columbia River Basin. Adapted with permission from Miles et al.[6]

6. Edward L. Miles et al., *Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin*, 36 J. AM. WATER RES. ASS'N 399–420, fig. 2 (2000).

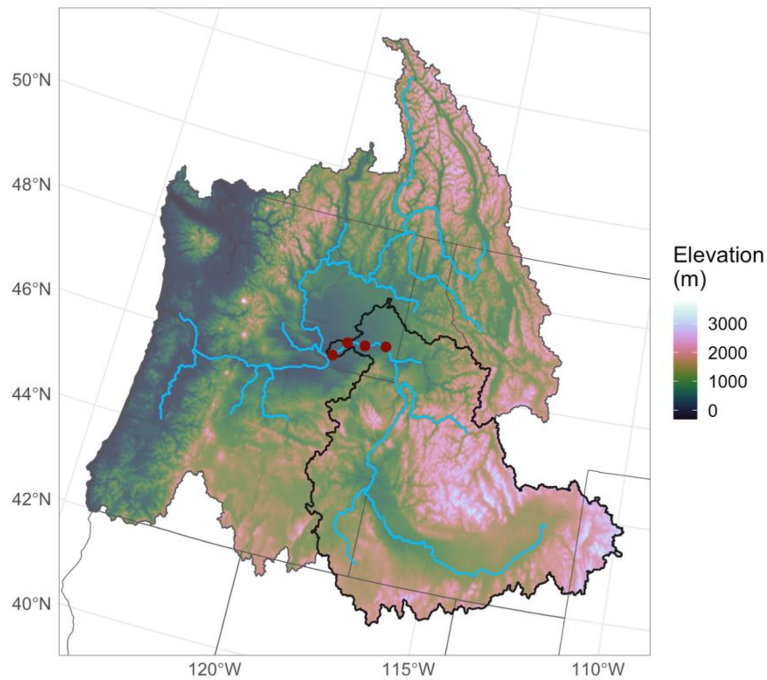

Figure 2. Study area map showing elevation throughout the Columbia River Basin, rivers with Strahler order of 6 or greater (cyan lines), the Snake River Basin (black outline), and the four lower Snake River dams (red points).

II. CHANGING CLIMATE

We now have strong evidence that the climate is changing, and that these changes are of anthropogenic origin.[7] Over the last 200 years, emissions of greenhouse gases such as carbon dioxide and methane have increased substantially as a result of human activity including fossil fuel combustion.[8] These gases augment the planet's natural greenhouse effect, trapping energy that would otherwise be emitted to space.[9] Evidence supporting the conclusion that the planet is warming due to human influence can be found all over the globe, on land (e.g., longer growing seasons, more severe fire seasons), in the oceans (e.g., sea level rise, ocean acidification), and in the atmosphere (e.g., warmer temperatures, changing precipitation amount and intensity, increases in atmospheric concentrations of greenhouse gases).[10]

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7. IPCC, CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE SIXTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (Masson-Delmotte, V., et al. eds., 2021).

8. *Id.*

9. T.M.L. WIGLEY & T.P. BARNETT, DETECTION OF THE GREENHOUSE EFFECT IN THE OBSERVATIONS 239–56 (1990).

10. IPCC, SUMMARY FOR POLICYMAKERS (Masson-Delmotte, V. eds.) (in press).

The effects of climate change are overlaid on patterns of natural climate variability. In some cases, such as for precipitation, the magnitude of natural variability is large enough that it obscures the effects of climate change in the historical record and constitutes a major source of uncertainty in future projections.[11] In contrast, trends in temperature are much more likely to be statistically significant and other sources of uncertainty, such as model or scenario uncertainty, dominate.[12] Two modes of natural climate variability that are particularly important in the CRB are the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), which vary on timescales of four to six years and roughly fifty years, respectively.[13] Combined, they can modify mean annual temperatures by 1°C and annual precipitation by 20%, while ENSO alone can modify annual snowfall by as much as 50%.[14] Through these mechanisms, natural variability can dramatically alter both water supply and demand.

Here we present evidence of historical climate change in the CRB and the SRB and discuss projections of future climate change in the context of natural variability and sources of uncertainty.

A. Observed Climate Change

According to an analysis of multiple temperature datasets, including those from station observations and reanalysis products, the United States Pacific Northwest warmed by 0.6°C to 0.8°C over the period 1901-2012, with enhanced warming in more recent decades.[15] This trend is comparable to that found by other studies in the region.[16] Warming has varied seasonally, with less warming in spring

11. Clara Deser et al., *Uncertainty in Climate Change Projections: The Role of Internal Variability*, 38 CLIMATE DYNAMICS 527, 528 (2012); Simone Fatichi et al., *Uncertainty Partition Challenges the Predictability of Vital Details of Climate Change*, 4 EARTH'S FUTURE 240, 240–51 (2016).

12. Ed Hawkins & Rowan Sutton, *The Potential to Narrow Uncertainty in Regional Climate Predictions*, 90 BULL. AM. METEOROLOGICAL SOC'Y 1095, 1096 (2009). *See also* Fig. 3, *infra*.

13. Alan F. Hamlet & Dennis P. Lettenmaier, *Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals*, 125 J. WATER RESOUR. PLAN. MANAG. 333–41 (1999).

14. A.C. Lute & J.T. Abatzoglou, *Role of Extreme Snowfall Events in Interannual Variability of Snowfall Accumulation in the Western United States*, 50 WATER RES. RSCH. 2874, 2885–86 figs. 8 & 9 (2014); Philip W. Mote et al., *Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest*, 61 CLIMATE CHANGE 45–88 (2003).

15. John T. Abatzoglou et al., *Seasonal Climate Variability and Change in the Pacific Northwest of the United States*, 27 J. CLIMATE 2125, 2134–35 (2014).

16. P. Zion Klos et al., *Indicators of Climate Change in Idaho: An Assessment Framework for Coupling Biophysical Change and Social Perception*, 7 WEATHER CLIMATE & SOC'Y 238–54 (2015); Philip Mote, *Trends in Temperature and Precipitation in the Pacific Northwest During the Twentieth Century*, 77 NW. SCI. 271–82 (2003); Mingliang Liu et al., *Spatial-temporal Variations of Evapotranspiration and Runoff/precipitation Ratios Responding to the Changing Climate in the Pacific Northwest During 1921-2006*, 118 J. GEOPHYSICAL RSCH. ATMOSPHERES 380–94 (2013).

coinciding with increased spring precipitation[17] and more warming in winter.[18] Mean annual minimum temperatures warmed more than mean annual maximum temperatures,[19] similar to broader scale findings,[20] resulting in a reduction in the diurnal temperature range.[21] The hottest temperature recorded each year increased about as much as the mean maximum temperature; whereas the coldest temperature each year warmed at a much faster rate of more than 1°C/decade in recent decades.[22]

Trends in annual precipitation over the CRB during the 20th century were mixed, with some studies reporting increases and others reporting no significant change,[23] perhaps as a result of large natural variability.[24] Relative to temperature, natural variability in precipitation is large in the CRB, making it more difficult to observe a statistically significant trend due to a low signal to noise ratio.[25] Seasonally, observations indicate statistically significant increases in spring precipitation on the order of 1-2% per decade[26] and statistically insignificant declines in summer precipitation.[27] Similar to global trends, precipitation intensity has increased in Idaho; the size of the largest one-day precipitation event increased 10% between 1975 and 2010.[28]

Observed warming has been accompanied by changes in associated indicators. Since 1970, the growing season, defined as the number of days between the last spring freeze and the first fall freeze, has lengthened by more than two weeks.[29] Warming temperatures and a longer growing season have resulted in a 9% increase in evapotranspiration over 1921-2006, despite decreased summer precipitation.[30] These changes have also resulted in an increase in the climatic water deficit.[31] Warming of extreme minimum temperatures is reflected in the updated United States Plant Hardiness Zone Map published in 2012, which categorized most of the region as a half zone to a whole zone warmer than the previous map, which was published in 1990.[32] Warming, particularly of the coldest temperatures, may alter

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17. Abatzoglou et al., *supra* note 15, at 2139.

18. Mote, *supra* note 16, at 271.

19. Abatzoglou et al., *supra* note 15, at 2126.

20. Luis A. Gil-Alana, *Maximum and Minimum Temperatures in the United States: Time Trends and Persistence*, 19 ATMOSPHERIC SCI. LETTERS APR. 2018, 1–3.

21. Abatzoglou et al., *supra* note 15, at 2129.

22. *See supra* Figures 4 & 6.

23. Abatzoglou et al., *supra* note 15, at 2137; Mote, *supra* note 16, at 277; Liu et al., *supra* note 16, at 386.

24. Abatzoglou et al., *supra* note 15, at 2137.

25. Abatzoglou et al., *supra* note 15, at 2130.

26. Abatzoglou et al., *supra* note 15, at 2129; Mote, *supra* note 16, at 277.

27. Abatzoglou et al., *supra* note 15, at 2135.

28. Klos et al., *supra* note 16, at 245.

29. Klos et al., *supra* note16, at 248; Abatzoglou et al., *supra* note 15, at 2127.

30. Liu et al., *supra* note 16, at 384.

31. Abatzoglou et al., *supra* note 15, at 2138.

32. Christopher Daly et al., *Development of a New USDA Plant Hardiness Zone Map for the United States*, 51 J. APPLIED METEOROL. CLIMATOL. 242, 254 (2012).

vegetation patterns and farming practices across the basin.[33] These changes and their impacts on vegetation and agriculture have implications for water resources and management as they may affect water demand, sustainability of dryland and irrigated agriculture,[34] and the partitioning of precipitation into runoff versus evaporation.[35]

33. T. Sheehan, D. Bachelet & K. Ferschweiler, *Projected Major Fire and Vegetation Changes in the Pacific Northwest of the Conterminous United States under Selected CMIP5 Climate Futures*, 317 ECOL. MODEL. 16, 26 (2015); Alexander Maas et al., *A (Mis)alignment of Farmer Experience and Perceptions of Climate Change in the U.S. Inland Pacific Northwest*, 162 CLIMATIC CHANGE 1011, 1021 (2020).

34. Wenchao Xu et al., *Climate Change, Water Rights, and Water Supply: The Case of Irrigated Agriculture in Idaho*, 50 WATER RES. RSCH. 9675, 9692–93 (2014); K. Rajagopalan et al., *Impacts of Near-Term Climate Change on Irrigation Demands and Crop Yields in the Columbia River Basin*, 54 WATER RES. RSCH. 2152, 2161–67 (2018).

35. Liu et al., *supra* note 16, at 391.

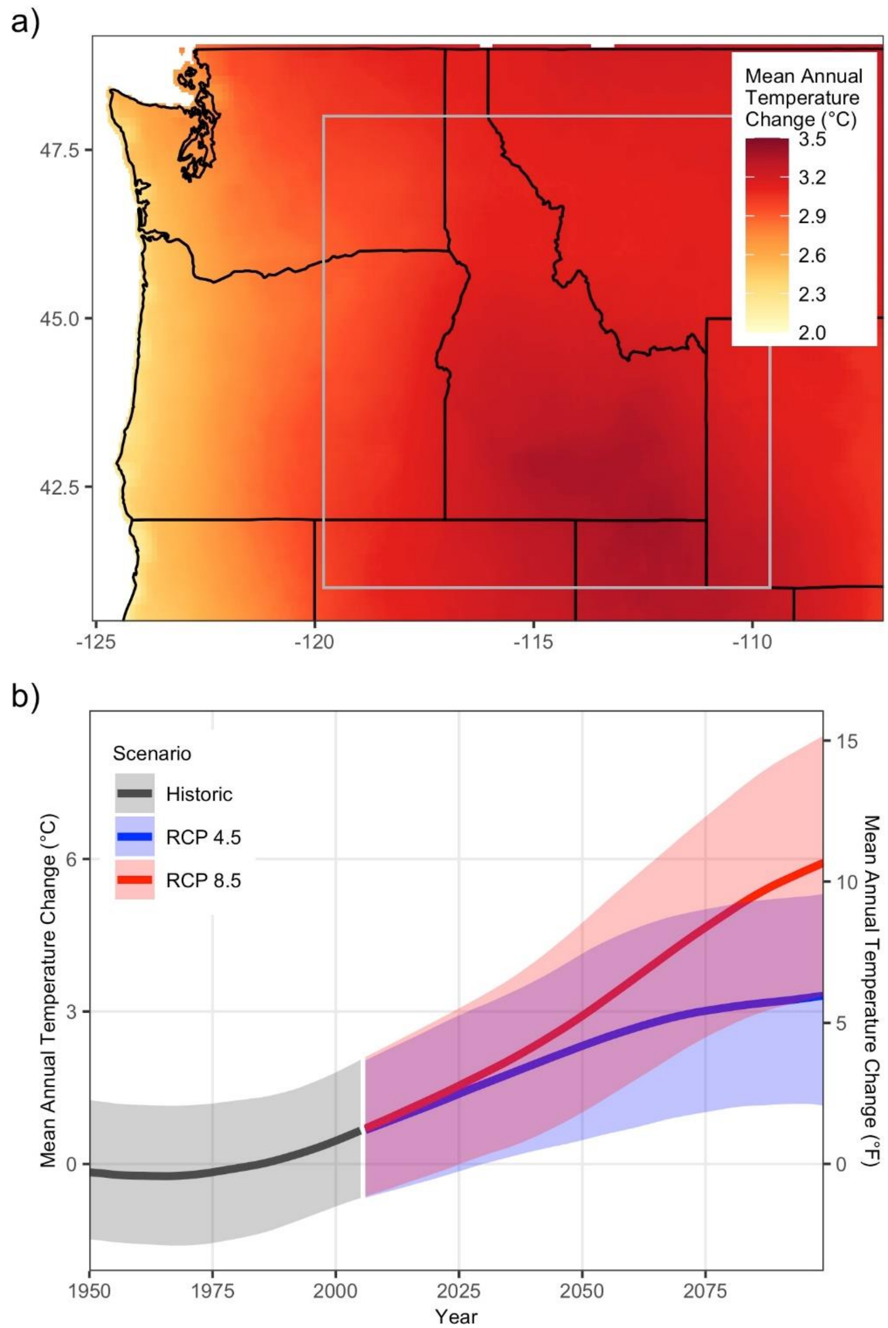

Figure 3.

