Columbia River Basin

SECURE Water Act Section 9503(c) Report to Congress

U.S. Department of the Interior

March 2021

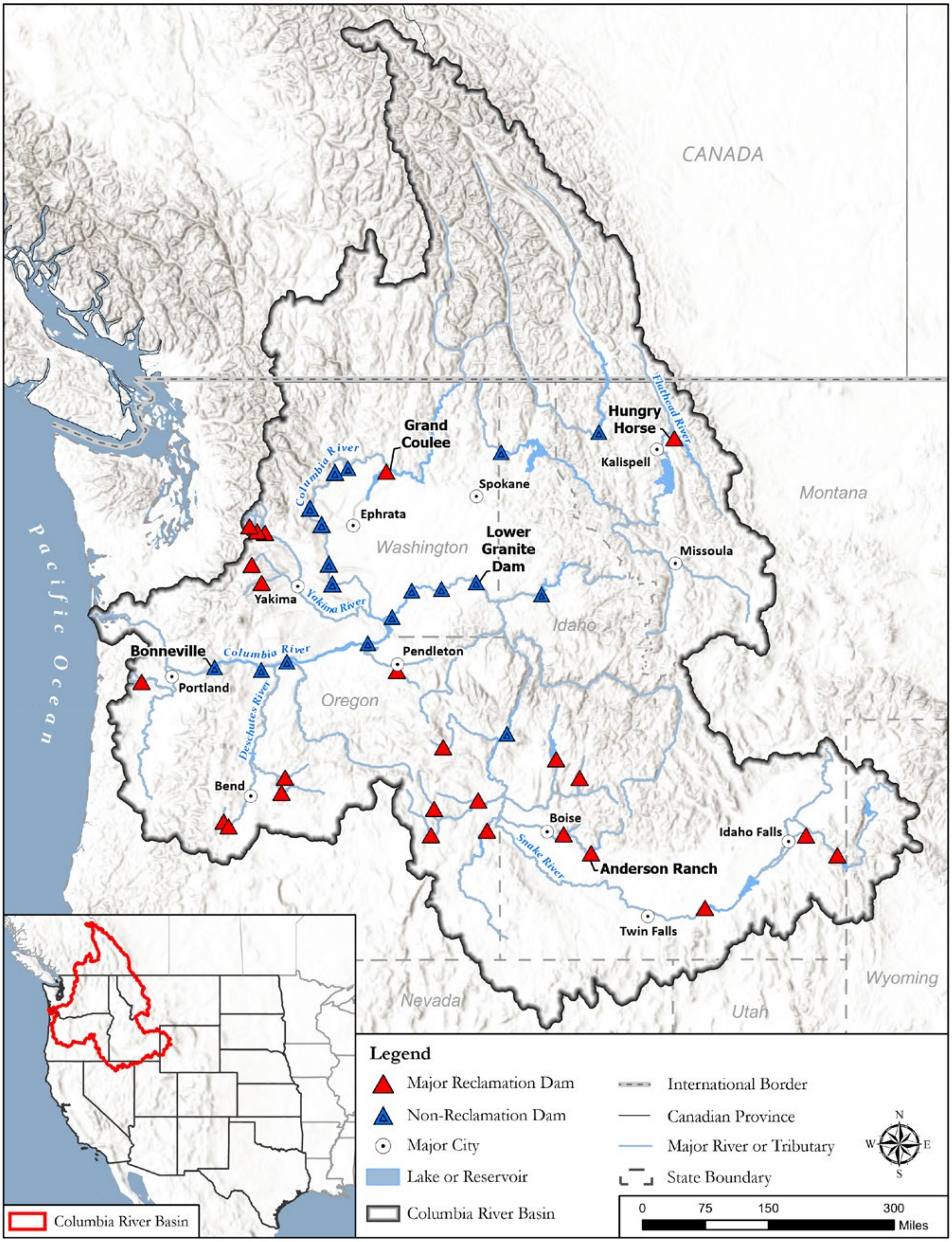
Mission Statements

The Department of the Interior conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acronyms and Abbreviations

°F	degrees Fahrenheit
BCSD	Bias Corrected Spatial Disaggregation
BPA	Bonneville Power Administration
CMIP5	Coupled Model Intercomparison Project Phase 5
ESA	Endangered Species Act
GCMs	Global Climate Models
MCM	Machine Condition Monitoring
NOAA Fisheries	National Oceanic and Atmospheric Administration National Marine Fisheries Service (formerly NMFS)
RCP	Representative