a) Projected change in mean annual temperature between 1971-2000 and 2070-2099 according to the multi-model mean from 20 GCMs from CMIP5 downscaled using the MACA method under the RCP 4.5 scenario. Grey box indicates the bounding box of the Snake River Basin above the lower Snake River dams.

b) Time series of changes in simulated historical and future temperatures relative to the 1950-2005 average temperature from 20 GCMs from CMIP5 for the region indicated by the rectangle shown in a). Bold lines indicate multi-model mean predictions and shaded areas cover the range of individual model predictions.[36]

B. Projected Climate Change

One of the primary ways that future changes in climate are understood is through the use of numerical computer models of the land-ocean-atmosphere system called general circulation models (GCMs).[37] These models include mathematical representations of physical processes, such as ocean currents and weather systems.[38] After validating these models against historical climate observations, scientists are able to perform experiments by varying different components and evaluating how the modeled climate responds.[39] One important international experiment is the Coupled Model Intercomparison Project (CMIP),[40] which asks modeling groups around the world to vary greenhouse gas emissions in their models in standardized ways that represent possible future scenarios.[41] These scenarios, which are called Representative Concentration Pathways (RCPs) in the 5th CMIP (CMIP5),[42] represent a range of future scenarios from significant action to reduce greenhouse gas emissions (RCP 2.6) to intermediate emissions reduction (RCP 4.5) to continued unmitigated emissions (RCP 8.5), among other possibilities.[43] The choice of climate scenario can have a large effect on the climate simulations from the GCMs.[44] While the RCP 8.5 scenario has provided the best match to historical emissions and is the most commonly used scenario in the CRB literature at this time, recent studies have shown that RCP 8.5 is becoming increasingly less

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36. Figure created by authors with data downloaded from the Climate Mapper and Future Time Series web tools at climatetoolbox.org. John T. Abatzoglou & Timothy J. Brown, *A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications*, 32 INT'L J. CLIMATOL. 772, 777 (2012); K. C. Hegewisch & J. T. Abatzoglou, "*Climate Mapper" Web Tool*, CLIMATE TOOLBOX, https://climatetoolbox.org (last visited Sept. 13, 2021); K. C. Hegewisch & J. T. Abatzoglou, *"Future Time Series" Web Tool*, CLIMATE TOOLBOX, https://climatetoolbox.org (last visited Sept. 13, 2021).

37. D. Chen et al., *Framing, Context, and Methods*, *in* IPCC, CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS 1:43–45 (Masson-Delmotte, et al. eds.) (In press).

38. *Id.*

39. *Id.*

40. Gerald A. Meehl et al., *The Coupled Model Intercomparison Project (CMIP)*, 81 BULL. AM. METEOROL. SOC'Y 313, 315 (2000).

41. *Id.*

42. Karl E. Taylor et al., *An Overview of CMIP5 and the Experiment Design*, 93 BULL. AM. METEOROL. SOC'Y 485,488–89 (2012).

43. *Id.*

44. Hawkins & Sutton, *supra* note 12, at 1103.

likely;[45] developments over the last decade suggest emissions will not reach RCP 8.5 levels.[46] Nonetheless, projections using the RCP 8.5 scenario remain useful as a plausible scenario given large uncertainties in climate feedbacks. Results from the sixth model intercomparison project (CMIP6) are newly available, however we focus on CMIP5 here because their outputs have been analyzed in more detail, particularly with respect to hydrology.

Comparing the climate simulated by the CMIP5 models in the historical period with observations can inform how much confidence we should have in the models' ability to simulate future climate. One such comparison in the Pacific Northwest examined the performance of 41 GCMs relative to five different gridded datasets of observed climate using a variety of metrics.[47] They found that the models matched temperature observations well.[48] However, they matched precipitation observations less well.[49] Importantly, the models captured the large-scale temperature and precipitation effects of ENSO, a mode of natural climate variability that has a strong effect on Pacific Northwest climate.[50] Evaluating the performance of individual GCMs can improve our understanding of model deficiencies, inform ongoing development, or indicate a subset of models to use. However, in assessments of future climate, multi-model mean projections are often used as they have been shown to reduce bias relative to individual models.[51]

One challenge with the use of GCM projections is the coarse spatial resolution; the spatial resolution of most GCMs is more than 100km, making it difficult to capture processes in complex terrain such as that of the CRB. To alleviate this problem, GCM output can be downscaled to finer resolution.[52] There are two categories of downscaling: dynamical downscaling uses GCM output to force a regional climate model which is run over smaller domains at finer scales, while statistical downscaling uses statistical relationships between the model output and observed climate.[53] Sources of climate projections for the CRB include GCMs, dynamically downscaled products, and statistically downscaled products.[54] The

45. Christopher R. Schwalm et al., *RCP8.5 Tracks Cumulative CO 2 Emissions*, 117 PROC. NAT'L ACAD. SCI. 1956, 1956 (2020).

46. Zeke Hausfather & Glen P. Peters, *Emissions – The 'Business as Usual' Story Is Misleading*, 577 NATURE 618, 619 (2020).

47. David E. Rupp et al., *Evaluation of CMIP5 20th Century Climate Simulations for the Pacific Northwest USA*, 118 J. GEOPHYS. RSCH. ATMOSPHERES 10,884, 10,897 (2013).

48. *Id.*

49. *Id.*

50. Kelly T. Redmond & Roy W. Koch, *Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices*, 27 WATER RES. RSCH. 2381, 2381 (1991).

51. S.J. Lambert & G.J. Boer, *CMIP1 evaluation and Intercomparison of Coupled Climate Models*, 17 CLIMATE DYN. 83, 83–4 (2001).

52. H.J. Fowler et al., *Linking Climate Change Modelling to Impacts Studies: Recent Advances in Downscaling Techniques for Hydrological Modelling*, 27 INT. J. CLIMATOL. 1547, 1547 (2007).

53. *Id.* at 1547–52.

54. David E. Rupp, John Abatzoglou & Philip Mote, *Projections of 21st Century Climate of the Columbia River Basin*, 49 CLIM. DYN. 1783–99 (2017); Oriana S. Chegwidden et al., *How Do Modeling*

primary sources of uncertainty in these projections include model uncertainty, which stems from assumptions and numerical equations in the GCM, scenario uncertainty, which is related to how greenhouse gas emissions will change in the future and is closely tied to policy and economics, and downscaling uncertainty, which stems in part from the fact that there are relatively few observations to constrain downscaled data.[55]

Decisions Affect the Spread Among Hydrologic Climate Change Projections? Exploring a Large Ensemble of Simulations Across a Diversity of Hydroclimates, 7 EARTHS FUTURE 623–37 (2019); Ali Ahmadalipour et al., *Accounting for Downscaling and Model Uncertainty in Fine-Resolution Seasonal Climate Projections over the Columbia River Basin*, 50 CLIM. DYN. 717–33 (2018); Eric P. Salathé et al., *Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations*, 15 J. HYDROMETEOROLOGY 1881–99 (2014).

55. Chegwidden et al., *supra* note 54; Ahmadalipour et al., *supra* note 54.

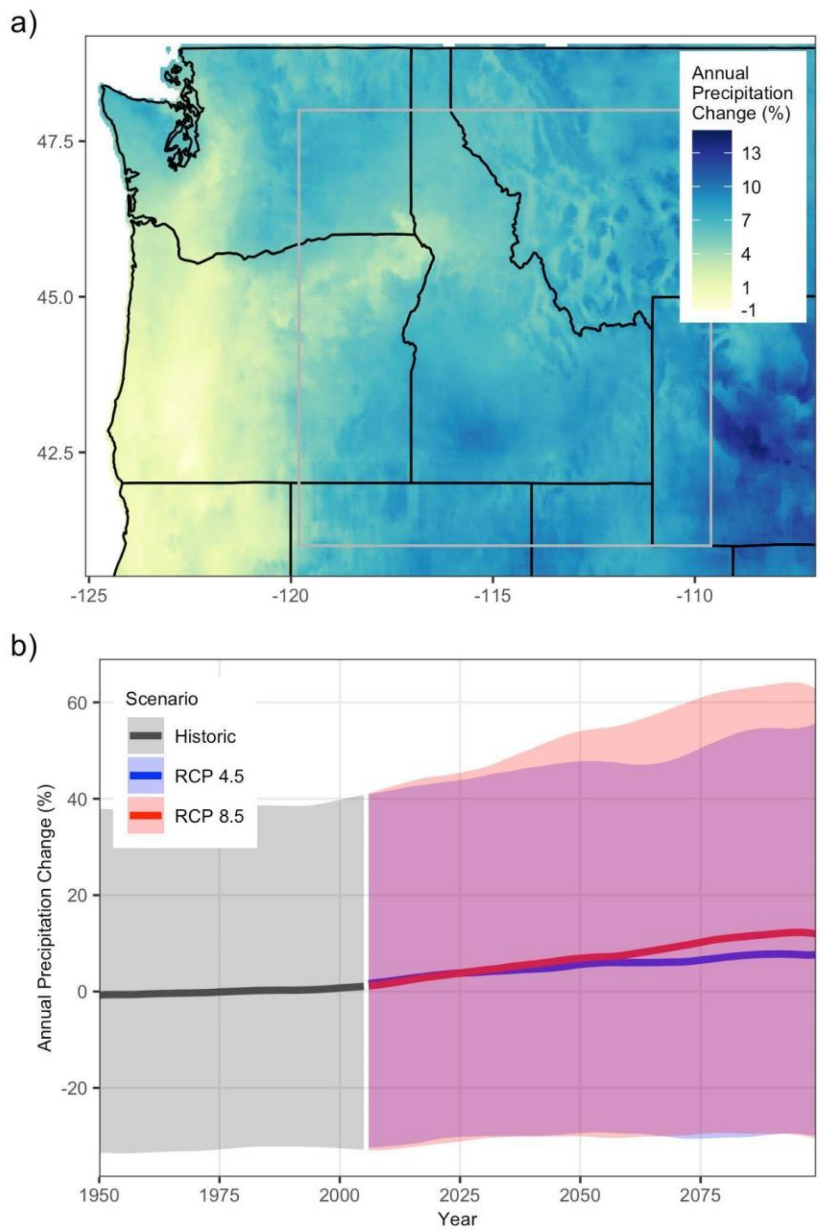

Figure 4.

a) Projected percent change in annual precipitation between 1971-2000 and 2070-2099 according to the multi-model mean from 20 GCMs from CMIP5 downscaled using the MACA method under the RCP 4.5 scenario. Grey box indicates the bounding box of the Snake River Basin above the lower Snake River dams.

b) Time series of simulated historical and future percent change in precipitation relative to the 1950-2005 mean from 20 GCMs from CMIP5 for the region indicated by the rectangle shown in a). Bold lines indicate multi-model mean predictions and shaded areas cover the range of individual model predictions.[56]

In general, projections of future climate in the Pacific Northwest suggest substantially warmer and slightly wetter conditions.[57] An analysis of climate projections from thirty-five GCMs found that temperatures by the end of the twenty-first century were likely to be 2.8°C to 5.0°C warmer and annual precipitation 5-8% greater than the 1979–1990 average under the RCP 4.5 and RCP 8.5 scenarios, respectively.[58] These projections are comparable to those from a study that used two downscaled versions of a ten GCM dataset and the same climate scenarios,[59] as well as to projections from a dataset of twenty downscaled GCMs for the same scenarios.[60] Spatially, projections of temperature and precipitation change are inconsistent across studies.[61] Temporally, projected warming is greatest in the summer months (under RCP 8.5), and interannual variability in temperature is not projected to change substantially.[62] Precipitation-change projections have distinct seasonal variability with increased precipitation projected during the winter and decreased precipitation projected during the summer in most models, although wintertime increases outweigh summer decreases to result in a projected net increase in annual precipitation.[63] Furthermore, precipitation intensity is projected to increase in the region, similar to global expectations.[64] Interannual variability in precipitation is expected to increase, particularly for winter precipitation (+22% under RCP 8.5 by end of century), which constitutes the bulk of annual precipitation in the CRB.[65]

In projections of temperature and precipitation change before 2100, model uncertainty is the main source of uncertainty when uncertainty from natural

56. Figure created by authors with data downloaded from the Climate Mapper and Future Time Series web tools at climatetoolbox.org. Abatzoglou & Brown, *supra* note 36, at 776–79; Hegewisch & Abatzoglou, *Climate Mapper*, *supra* note 36; Hegewisch & Abatzoglou, *Future Time Series*, *supra* note 36.

57. Rupp, Abatzoglou & Mote, *supra* note 54, at 1794. *See also* Figs. 3 & 4.

58. Rupp, Abatzoglou & Mote, *supra* note 54, at 1783. *See also* Figs. 3&4.

59. Ali Ahmadalipour, Hamid Moradkhani & Arun Rana, *Accounting for Downscaling and Model Uncertainty in Fine-Resolution Seasonal Climate Projections over the Columbia River Basin*, 50 CLIMATE DYNAMICS 717, 721 (2018).

60. Abatzoglou & Brown, *supra* note 36. *See also* Figs. 3 & 4.

61. Ahmadalipour, Moradkhani & Rana, *supra* note 59, fig. 8. *Contra* Hegewisch & Abatzoglou, *supra* note 36.

62. Rupp, Abatzoglou & Mote, *supra* note 54, at tbl.1 & fig.6.

63. Rupp, Abatzoglou & Mote, *supra* note 54, at tbl. 2.

64. Salathé et al., *supra* note 54, at fig. 3; *see also* Gerald A. Meehl, Julie M. Arblaster & Claudia Tebaldi, *Understanding Future Patterns of Increased Precipitation Intensity in Climate Model simulations*, 32 GEOPHYSICAL RSCH. LETTERS L18719 (Sept. 2005).

65. Rupp, Abatzoglour & Mote, *supra* note 54, at 1792.

variability is not considered.[66] As discussed above and illustrated in Figure 4.b, for precipitation, uncertainty stemming from natural variability can also be substantial.[67] Interestingly, models that do a better job of replicating historical climate tend to have higher sensitivities, resulting in these models projecting more warming and wetting than the average model.[68] For temperature, the uncertainty stemming from the choice of scenario becomes increasingly important with longer timeframes as emissions under RCP 4.5 and RCP 8.5 diverge with time[69] (fig. 3b). For precipitation, the uncertainty stemming from the choice of downscaling method equals or exceeds the scenario uncertainty.[70] In fact, projections of opposite signs have been found for summer precipitation depending on downscaling method.[71] This highlights the importance of downscaling uncertainty, but also the large uncertainty in precipitation projections relative to temperature projections (fig. 4b). While downscaled CMIP6 projections are not yet available for the Pacific Northwest, the GCMs project the same direction of precipitation change as CMIP5 models in the winter but disagree on the direction of summer precipitation.[72] Differences in magnitude of projected change are difficult to compare due to differences in the experimental design.

III. IMPACTS OF CLIMATE CHANGE ON HYDROLOGY

Changes in climate are expected to have significant impacts on the hydrology of the CRB, principally through changes in snowpack amount and snowmelt runoff timing.[73] Here, we discuss observed and projected changes in snowpack amount, timing, and variability, as well as observed and projected changes in streamflow magnitude, timing, floods, and low flows, followed by a brief discussion of potential changes to water quality.

A. Snow

In the CRB, snowpack is a valuable natural reservoir that stores water through the winter months and releases it gradually in the spring and summer when precipitation declines and water demand from humans and ecosystems increases.[74] In the mountainous regions of the Basin, more than 60% of runoff comes from

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66. Ahmadalipour, Moradkhani & Rana, *supra* note 59, at fig.10.

67. *See* Deser et al., *supra* note 11, at 536, fig. 9; Rupp, Abatzoglou, & Mote, *supra* note 54, at fig.8.

68. Rupp, Abatzoglou & Mote, *supra* note 54, at figs.9 & 10.

69. Ahmadalipour, Moradkhani & Rana, *supra* note 59, at fig. 10.

70. Ahmadalipour, Moradkhani & Rana, *supra* note 59, at fig. 10.

71. Ahmadalipour, Moradkhani & Rana, *supra* note 59, at 730.

72. B.I. Cook et al., *Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios*, 8 EARTH'S FUTURE 2019EF001461 (2020).

73. *See* Fig. 1.

74. Erica R. Siirila-Woodburn et al., *A Low-to-No Snow Future and Its Impacts on Water Resources in the Western United States*, 2 NATURE REV. EARTH & ENV'T 800, 800 (2021).

snowmelt.[75] Mountain snowpack is therefore a key component of the water management system in the CRB and changes in snowpack could force major changes to the water management system.

i. Observed Changes in Snow

At snow course measurement sites in the SRB, historically more than 60% of precipitation fell as snow, and snowpack typically reached its maximum water equivalent volume in April and disappeared in July.[76] The highest snowpack years had twice as much snow as the lowest snowpack years[77] due to modes of natural climate variability including ENSO, the Pacific-North American (PNA) pattern, the North Pacific Index (NPI), and the PDO.[78] At higher elevations, snowpack variability has historically been more closely tied to precipitation variability than to temperature variability.[79]

Over the last century, the effects of climate change on snowpack in the basin have become evident in the form of less precipitation falling as snow,[80] increased snowmelt during the snowpack accumulation season,[81] and reduced peak snowpack as measured by the snow water equivalent (SWE).[82] In particular, SWE on April 1, a metric that has historically been used to inform water management decisions, has declined 15–45% from 1950–2000 at most snow courses across the SRB, with larger declines in warmer locations such as lower elevations and the downstream portions

75. Dongyue Li et al., *How Much Runoff Originates as Snow in the Western United States, and How Will That Change in the Future?*, 44 GEOPHYSICAL RSCH. LETTERS 6163, 6172 (2017).

76. Mark C. Serreze et al., *Characteristics of the Western United States Snowpack from Snowpack Telemetry (SNOTEL) Data*, 35 WATER RES. RSCH. 2145, 2154 tbls. 5 & 6 (1999).

77. *Id.* at 2155.

78. Daniel R. Cayan, *Interannual Climate Variability and Snowpack in the Western United States*, 9 J. CLIMATE 928, 948 (1996); Gregory J. McCabe & Michael D. Dettinger, *Primary Modes and Predictability of Year-to-Year Snowpack Variations in the Western United States from Teleconnections with Pacific Ocean Climate*, 3 J. HYDROMETEOROLOGY 13, 25 (2002); Lute & Abatzoglou, *supra* note 14.

79. Cayan, *supra* note 78; Jason Scalzitti, Courtenay Strong & Adam Kochanski, *Climate Change Impact on the Roles of Temperature and Precipitation in Western U.S. Snowpack Variability*, 43 GEOPHYSICAL RSCH. LETTER 5361, 5369 (2016).

80. Noah Knowles, Michael D. Dettinger & Daniel R. Cayan, *Trends in Snowfall Versus Rainfall in the Western United States*, 19 J. CLIMATE 4545 (2006).

81. Keith N. Musselman et al., *Winter Melt Trends Portend Widespread Declines in Snow Water Resources*, 11 NAT. CLIMATE CHANGE 418 (2021).

82. Philip W. Mote, *Trends in Snow Water Equivalent in the Pacific Northwest and Their Climatic Causes*, 30 GEOPHYSICAL RESCH. LETTERS 1601 (2003) [hereinafter Mote, *Trends in Snow Water*]; Philip W. Mote et al., *Declining Mountain Snowpack in Western North America*, 86 BULL. AM. METEOROLOGY SOC'Y 39 (2005); Philip W. Mote, *Climate-Driven Variability and Trends in Mountain Snowpack in Western North America*, 19 J. CLIMATE 6209 (2006); Philip W. Mote et al., *Dramatic Declines in Snowpack in the Western US*, 1 NPJ CLIMATE ATMOSPHERIC SCI. 2 (2018) [hereinafter Mote et al., *Dramatic Declines in Snowpack*].

of the CRB.[83] An updated evaluation covering the more recent period, 1955–2016, found even larger declines in April 1 SWE.[84] Relative to trends of decreasing April 1 SWE, trends of increasing snowmelt during the accumulation season (before April 1) are more widespread and more statistically significant.[85] As a metric, accumulation season melt is more sensitive to temperature than April 1 SWE; April 1 SWE is primarily sensitive to precipitation.[86] The integrated effect of these changes in the snow dominated upper portions of the CRB is a shift in snowmelt runoff timing of five to twenty days earlier over 1948–2008, while in the rain dominated lower portions of the basin trends in timing have been mixed.[87]

These declines in snowpack have occurred in spite of increases in precipitation in some parts of the basin.[88] Whereas the effect of precipitation trends on snowpack trends over the last half century has been mixed due to mixed trends in precipitation, the effect of temperature trends on snowpack trends has been almost universally negative[89] and the role of temperature in shaping interannual SWE variability is increasing.[90] According to a modeling study that isolated trends in snowpack due to precipitation and due to temperature, declines in SWE over the last century are primarily due to warming temperatures.[91] With continued warming, the lower elevations of the seasonal snow zone will become increasingly influenced by temperature rather than precipitation, making these areas increasingly sensitive to warming.[92]

In addition to comparing the roles of temperature and precipitation, trends in SWE can also be viewed through the lens of natural variability and anthropogenic climate change. A comparison of trends in April 1 SWE at snow courses and indices of the NPI and PDO found that about 40% of the observed SWE trend across the Pacific Northwest could be attributed to NPI and a much smaller portion could be attributed to PDO.[93] Modeling work has shown that the tendency of the PNA over the last half century has also enhanced declines in snowpack in the western US.[94] On the other hand, a detection and attribution analysis in the western US suggests that up to 60% of trends in hydrology (including snowpack) for the period 1950-1999

83. Mote, *Trends in Snow Water*, *supra* note 82, at fig.1.

84. Mote et al., *Dramatic Declines in Snowpack, supra* note 82, at 4 fig.1.

85. Musselman et al., *supra* note 81, at 420.

86. Musselman et al., *supra* note 81, at 422.

87. Holger Fritze, Iris T. Stewart & Edzer Pebesma, *Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades*, 12 J. HYDROMETEOROLOGY 989 (2011).

88. Mote, *Trends in Snow Water*, *supra* note 82, at 1601.

89. Mote, *Trends in Snow Water*, *supra* note 82, at 1062 fig.2.

90. Gregory J. McCabe & David M. Wolock, *Recent Declines in Western U.S. Snowpack in the Context of Twentieth-Century Climate Variability*, 13 EARTH INTERACT. 1 *passim* (2009).

91. Alan F. Hamlet et al., *Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States*, 18 J. CLIMATE 4545, 4545 (2005).

92. Scalzitti et al., *supra* note 79, at 5361; Charles H. Luce, Viviana Lopez-Burgos & Zachary Holden, *Sensitivity of Snowpack Storage to Precipitation and Temperature Using Spatial and Temporal Analog Models*, 50 WATER RES. RSCH. 9447 *passim* (2014).

93. Mote, *Trends in Snow Water*, *supra* note 82, at 1602.

94. John T. Abatzoglou, *Influence of the PNA on Declining Mountain Snowpack in the Western United States*, 31 INT'L J. CLIMATOLOGY 1135, 1135 (2011).

can be attributed to human influence.[95] Tree ring reconstruction work in the Northern Rockies and Yellowstone region also suggests that recent changes are anomalous; this work found only two times in the last 800 years with snowpack as low as it has been in the 20th century.[96] The leading role of temperature in observed snowpack decline and the attribution of snowpack declines in significant part to human causes suggests that snowpack decline will continue in the coming decades with continued climate change, as discussed in the next section.

ii. Projected Changes in Snow

Future changes in snow can be assessed using a variety of methods, ranging from simple to more complex. Simpler approaches include using empirical relationships between temperature, precipitation, and snow to assess changes in the amount of precipitation falling as snow and changes in snowpack timing and duration. More complex approaches include using outputs from regional climate models which include their own physically based snow models or using global climate model outputs downscaled to finer resolution which are then used to force a snow model. A variety of approaches have been used to assess future snow in the CRB.

Continued warming through the end of the twenty-first century will decrease the portion of winter precipitation falling as snow for all but the very coldest locations.[97] Locations that previously received the majority of their winter precipitation as snow, such as the headwaters of the SRB, will shift to a rain and snow mix, while warmer locations that historically received some rain in the winter will become increasingly rain dominated.[98] Under the high emissions scenario (RCP 8.5) by the end of the twenty-first century, the portion of the basin that is snow dominated is projected to decline by 30-50% (depending on subbasin) while the portion that is rain dominated is projected to increase by 8-25%.[99] These shifts will affect the frequency and intensity of rain-on-snow events, which have historically caused record flooding in the CRB.[100] The risk of rain-on-snow events is projected to

95. T.P. Barnett et al., *Human-Induced Changes in the Hydrology of the Western United States*, 319 SCI. 1080, 1082 (2008).

96. Gregory T. Pederson et al., *The Unusual Nature of Recent Snowpack Declines in the North American Cordillera*, 333 SCI. 332, 333 (2011).

97. P. Zion Klos, Timothy E. Link & John T. Abatzoglou, *Extent of the Rain-Snow Transition Zone in the Western U.S. under Historic and Projected Climate*, 41 GEOPHYS. RSCH. LETTERS 4560, 4561 (2014).

98. Ingrid M. Tohver, Alan F. Hamlet & Se-Yeun Lee, *Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America*, 50 JAWRA J. AM. WATER RES. ASS'N 1461 *passim* (2014).

99. Klos et al., *supra* note 97, at 4563.

100. Danny Marks et al., *The Sensitivity of Snowmelt Processes to Climate Conditions and Forest Cover During Rain-On-Snow: A Case Study of the 1996 Pacific Northwest Flood*, 12 HYDROLOGICAL PROCESS 1569 *passim* (1998).

increase in most mountains of the SRB and the magnitude of runoff from rain-on-snow flooding events is also projected to increase.[101]

While the ratio of snow to rain is primarily a function of temperature, the change in the actual snowfall amount is a function of both temperature and precipitation.[102] The large uncertainty in projections of future precipitation discussed above contributes to large uncertainty in the magnitude of snowfall change; projected percent changes in snowfall in the western U.S. between 2000-2060 across a 40 member GCM ensemble span a range of >20%.[103] In contrast, the sign of snowfall changes is much less uncertain (negative in all but the coldest locations).[104] End of twenty-first century simulations from a high resolution regional climate model under the RCP 8.5 scenario show increased annual rainfall and reduced annual snowfall across the entire CRB, despite some increases (0-30%) in snowfall during December, January, and February in the coldest locations (central Idaho and western Wyoming).[105] Percent reductions in annual snowfall were largest (60-90%) in the warmest locations that historically had small snowpacks, whereas absolute reductions in annual snowfall were largest in the moderate elevation mountains (~250 mm in portions of the SRB).[106] Additionally, several studies have projected increases in the intensity of snowfall in the coldest portions of the SRB, due to increasing precipitation intensity.[107] These trends will make annual snowfall totals more dependent on a handful of large snowfall events[108] and may modestly mitigate the effects of warming on snowpack in these locations.[109]

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101. Keith N. Musselman et al., *Projected Increases and Shifts in Rain-On-Snow Flood Risk Over Western North America*, 8 NATURE CLIMATE CHANGE 808 *passim* (2018).

102. A.C. Lute, J.T. Abatzoglou & K.C. Hegewisch, *Projected Changes in Snowfall Extremes and Interannual Variability of Snowfall in the Western United States*, 51 WATER RESOUR. RES. 960–972, 969 (2015).

103. Justin S. Mankin & Noah S. Diffenbaugh, *Influence of Temperature and Precipitation Variability on Near-Term Snow Trends*, 45 CLIMATE DYNAMICS 1099, fig. 3 (2015).

104. Lute, *supra* note 102, at fig. 3 & 4.

105. Kyoko Ikeda et al., *Snowfall and Snowpack in the Western U.S. as Captured by Convection Permitting Climate Simulations: Current Climate and Pseudo Global Warming Future Climate*, 57 CLIMATE DYNAMICS 2191, fig. 5 & 6 (2021).

106. *Id.* at 2191, fig.5.

107. Lute et al., *supra* note 102, at fig 5.; Adrienne M. Marshall et al., *Higher Snowfall Intensity is Associated with Reduced Impacts of Warming Upon Winter Snow Ablation*, 47 GEOPHYSICAL RSCH. LETTERS 1 (2020), FIG 3.

108. Lute et al., *supra* note 102, at fig. 3 & 5.

109. Marshall et al., *supra* note 107, at fig. 4.

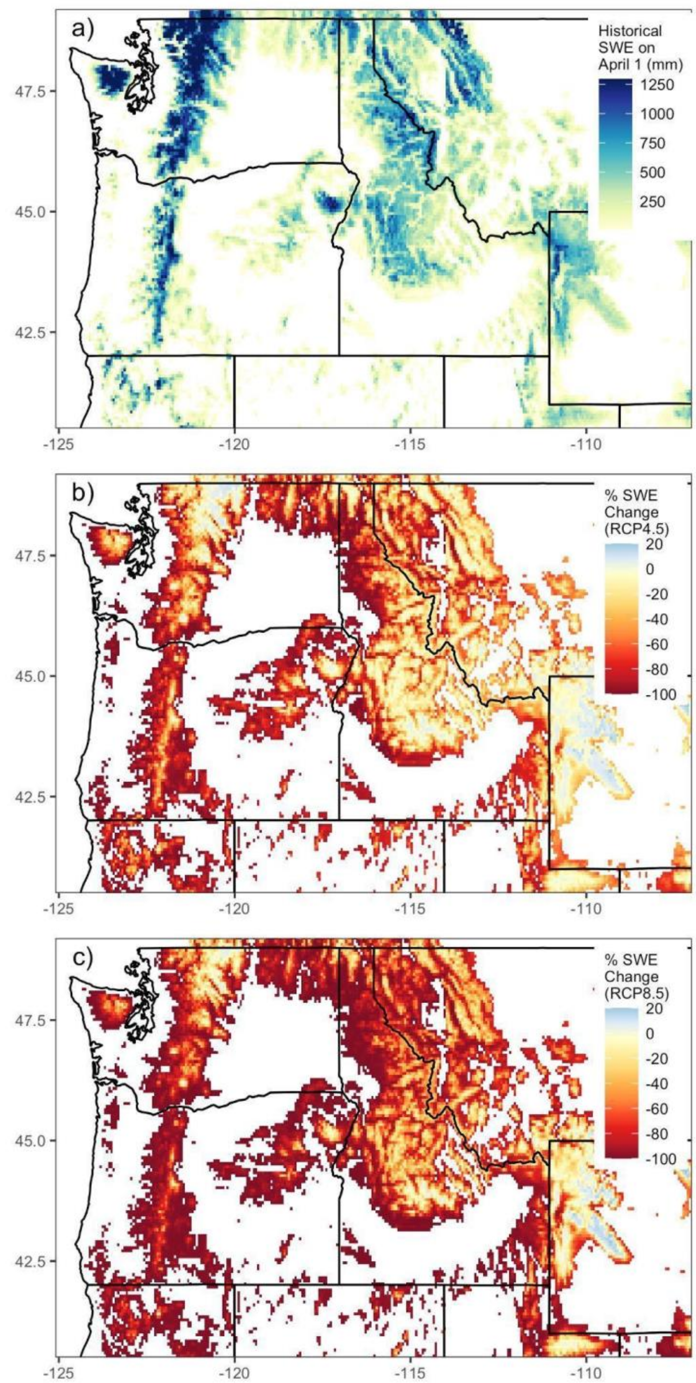
a)
Historical SWE on April 1 (mm)
1250
1000
750
500
250
47.5
45.0
42.5
-125
-120
-115
-110
b)
% SWE Change (RCP4.5)
20
0
-20
-40
-60
-80
-100
c)
% SWE Change (RCP8.5)

Figure 5.

a) Average historical (1971-2000) snow water equivalent (SWE) on April 1st;

b) Percent change in SWE on April 1st between the historical period and late twenty-first century period (2070-2099) under the RCP 4.5 scenario; and

c) the RCP 8.5 scenario. Areas with historical mean April 1 SWE less than 10mm are masked.[110]

Changes in snowfall, combined with snow melt dynamics, shape the snowpack on the ground. Studies have predicted reduced and earlier maximum SWE and shorter snow cover duration.[111] April 1 SWE, which historically captured the approximate maximum SWE of the season, is expected to decline by 10-50% at observation stations across the SRB under a +3°C warming scenario.[112] According to outputs from a hydrologic model forced by downscaled GCM simulations under the RCP 4.5 and 8.5 scenarios, April 1 SWE is expected to disappear at low elevations, experience substantial declines in most mountains, and may increase slightly in the highest, coldest mountain ranges by the end of the twenty-first century,[113] although other modeling work predicts no areas of enhanced April 1 SWE in the region.[114] Based on end of twenty-first century projections under RCP 8.5, the date of maximum SWE is expected to shift earlier in the season by roughly one month,[115] shifting snowmelt runoff earlier and making April 1 SWE an increasingly poor metric for water management.[116] This coincides with a predicted shorter snow cover season (10-40% shorter), as indicated by studies of a +3°C warming scenario as well as from a snow model forced with end of twenty-first century climate data under RCP 8.5.[117] Across the SRB, the maximum SWE of the season, in addition to occurring earlier, is predicted to be roughly half of its historic value by the end of the twenty-first century under RCP 8.5.[118] This will result in a reduction in the portion of runoff that comes from snowmelt; by the end of the twenty-first century under the RCP 4.5 and RCP 8.5 scenarios, the contribution of snowmelt to runoff is expected to decline by 5-15% and 5-30%, respectively.[119]

110. Figure created by authors with data downloaded from the Climate Mapper web tool at climatetoolbox.org. Abatzoglou & Brown, *supra* note 36; Xu Liang et al., *A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models*, 99 J. GEOPHYSICAL RSCH. 14415 (1994); Hegewisch & Abatzoglou, "*Climate Mapper" Web Tool, supra* note 36.

111. Luce et al., *supra* note 92, at fig. 11; Chegwidden et al., *supra* note 54, at 623 (2019); Ikeda et al., *supra* note 105, at fig. 7 & 8; A.C. Lute et al., *SnowClim v1.0: High-Resolution Snow Model and Data for the Western United States*, GEOSCIENCE MODEL DEV. DISCUSS. (in review), https://doi.org/10.5194/gmd-2021-407, at fig. 6.

112. Luce et al., *supra* note 92, at 9457–59.

113. Abatzoglou & Brown, *supra* note 36; Liang et al., *supra* note 110; Hegewisch & Abatzoglou, "*Climate Mapper" Web Tool, supra* note 36. *See also* Fig. 5.

114. Ikeda et al., *supra* note 105, at fig. 7.

115. Chegwidden et al., *supra* note 54, at 629; Ikeda et al., *supra* note 105, at 3000.

116. Li et al., *supra* note 75, at 6168–70.

117. Luce et al., *supra* note 92, at 9457–59; Lute et al., *supra* note 111, at fig. 6.

118. Ikeda et al., *supra* note 105, at 2199–205; Lute et al., *supra* note 111, at fig. 6.

119. Li et al., *supra* note 75, at 6168.

The variability of snowpack from year to year, which has historically been a major challenge for water management in the basin, is also expected to shift. Annual snowfall will become increasingly dependent on a handful of large snowfall events, suggesting greater year-to-year variability.[120] However, lower snowpack totals mean that the magnitude of year-to-year variability will be smaller.[121] The timing of maximum SWE is projected to become more variable, which, like shifts to earlier peak SWE, will make the April 1 SWE metric increasingly unreliable.[122] By mid-twenty-first century under RCP 8.5, high snow years (defined as the top 25% of historic snow years, or occurring once every four years) are projected to occur only once every five to thirty years depending on location.[123] Low snow years (defined as the lowest twenty-five percent of historic snow years) are projected to occur once every one to two and one-half years[124] and consecutive low snow years (i.e., snow droughts) are projected to occur most years in the warmer portions of the basin.[125]

While the sign of these changes is largely consistent across studies, the magnitude of projected snowpack changes is subject to uncertainty, stemming from choice of GCM, regional climate model, downscaling approach, hydrologic or snow model structure and parameters, future scenario, and natural variability.[126] For example, one study that considered many of these sources of uncertainty suggested that the date of max SWE would shift earlier by roughly a month, but the spread in projections across models, downscaling methods, hydrologic models, and scenarios was one to two weeks.[127] The greatest uncertainty in future snow changes on the landscape is in the snow/rain transitional zones, which are prevalent in the SRB.[128] In the next several decades, natural climate variability represents the largest source of uncertainty in projections of changing snowpack on March 1; however, the portions of uncertainty stemming from choice of GCM and downscaling method increase toward the end of the twenty-first century.[129]

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120. Lute et al., *supra* note 102, at 961, 970.

121. Adrienne M. Marshall et al., *Projected Changes in Interannual Variability of Peak Snowpack Amount and Timing in the Western United States*, 46 GEOPHYSICAL RSCH. LETTERS 8882, 8889–90 (2019).

122. *Id.*

123. Lute et al., *supra* note 102, at 968, fig. 8b.

124. Lute et al., *supra* note 102, at 968, fig. 8a.

125. Marshall et al., *supra* note 121, at 8885 fig. 1d.

126. Chegwidden et al., *supra* note 54, at 629 and fig. 5c; Jay R. Alder & Steven W. Hostetler, *The Dependence of Hydroclimate Projections in Snow-Dominated Regions of the Western United States on the Choice of Statistically Downscaled Climate Data*, 55 WATER RES. RSCH. 2279 *passim* (2019).

127. Chegwidden et al., *supra* note 54, at 630 fig.5.

128. Chegwidden et al., *supra* note 54, at 629.

129. Alder & Hostetler, *supra* note 126, at 2294 fig.9.

B. Average annual runoff

The potential impacts of climate change on streamflow include changes in total annual runoff, the timing of runoff, the distribution of high and low flows, and water quality. Each of these changes has different implications for dam and reservoir operations and sustainability.

The impacts of climate change on annual flow are complex: increased precipitation would tend to increase streamflow; meanwhile, warming temperatures increase evaporative demand, which tends to reduce water available for streamflow.[130] Moreover, while warming is decreasing snowpack in the CRB, the extent to which decreasing snowpack increases or decreases runoff is still a matter of scientific debate.[131]

Evaluating the observed impacts of climate change on SRB or CRB streamflow magnitudes is made somewhat difficult by the highly regulated nature of the system, but methods to estimate non-modified flow (sometimes called "virgin" or "naturalized" flow) include dendrochronological (tree ring) reconstructions, statistical adjustments to observed runoff, and hydrologic models. Other early efforts to evaluate potential impacts of climate change on streamflow in the CRB evaluated the sensitivity of annual runoff to observed climate variability due to ENSO, finding that runoff was twelve percent lower than average in an average El Niño year, and eight percent higher than average in an average La Niña year.[132] While these findings do not directly inform the climate change response, they provided early evidence that total streamflow in the Columbia River is responsive to observed climate variability. However, the response of streamflow to climate is complex and influenced by many other factors: when dendrochronological records were used to reconstruct streamflow since 1750, the results suggested that land cover changes in the twentieth century altered the relationship between climate and streamflow, and that large-scale circulation patterns such as ENSO had a strong link with streamflow in the twentieth century, but not prior to that.[133] Estimates of non-modified flow (removing irrigation extractions and dam operation effects) at the Dalles suggest that annual average flows decreased by seven percent from 1879–1899 to 1946–1999.[134] These methods do not account for the impacts of land cover change—primarily deforestation—and may therefore underestimate the impacts of climate change on streamflow over this period. Observed changes in average annual flows may also mask another important trend: that annual

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130. Sergio M. Vicente-Serrano et al., *Unraveling the Influence of Atmospheric Evaporative Demand on Drought and Its Response to Climate Change*, 11 WIREs CLIMATE CHANGE e632, at 3, 6 tbl.1 (2020).

131. W. R. Berghuijs et al., *A Precipitation Shift from Snow Towards Rain Leads to a Decrease in Streamflow*, 4 NATURE CLIMATE CHANGE 583, 583–86 (2014). *But see* Theodore B. Barnhart et al., *The Counteracting Effects of Snowmelt Rate and Timing on Runoff*, 56 WATER RES. RSCH. e2019WR026634 (2020).

132. Miles et al., *supra* note 6, at 404.

133. Ze'ev Gedalof et al., *Columbia River Flow and Drought Since 1750*, 40 J. AM. WATER RES. ASS'N 1579, 1583, 1588 (2004).

134. Pradeep K. Naik & David A. Jay, *Estimation of Columbia River Virgin Flow: 1879 to 1928*, 19 HYDROLOGICAL PROCESSES 1807, 1819 (2005).

streamflow in the driest years is drying faster than average years throughout the Pacific Northwest and in the SRB,[135] with potentially significant impacts on water allocation and reservoir refill capabilities.

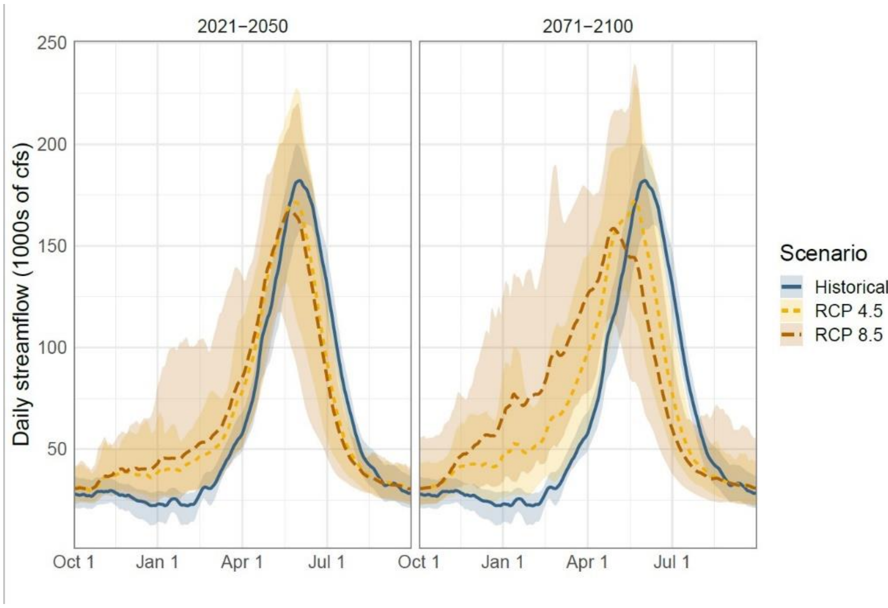

Figure 6. Historical (1971–2000), mid-century (2021–2050), and late-century (2071–2100) streamflow at Lower Granite Dam, showing RCP 4.5 and RCP 8.5 for 160 model configurations including ten GCMs, two climate scenarios, two downscaling methods, and four hydrologic model implementations.[136] Lines show the mean value across years and models for each case; shaded areas show the range across models for each case.

Estimates of future streamflow in the CRB generally require hydrologic modeling, typically using downscaled climate model outputs as input to a hydrologic model. The practice of using regional or global climate models to simulate streamflow in the CRB has a long history. At least as early as 1997, climate model outputs were used as inputs to hydrologic models in the Upper CRB to evaluate the extent to which basin hydrology could successfully be modeled at this scale and

135. C. H. Luce & Z. A. Holden, *Declining Annual Streamflow Distributions in the Pacific Northwest United States, 1948–2006*, 36 GEOPHYSICAL RSCH. LETTERS L16401 *passim* (2009).

136. ERIK PYTLAK ET AL., RIVER MGMT. JOINT OPERATING COMM., CLIMATE AND HYDROLOGY DATASETS FOR RMJOC LONG-TERM PLANNING STUDIES: SECOND EDITION (RMJOC-II) PART I: HYDROCLIMATE PROJECTIONS AND ANALYSES (2nd ed. 2018) [hereinafter RMJOC PART I], https://www.bpa.gov/-/media/Aep/power/hydropower-data-studies/rmjoc-ll-report-part-l.pdf. Figure created by authors with data described in cited document and available at https://www.hydro.washington.edu/CRCC/data/.

identify important sources of uncertainty.[137] In one of the earliest efforts to directly model the impacts of future climate change on runoff in the CRB, two climate models with temperature increases of 2.3°C to 2.9°C and precipitation changes ranging from -1% to +20% by 2045 estimated total runoff changes ranging from 85% to 110% of the historical case.[138] Across the CRB, some modeling efforts suggest a decrease (of 3.5%) in mean annual streamflow for the 2020s relative to 1980s, but this trend reverses to yield increases of 0.6% and 5.5% by the 2040s and 2080s, respectively;[139] these changes are attributed to an increase in evaporative demand by the 2020s, with a projected increase in precipitation having a larger effect later in the century.[140] Current efforts that incorporate uncertainty arising from choice of GCM, climate change scenario, method of climate model downscaling, and hydrologic model structure and parameterization show that annual streamflow is projected to increase across all locations in the CRB (Figure 6).[141] In the SRB specifically, choice of GCM is generally the greatest contributor to uncertainty in total annual streamflow changes by the 2080s.[142] In the region of the four lower dams, the contribution of GCM uncertainty is followed by that of variability internal to the climate system and choice of climate change scenario.[143]

C. Streamflow timing

While projected changes in average annual runoff are somewhat uncertain, observed and projected changes in streamflow timing on the Snake and throughout the CRB are undisputed: decreasing snow to precipitation ratios and more accumulation season snowmelt tend to yield runoff that occurs relatively more in the winter and spring, and less in the summer. These changes are often expressed as the center of timing (CT) of runoff, which is the date at which the streamflow center of mass passes a given point.

Observational evidence has indicated since at least 2002 that streamflow CT in snow-dominated watersheds of the western U.S., including those contributing to the Snake, has shifted substantially earlier in the year.[144] The magnitude of observed advance in CT depends somewhat on methods; one study[145] indicated a ten-to-

137. *See, e.g.*, G. W. Kite, *Simulating Columbia River Flows with Data from Regional-Scale Climate Models*, 33 WATER RES. RSCH. 1275 *passim* (1997); A. W. Wood et al., *Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs*, 62 CLIMATIC CHANGE 189 *passim* (2004).

138. *See* Alan F. Hamlet & Dennis P. Lettenmaier, *Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin*, 35 J. AM. WATER RES. ASS'N 1597 *passim* (1999).

139. *See, e.g.*, Huan Wu et al., *Projected Climate Change Impacts on the Hydrology and Temperature of Pacific Northwest Rivers*, 48 WATER RES. RSCH. W11530 *passim* (2012).

140. *Id.*

141. Oriana S. Chegwidden et al., *How Do Modeling Decisions Affect the Spread Among Hydrologic Climate Change Projections? Exploring a Large Ensemble of Simulations Across a Diversity of Hydroclimates*, 7 EARTH'S FUTURE 623, 630 fig.6 (2019).

142. *Id.* at 632.

143. *Id.* at 631–34.

144. Iris T. Stewart et al., *Changes Toward Earlier Streamflow Timing Across Western North America*, 18 J. CLIMATE 1136 at fig. 2b (2005).

145. *Id.* at 1141 fig.2.

twenty-day advance over the latter half of the twentieth century, while another identified a mean advance of six days across the CRB over the last 100 years.[146] In contrast to snow-dominated basins, streamflow CT in rain-dominated coastal watersheds has generally shifted later in the year, suggesting that the trends in snow-dominated watersheds are attributable to declining snowpack. At the scale of the CRB, observed changes in streamflow CT are attributable to anthropogenic greenhouse gas emissions; indeed, the attribution of these changes is stronger in the CRB than that in the Colorado River, San Joaquin, or Sacramento Rivers.[147]

Streamflow CT is projected to continue to advance throughout the western U.S. and in the SRB. A simple empirical linear regression method suggested that CT throughout the CRB would advance by 3 to 9 days/°C of warming, while a precipitation increase of 1 mm/day would not yield a detectable change in CT.[148] Physically based hydrologic models have also long projected advancing streamflow timing throughout snow-dominated parts of the CRB.[149] More recent sophisticated hydrological models indicate that in the lower Snake, streamflow timing will occur earlier: flood peaks, rather than CT, are another important indicator of runoff timing, and are projected to occur much earlier in future scenarios with greater interannual variability.[150] While flood peaks historically occurred in mid-May to mid-July in models without reservoir operations, they are projected to range from December to June in the second half of the 21st century.[151] In the CRB, uncertainty in future changes in CT is most affected by the choice of global climate model and emissions scenario; in the SRB, choice of emissions scenario is the greatest contributor to uncertainty in CT change;[152] this implies that climate policy will have a large influence on changing streamflow timing in the Snake. In general, hydrologic models suggest that the transitional elevations with greatest projected changes in snowpack are likely to have the largest changes in runoff timing.[153]

146. Kyle Dittmer, *Changing Streamflow on Columbia Basin Tribal Lands—Climate Change and Salmon*, 120 CLIMATIC CHANGE 627, 627, 634 (2013).

147. H. G. Hidalgo et al., *Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States*, 22 J. CLIMATE 3838, 3838–55, 3846 fig.5 (2009).

148. Iris T. Stewart et al., *Changes in Snowmelt Runoff Timing in Western North America under a `Business as Usual' Climate Change Scenario*, 62 CLIMATIC CHANGE 217, 217–32, 225 fig.4 (2004).

149. Hamlet & Lettenmaier, *supra* note 138, at 1597; Alan F. Hamlet et al., *An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results*, 51 ATMOSPHERE-OCEAN 392 (2013).

150. Laura E. Queen et al., *Ubiquitous Increases in Flood Magnitude in the Columbia River Basin Under Climate Change*, 25 HYDROLOGY EARTH SYS. SCI. 257 (2021).

151. *Id.* at 269 fig.11.

152. Chegwidden et al., *supra* note 141, at 633 fig.10.

153. Julie A. Vano et al., *Seasonal Hydrologic Responses to Climate Change in the Pacific Northwest*, 51 WATER RES. RSCH. 1959, 1967 fig.5 (2015).

D. Flood peaks

As with average annual runoff, changes in flood peaks are fairly uncertain and spatially variable. Increasing precipitation intensity[154] or rain-on-snow events at higher elevations[155] could increase flood peaks. In contrast, reductions in snow melt, soil moisture, or storm extent could all limit flooding,[156] as could the slower snowmelt associated with warming, though these impacts have not been fully scientifically resolved.[157] Moreover, as basins shift from snow to rain-dominated, the processes controlling flood magnitude will change from snowmelt to precipitation events, which are in turn more sensitive to increases in precipitation.[158] Floods are sometimes defined as annual peak flows, but are often defined based on a statistical analysis as the runoff value associated with a particular return interval; i.e., the maximum value that would statistically be expected every *n* years. We refer to that value here as the *n*-year flood event. Theoretically, floods with the largest return intervals and flows in smaller catchments should increase the most in response to warming and greater precipitation extremes.[159]

Observations of trends in flood peaks globally generally fail to indicate an observed increase in flood extremes[160] despite observed increases in precipitation intensity.[161] Observational studies of changing flood peaks in the CRB or in the SRB specifically are scant; this may be because the highly engineered nature of the system in conjunction with statistical issues associated with evaluating rare events that make detection of trends in observations challenging. In the CRB, peak values of observed flow, flow adjusted to remove the effect of reservoir operations, and flow adjusted to remove reservoir operations and irrigation withdrawals decreased by 31, 15, and 7%, respectively, from 1879–99 to 1946–99.[162] A hydrologic model simulation study also showed decreased flood peaks in the SRB over the period from 1915 to 2003 due to decreases in snowpack.[163]

154. Paul A. O'Gorman & Tapio Schneider, *The Physical Basis for Increases in Precipitation Extremes in Simulations of 21st-century Climate Change*, 106 PROC. NAT'L. ACAD. SCI. 14773, 14773–77 *passim* (2009).

155. Keith N. Musselman et al., *Projected Increases and Shifts in Rain-on-Snow Flood Risk Over Western North America*, 8 NATURE CLIMATE CHANGE 808, 808–12 *passim* (2018).

156. Ashish Sharma et al., *If Precipitation Extremes Are Increasing, Why Aren't Floods?*, 54 WATER RES. RSCH. 8545 *passim* (2018).

157. Keith N. Musselman et al., *Slower Snowmelt in a Warmer World*, 7 NATURE CLIMATE CHANGE 217 (2017).

158. Oriana S. Chegwidden et al., *Climate Change Alters Flood Magnitudes and Mechanisms in Climatically-Diverse Headwaters Across the Northwestern United States*, 15 ENV'T RSCH. LETTERS 094048, at 1 (2020).

159. *See* Vano et al., *supra* note 153, at 1964 fig.2.

160. Sharma et al., *supra* note 156, at 8545.

161. R. Barbero et al., *Is the Intensification of Precipitation Extremes with Global Warming Better Detected at Hourly than Daily Resolutions?*, 44 GEOPHYSICAL RSCH. LETTERS 974 (2017).

162. P. K. Naik & D. A. Jay, *Human and Climate Impacts on Columbia River Hydrology and Salmonids*, 27 RIVER RSCH. APPLICATIONS 1270, 1273 (2011).

163. Alan F. Hamlet & Dennis P. Lettenmaier, *Effects of 20th Century Warming and Climate Variability on Flood Risk in the Western U.S.*, 43 WATER RES. RSCH. 1, 9–10 figs.5 & 6 (2007).

Projected future changes in flood peaks on the Snake and throughout the CRB are somewhat uncertain, but the most recent and highest quality evidence suggests that flood peaks are projected to increase. For instance, one study projected changes in monthly 20-year flood magnitudes in the CRB that range from up to 20% decrease in March to 50% increases throughout the other months, with increases much more ubiquitous than decreases; the same pattern holds true for the 100-year return interval, with more extreme projected increases, up to 80% in May.[164] Of these, projected changes in flood magnitudes in the Snake are relatively modest.[165] Other studies also projected increases in flood peaks,[166] with greater certainty of flood peak increases in high emissions, late twenty-first century scenarios.[167] In the most recent hydrologic simulations for the CRB that adequately account for multiple sources of uncertainty, winter and spring flows on the Snake are projected to increase[168] and 10-year flood magnitudes on the Snake below its confluence with the Salmon are projected to increase by 20% and 100-year events by 30%.[169] In the CRB and the Snake specifically, climate change is expected to reduce the synchrony of flood events across sub-basins as snowpack in each basin has differing sensitivities to warming, but flood events may become more synchronous at higher levels of warming.[170]

E. Low flows

As in much of the western United States, climate change in the SRB could decrease the volume of low flows by shifting streamflow earlier in the season.[171] Increases in evaporative demand can also leave less water available for runoff in the summer. Low streamflow values can be defined in several different ways and evaluated over multiple timescales; these definitional issues have large impacts on the magnitude and direction of estimated changes in low flows due to climate change. Low flows are often described using statistics such as 7Q10, which is the lowest 7-day average flow that occurs once on average every 10 years. In other cases, low flows are evaluated as a monthly value relative to historical average flows or as the change in a given percentile (e.g., tenth percentile) of flows per month.

164. Tohver et al., *supra* note 98.

165. *Id.* at 1467–68 figs. 3 & 5.

166. Eric P. Salathé et al., *Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations*, 15 J. HYDROMETEOROLOGY 1881, 1881–99 (2014).

167. Hamlet et al*., supra* note 149, at 407 fig.10.

168. Chegwidden et al., *supra* note 141, at 630 fig.6.

169. Queen et al., *supra* note 150, at 265.

170. David E. Rupp et al., *Changing River Network Synchrony Modulates Projected Increases in High Flows*, 57 WATER RES. RSCH. e2020WR028713, at 1 (2021).

171. M. G. Cooper et al., *Climate Elasticity of Low Flows in the Maritime Western U.S. Mountains*, 54 WATER RES. RSCH. 5602 (2018).

A few studies have evaluated observed trends in minimum flows. On the Columbia River, April-July flow volume has declined 16% over 100 years (from 1904–2009); mid-Columbia 7Q10 flows have decreased 5–38%.[172] In the locations in Idaho that contribute to flows on the Snake River, decreasing minimum daily flows have been observed over the period from 1967–2007.[173] At the monthly scale, June and July streamflow in the CRB has decreased over the period from 1960–2012, with particularly high occurrence of relatively severe or long-lasting droughts in the SRB, relative to the rest of the CRB.[174] The extensive engineering infrastructure on the Columbia and Snake River systems makes evaluation of low flow changes somewhat challenging, which may limit the number of studies evaluating these changes in the observational record.

Decreases in low flows are consistently projected in hydrologic models across the CRB. As early as 1999, studies projected summer flows that were 10–25% lower than the historical case by 2045.[175] Since then, numerous other studies have projected changes in low flows in the CRB and on the Snake specifically of similar magnitudes.[176] One caveat is that the hydrologic models used in these studies do not simulate deep groundwater, which may mediate the effects of climate change on low flows in streams with significant groundwater contributions.[177] In the lower Snake, hydrologic model implementation and choice of GCM both contribute to uncertainty in projected low flows; around the four lower dams, most of the uncertainty originates from GCM choice.[178] This is relatively unique—in the rest of the CRB, most of the spread in low flow projections comes from hydrologic model implementation.[179] Within the CRB, the Snake has some of the greatest uncertainty in projected changes in fall low flows.[180] However, these changes are relatively small in comparison with projected changes in flows during the winter and spring.[181]

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172. Dittmer, *supra* note 146, at 627.

173. Gregory M. Clark, *Changes in Patterns of Streamflow from Unregulated Watersheds in Idaho, Western Wyoming, and Northern Nevada*, 46 J. AM. WATER RES. ASS'N 486 *passim* (2010).

174. Shengzhi Huang et al., *Linkages Between Hydrological Drought, Climate Indices and Human Activities: A Case Study in the Columbia River Basin*, 36 INT'L J. CLIMATOLOGY 280 *passim* (2016).

175. Hamlet and Lettenmaier, *supra* note 138, at 1622.

176. *See* Hamlet et al., *supra* note 149, at 408 fig.11; Wu et al., *supra* note 139, at 19 tbl.2; Tohver et al., *supra* note 98, at 1472.

177. Zachary P Meyers et al., *Old Groundwater Buffers the Effects of a Major Drought in Groundwater-Dependent Ecosystems of the Eastern Sierra Nevada (CA)*, 16 ENV'T RSCH. LETTERS 044044, at 1 (2021); Christina Tague et al., *Deep Groundwater Mediates Streamflow Response to Climate Warming in the Oregon Cascades*, 86 CLIMATIC CHANGE 189, 189–210 (2008).

178. Chegwidden et al., *supra* note 141, at 631–32.

179. *Id.* at 623, 633 fig.10c.

180. *Id.* at 630 fig.6.

181. BRUCE GLABAU ET AL., RIVER MGMT. JOINT OPERATING COMM., CLIMATE AND HYDROLOGY DATASETS FOR RMJOC LONG-TERM PLANNING STUDIES: SECOND EDITION (RMJOC-II) PART II: COLUMBIA RIVER RESERVOIR REGULATION AND OPERATIONS—MODELING AND ANALYSES 98 fig.53 (Liz Malliris & Emily Moynihan eds., 2nd ed. 2020) [hereinafter RMJOC PART II], https://www.bpa.gov/-/media/Aep/power/hydropower-data-studies/rmjoc-ll-report-part-ll.PDF.

F. Water quality

Climate change also has the potential to alter water quality, predominantly through changing water temperatures and sediment transport dynamics as flood characteristics change. Water temperatures are consistently projected to increase, which may decrease dissolved oxygen, increase the rate of chemical reactions, and increase fluxes of carbon and nutrients from sediments.[182] Observations of stream temperatures across the Pacific Northwest from 1976–2015 indicate average warming during the summer and early fall of 0.1–0.3°C/decade, with greater warming in more recent decades.[183] Studies exploring trends in other water quality metrics in the SRB are scant, perhaps due to the limited period of record of most observations.

Projections of changing water temperatures indicate that mean annual stream temperatures could warm by around 0.6°C by the 2020s, and up to 1.7°C by the 2080s across rivers in the Pacific Northwest.[184] Summer stream temperatures are expected to warm more, by 0.9°C to 2.1°C depending on the time period.[185] In the SRB specifically, August stream temperatures are expected to increase by 0.6–1.2°C by the 2040s and 1.2–2.4°C by the 2080s under a scenario that falls between RCP 4.5 and RCP 8.5.[186] Under the more aggressive RCP 8.5 scenario, annual stream temperatures are projected to warm by 2.2–4.3°C and summer stream temperatures by 3.7–7.0°C, depending on subbasin of the Snake.[187] Projected changes in stream temperatures are primarily a function of changes in air temperature, although changes in precipitation and snowmelt are also important.[188] In particular, declining snowpack and therefore snowmelt contributions to streamflow are expected to increase stream thermal sensitivity.[189] Streams with substantial groundwater contributions may experience more modest warming, at least until groundwater temperatures equilibrate to warming.[190]

182. Peter S. Murdoch et al., *Potential Effects of Climate Change on Surface-Water Quality in North America*, 36 J. AM. WATER RES. ASS'N 347 *passim* (2000).

183. Daniel J. Isaak et al., *Global Warming of Salmon and Trout Rivers in the Northwestern U.S.: Road to Ruin or Path Through Purgatory?*, 147 TRANSACTIONS AM. FISHERIES SOC'Y 566 *passim* (2018).

184. Wu et al., *supra* note 139, at 21 tbl.3.

185. *Id.*

186. Daniel J. Isaak et al., *The NorWeST Summer Stream Temperature Model and Scenarios for the Western U.S.: A Crowd-Sourced Database and New Geospatial Tools Foster a User Community and Predict Broad Climate Warming of Rivers and Streams*, 53 WATER RES. RSCH. 9181 *passim* (2017).

187. D. L. Ficklin et al., *Climate Change and Stream Temperature Projections in the Columbia River Basin: Habitat Implications of Spatial Variation in Hydrologic Drivers*, 18 HYDROLOGY EARTH SYS. SCI. 4897 *passim* (2014).

188. *Id.*

189. *Id.*

190. Jason A. Leach & R. Dan Moore, *Empirical Stream Thermal Sensitivities May Underestimate Stream Temperature Response to Climate Warming*, 55 WATER RES. RSCH. 5453 *passim* (2019).

Much of the work on understanding future changes in other water quality metrics is qualitative and demonstrates large uncertainty. For example, climate change may increase wind and water erosion on rangelands with the potential to increase stream sediment loads; however, changes in erosion are uncertain and dependent on many factors including changes in vegetation, land use, fire regimes, soil moisture, near-surface wind speeds, and precipitation intensity.[191] More severe floods could increase stream sediment loads while lower low flows could increase contaminant concentrations.[192] One of the few quantitative water quality projection studies in the basin modeled changes in water quality metrics under three future climate scenarios and for three future time periods in the Boise River Watershed.[193] Under all scenarios and future time periods they projected decreases in spring and summer streamflow, sediment load, total nitrogen, and total phosphorus which were partly countered by increases in fall and winter streamflow, sediment load, total nitrogen, and total phosphorus.[194]

The impacts of Snake River dam removals on water quality in a climate change context were discussed qualitatively in the 2020 Environmental Impact Statement (EIS) that ultimately resulted in the rejection of the dam removal alternative.[195] Free-flowing rivers would be expected to have larger diurnal variability in water temperatures, but climate change could minimize the amount of nighttime cooling.[196] Relative to dammed rivers, a free-flowing river would also warm earlier in the summer, and cool earlier in the fall.[197] Dam removal would also interact with the impacts of climate change on sediment transport, with the potential to enhance sediment transport below the dams.[198] The authors of the EIS note that the additional sediment would be expected to accumulate in the McNary Reservoir, and that greater flood peaks not attenuated by dams could increase erosion downstream.[199] A quantitative evaluation of this issue may be useful, particularly given the relatively small storage capacity of the four lower dams.

G. Additional Uncertainties

There are many uncertainties in projecting hydrologic responses to changing climate, including uncertainties stemming from emissions scenarios, climate

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191. B.L. Edwards et al., *Climate Change Impacts On Wind and Water Erosion On US Rangelands*, 74 J. SOIL WATER CONSERVATION 405 *passim* (2019).

192. P. G. Whitehead et al., *A Review of the Potential Impacts of Climate Change on Surface Water Quality*, 54 HYDROLOGICAL SCI. J. 101 *passim* (2009).

193. JungJin Kim & Jae Hyeon Ryu, *Modeling Hydrological and Environmental Consequences of Climate Change and Urbanization in the Boise River Watershed, Idaho*, 55 J. AM. WATER RES. ASS'N 133 *passim* (2019).

194. *Id.*

195. U.S. ARMY CORPS OF ENG'RS, BUREAU OF RECLAMATION & BONNEVILLE POWER ADMIN., COLUMBIA RIVER SYSTEM OPERATIONS FINAL ENVIRONMENTAL IMPACT STATEMENT 3-276, 4-32 (2020) [hereinafter COLUMBIA RIVER SYSTEM EIS], https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/14958.

196. *Id.*

197. *Id.*

198. *Id.* at 3-278.

199. *Id.* at 3-279.

models, initial conditions, downscaling methods, hydrologic models, and hydrologic parameters, among others.[200] Many of these sources of uncertainty have been addressed throughout this text in the context of projected climatic and hydrologic changes.[201] However, several additional sources of uncertainty have the potential to alter the projections presented here and may be important for water management decisions such as dam removal. Two primary additional uncertainties are land use and land cover change and upstream management.

Land use and land cover changes can significantly modify hydrologic response to climate change,[202] but are often unaccounted for in hydrologic impact studies. Climate change may alter vegetation in the basin directly through changes in growing season length and summer soil moisture or indirectly through disturbance mechanisms such as wildfire or pine beetle outbreaks.[203] Land use and land cover change may also occur as a function of socioeconomic pressures or management practices, and might include changes in logging extent or practices, fire suppression, or conversion of natural or agricultural land to urban landscapes, for example.[204] Vegetation and land use change can affect hydrology by altering snow accumulation and runoff timing,[205] the amount of water lost to evapotranspiration,[206] erosion and sediment transport to surface water bodies,[207] and, on a larger scale, atmospheric greenhouse gas concentrations.[208] Several studies have predicted vegetation changes in the twenty-first century in the CRB as a result of climate change, including increased forest productivity[209] and transition of subalpine vegetation to

200. Martyn P. Clark et al., *Characterizing Uncertainty of the Hydrologic Impacts of Climate Change*, 2 CURRENT CLIMATE CHANGE REP. 55, 55–64 (2016).

201. *Id.*

202. *See* Kabir Rasouli et al., *Are the Effects of Vegetation & Soil Changes as Important as Climate Change Impacts on Hydrological Processes?*, 23 HYDROLOGY & EARTH SYS. SCI. 4933 *passim* (2019).

203. Jessica E. Halofsky et al., *Changing Wildfire, Changing Forests: The Effects of Climate Change on Fire Regimes and Vegetation in the Pacific Northwest, USA*, 16 FIRE ECOLOGY, art. no. 4, 2020, at 1.

204. D.G. Brown et al., *Ch. 13: Land Use and Land Cover Change*, *in* CLIMATE CHANGE IMPACTS IN THE UNITED STATES: THE THIRD NATIONAL CLIMATE ASSESSMENT 318–32 (Jerry M. Melillo, Terese C. Richmond & Gary W. Yohe eds. 2014).

205. Bernt Matheussen et al., *Effects of Land Cover Change on Streamflow in the Interior Columbia River Basin (USA and Canada)*, 14 HYDROLOGICAL PROCESSES 867, 882–83 (2000).

206. *Id.*

207. *See* W. R. Osterkamp et al., *The Interactions Between Vegetation & Erosion: New Directions for Research at the Interface of Ecology and Geomorphology*, 37 EARTH SURFACE PROCESSES & LANDFORMS 23, 23–36 (2011).

208. Brown et al., *supra* note 204, at 319.

209. Gregory Latta et al., *Analysis of Potential Impacts of Climate Change on Forests of the United States Pacific Northwest*, 259 FOREST ECOLOGY & MGMT. 720, 728 (2010).

warmer forest types.[210] In addition, wildfire area burned and burn severity are projected to increase substantially,[211] which may dramatically alter vegetation communities and accelerate vegetation succession.[212] Modeling work at several catchments across North America demonstrated the potential for vegetation and soil changes to change or even reverse hydrologic outcomes from climate change scenarios that do not include vegetation and soil effects.[213] More work is needed to understand connections between vegetation change, fire, and hydrology in the CRB.[214]

Upstream management constitutes an additional source of uncertainty in hydrologic projections. Consumptive water use above the four lower Snake River dams is primarily tied to irrigated agriculture[215] and is enabled by significant infrastructure in the form of dams, reservoirs, canals, wells, and other structures.[216] Changes in water management have the potential to significantly modify downstream flows.[217] For instance, greater summer evapotranspiration and lower summer streamflow could spur increased groundwater pumping, altering groundwater levels and downstream baseflow.[218] Climate change has already begun to force management changes in the basin,[219] as discussed in the next section. Despite these adjustments, the potential for excesses and shortfalls at reservoirs has increased,[220] suggesting that further management changes may be needed in the long-term. Most of the state-of-the-art projections of changes in hydrology in the CRB and the SRB do not simulate the extensive dam infrastructure that alters flow timing, flood and low flow magnitudes, and total runoff;[221] although some projects have incorporated hydrologic simulations into reservoir operations.[222]

210. T. Sheehan et al., *Projected Major Fire and Vegetation Changes in the Pacific Northwest of the Conterminous United States Under Selected CMIP5 Climate Futures*, 317 ECOLOGICAL MODELLING 16, 27 (2015).

211. Brendan M. Rogers et al., *Impacts of Climate Change on Fire Regimes and Carbon Stocks of the U.S. Pacific Northwest*, 116 J. GEOPHYSICAL RSCH. G03037, at 1 (2011).

212. Halofsky et al., *supra* note 203, at 17.

213. *See* Rasouli et al., *supra* note 202.

214. Adrienne M. Marshall et al., *Climate Change Literature & Information Gaps in Mountainous Headwaters of the Columbia River Basin*, 20 REG'L ENV'T CHANGE, art. no. 134, 2020, at 1, 14.

215. ERIN M. MURRAY, U.S. GEOLOGICAL SURV., IDAHO WATER USE, 2015 (2018), https://pubs.usgs.gov/fs/2018/3036/fs20183036.pdf.

216. J.D. Wulfhorst & Evan Glenn, *Irrigation, Community, and Historical Development along the Upper Snake River*, 76 AGRIC. HIST. 434, 434 (2002).

217. *See* Erin E. Donley et al., *Strategic Planning for Instream Flow Restoration: A Case Study of Potential Climate Change Impacts in the Central Columbia River Basin*, 18 GLOB. CHANGE BIOLOGY 3071, 3071–86 (2012).

218. *See* Jason J. Gurdak, *Climate-Induced Pumping*, 10 NATURE GEOSCIENCE 71, 71 (2017).

219. Julia A. Jones & John C. Hammond*, River Management Response to Multi-Decade Changes in Timing of Reservoir Inflows, Columbia River Basin, USA*, 34 HYDROLOGICAL PROCESSES 4814, 4814–30 (2020).

220. *Id.* at 4814.

221. Chegwidden et al., *supra* note 111, at 626; Tohver et al., *supra* note 98, at 1463; Vano et al., *supra* note 153.

222. Hamlet & Lettenmaier, *supra* note 138; Miles et al., *supra* note 6, at 405; Tohver et al., *supra* note 98, at 3–4.

Notable exceptions are the Columbia River Management Joint Operating Committee (RMJOC) studies used in the EIS that ultimately declined the Snake River dam removal alternative in 2020.[223] These studies combined state-of-the-art hydrologic projections incorporating uncertainty from hydrologic models, climate models, and climate scenarios with operational models in order to simulate regulated and unregulated CRB flows in historical and future climates. However, these models do not appear to have been run in a scenario with the four lower Snake dams removed. Upstream water management may co-evolve with dam removal decisions; for instance, the 2020 EIS noted that dam removal could lower groundwater levels,[224] but to our knowledge, this has not been evaluated quantitatively. Quantitatively incorporating water management, including potential changes over time, into projections of future hydrologic change would better inform adaptation and management decisions such as the removal of the lower Snake dams.

IV. MANAGEMENT IMPLICATIONS

The designated purposes of the four lower Snake River dams include navigation, hydropower production, recreation, and fish and wildlife ponds;[225] irrigation water is also drawn from their reservoir pools and nearby groundwater.[226] Scientific literature on the impacts of climate change on hydrology and reservoir operations predominantly addresses hydropower issues, with relatively rare attention to navigation, recreation, or fish and wildlife pond issues; therefore, the following discussion reflects the purposes of the dams as well as the weight of scientific literature. Management of reservoirs in the CRB is already responding to climate change.[227] Changing streamflow timing, with associated higher winter/spring and lower summer/fall flows, is the most consistently observed and projected climate change impact, and is the impact to which management has most clearly responded.[228] Throughout the basin (though this has not specifically been evaluated for the four lower Snake River dams), unmanaged reservoir inflows have increased slightly in early spring, and decreased in the summer and fall.[229] In response, reservoirs have increased hedging, holding more water in the spring in anticipation of lower summer flows.[230] Despite the additional hedging, vulnerability,

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223. *See* RMJOC PART II , *supra* note 181, at 23.

224. *Id.*

225. *Ice Harbor Dam, Lower Monumental Dam, Little Goose Dam*, *Lower Granite Lock and Dam;* NAT'L INVENTORY OF DAMS DATABASE, https://nId.usace.army.mil/#/dams/system/549901/structure (Apr. 08, 2022).

226. COLUMBIA RIVER SYSTEM EIS, *supra* note 195, at 3–13, 19–20.

227. Jones & Hammond, *supra* note 219, at 4814.

228. *Id.* at 4823 fig.5b.

229. *Id.* at 4823 fig.5b, 4824 fig.6.

230. *Id.* at 4823 fig.5c.

measured as the potential for excess releases in the spring and shortfalls in the summer, has increased.[231]

Looking forward, the relatively large shifts in timing projected for the Snake River have prompted calls to re-evaluate existing rule curves.[232] Previous evaluations of the likely impact of climate change on the Columbia River system suggest that reduced water supplies overall could lead to increased competition between users, with allocation impacted by the seniority of water rights holders,[233] and that meeting minimum flow requirements on the Columbia mainstem could become more difficult.[234] On a more positive note, current water management approaches may mitigate some of the effects of climate change on streamflow; modeling of future conditions suggests that regulation in the CRB dampens climate change impacts on streamflow in winter and summer and delays the appearance of climate change signals, and that in the lower Snake, regulation mitigates the impact of climate change on low flow signals.[235]

However, the relatively small storage capacity of the Snake River dams reduces their potential role in hedging for summer low flows. For instance, an analysis based on the National Institute of Dams' recorded storage indicates that the total storage capacity of the four dams together is only about 28% of the additional flow expected, on average, over October 1-May 1 in the late twenty-first century relative to the historical case in a high-emissions climate scenario (Table 1). Critically, these estimates should also be interpreted in light of the fact that the reservoirs do not typically start a water year at zero percent of their full capacity, so the true potential to hold additional flows is likely lower than these values. An inspection of reservoir elevations and outflow at Lower Granite Dam over the 2021 water year illustrates that the Snake River dams are primarily managed as run-of-river facilities at the seasonal scale that respond to daily peaking energy demands (Figures 7, 8): water levels vary minimally at seasonal scales, but the reservoir operations respond to daily energy demands in ways that vary seasonally, with the strongest diurnal patterns in colder winter months.

Time period	Climate scenario	Dam storage/ total October-April flow (%)	Dam storage/ additional October-April flow relative to historical (%)
1971-2000	Historical	29	-

231. *Id.* at 4825 fig.8.

232. Queen et al., *supra* note 150, at 270.

233. Stewart J. Cohen et al., *Climate Change and Resource Management in the Columbia River Basin*, 25 WATER INT. 253, 254 (2000).

234. Hamlet and Lettenmaier, *supra* note 138, at 1606.

235. Tian Zhou et al., *Sensitivity of Regulated Flow Regimes to Climate Change in the Western United States*, 19 J. HYDROMETEOROL. 499, 506 (2018); Jane Harrell, Where and When Does Streamflow Regulation Significantly Affect Climate Change Outcomes 29 (2021) (unpublished M.S. Thesis, University of Washington) (on file with University of Washington).

2021-2050	RCP 4.5	20	68
2021-2050	RCP 8.5	19	55
2071-2100	RCP 4.5	18	47
2071-2100	RCP 8.5	14	28

Table 1. Storage at the four lower Snake River dams as a fraction of simulated historical and future mean flows over October 1-April 30, and of the difference between future and historical flows over the same period. Storage data from the National Inventory of Dams;[236] flow data is from Chegwidden et al.[237]

The projected changes in seasonal flow timing that characterize the Columbia River and Snake River system responses to climate change will interact with the hydropower system and power generation role of the dams. In the absence of dam removal, climate change is expected to increase winter hydropower generation on the Columbia River system through March and April, with decreased generation potential in the summer months.[238] However, power system dynamics are more complex than a simple sum of power generated: for instance, hydropower also provides flexible power generation and important ancillary services.[239] Hydropower production in the Columbia River system impacts the rest of the western U.S. electrical grid via the interconnection of the grid, explaining 35-50% of interannual variability in simulated net generation in other regions.[240] Projected changes in energy demand and changes in flow act in opposite directions: in the summer months, flows are expected to decrease while energy demand increases; in the winter, energy demand could decrease while flows increase.[241] These dynamics could exacerbate the impacts of dam removal on power generation relative to the power generation impacts in a scenario without climate change. Climate-related

236. NAT'L INVENTORY OF DAMS DATABASE, https://nid.usace.army.mil/#/downloads (May 11, 2022) (download data file "nation.csv"). Storage was calculated by summing the NID Storage column for the lower four dams (Ice Harbor: WA00347; Lower Monumental: WA00270; Little Goose: WA00331; Lower Granite: WA00349).

237. RMJOC PART I, *supra* note 136. Flows were calculated by summing bias-corrected October-April flow coming into the lower four Snake River Dams at Lower Granite Dam for each of the time periods and scenarios indicated.

238. RMJOC PART II , *supra* note 181, at 142 fig.83, 143 tbl.8.

239. Jaquelin Cochran, Trieu Mai & Morgan Bazilian, *Meta-analysis of High Penetration Renewable Energy Scenarios*, 29 RENEW. SUSTAIN. ENERGY REV. 246 (2014).

240. Nathalie Voisin et al., *Impact of Climate Change on Water Availability and its Propagation through the Western U.S. Power Grid*, 276 APPL. ENERGY 115467 (2020).

241. COLUMBIA RIVER BASIN EIS, *supra* note 195, at 26.

impacts to other parts of the western U.S. electricity grid could also have spillover impacts on the electricity grid and markets in the Pacific Northwest,[242] further complicating the estimation of the impacts of dam removal on power system dynamics. Moreover, the impacts of hydropower operations on climate forcings are not limited to their offsets of higher-emissions fuel sources: for instance, inundated surfaces have a lower albedo than the surrounding landscape, reducing the climate benefits of reservoirs that are managed largely for hydropower.[243] Reservoirs can also have complex impacts on local climate[244] and can have considerable methane emissions, though this is more commonly a concern in the case of reservoirs with large fluctuations in the water surface elevation and in tropical reservoirs.[245]

The Snake River dams are also used for navigation and barge traffic; this has been listed as one concern in the case of dam removal.[246] To our knowledge, a detailed evaluation of the impacts of climate change on barging in the Snake River system has not been conducted, although some authors have noted that lower summer flows due to climate change could extend the period over which barge traffic is stopped on the Snake, regardless of dam removal.[247]

242. Joy Hill et al., *The Effects of Climate Change on Interregional Electricity Market Dynamics on the U.S. West Coast* (Nat'l Sci. Found., Working Paper, 2021), https://www.proquest.com/docview/2510982366/abstract/7A3DE2189C0C4C3EPQ/1.

243. Georg Wohlfahrt et al., *The Albedo–Climate Penalty of Hydropower Reservoirs*, 6 NAT. ENERGY 372 (2021).

244. Zhao et al., *Impacts of Dams and Reservoirs on Local Climate Change: A Global Perspective*, 16 ENV'T RSCH. LETTERS 104403 (2021).

245. W. W. Phyoe & F. Wang, *A Review of Carbon Sink or Source Effect on Artificial Reservoirs*, 16 INT'L J. ENV'T. SCI. TECH. 2161, 2162 (2019).

246. COLUMBIA RIVER SYSTEM EIS, *supra* note 195, 4-80, Table 6-30.

247. Cohen et al., *supra* note 233, at 265.

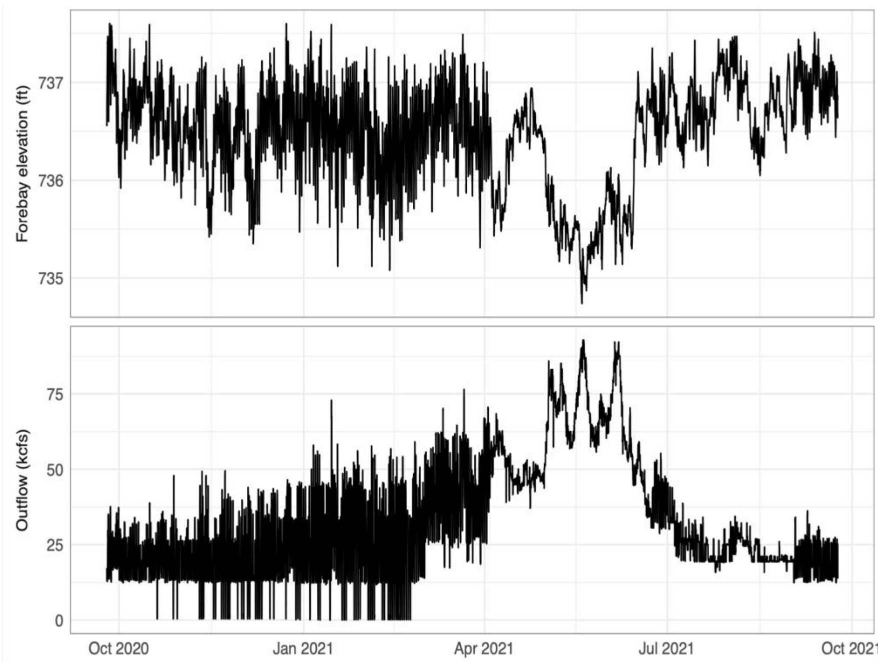

Figure 7. Hourly reservoir elevation (top panel) and outflow (bottom panel) over the 2021 water year at Lower Granite Dam; data from US Army Corps of Engineers.[248]

248. Figure made by authors with data from: U.S. Army Corps of Eng'rs, https://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/?k=lower%20granite (last visited May 21, 2022).

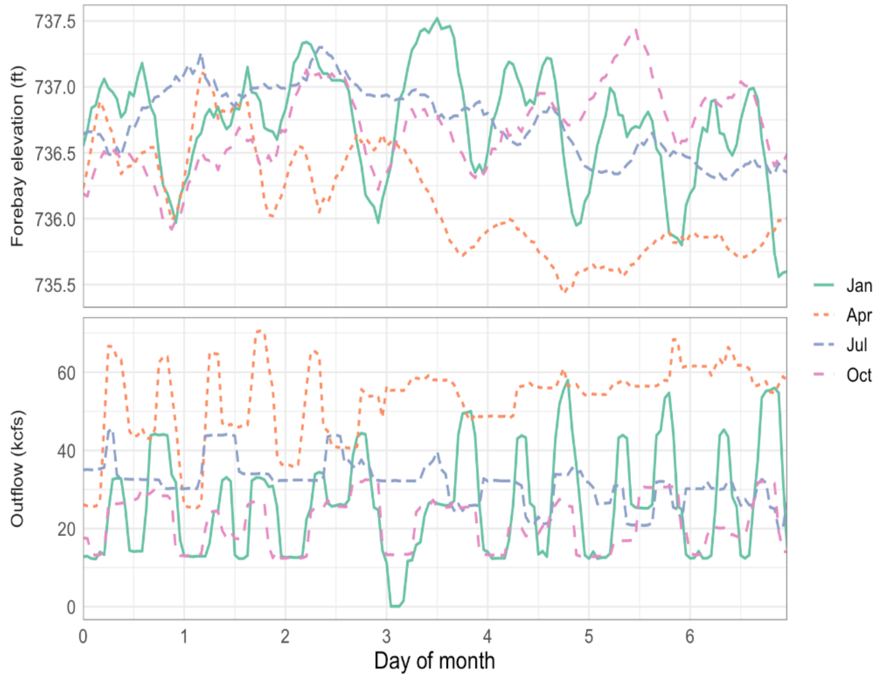

Figure 8. Hourly patterns of reservoir elevation and outflow at Lower Granite Dam, showing the first week of four selected months in water year 2021 (illustrated by color and linetype).[249]

V. CONCLUSIONS

The largest effect of climate change on streamflow in the SRB is expected to be a shift towards earlier streamflow timing as precipitation becomes rain—rather than snow-dominated in much of the basin. Minimum flows, flooding, and changes in average annual runoff are all less certain, with impacts that might be mitigated by upstream infrastructure. Ultimately, a review of the observed and projected impacts of climate change on the SRB provides information about the future conditions in which the four lower Snake River dams would likely need to operate, but is limited in its ability to inform us directly about what should be done with the dams. In light of advancing streamflow timing, potential for higher winter floods, and lower summer low flows, an argument could easily be made that the dams serve an important role in mitigating seasonal flow variability while producing power that reduces greenhouse gas emissions. However, we argue that ultimately this viewpoint may be too simplistic. Climate change will also create new and worsening environmental justice challenges; while these challenges are not interchangeable, they may heighten a moral imperative for righting historical wrongs and provide opportunities to make different decisions in a changing world. Evaluations of potential Snake River dam removal should also take into consideration other relevant factors, including fish populations, changing values, economics, and policy,

249. *Id.*

some of which are addressed in other articles in this issue. Challenges related to changing streamflow timing and high and low flows should therefore be considered carefully, quantitatively, and in the broader ecological, socio-cultural, economic, and political context, but should not be used reflexively to maintain the dams.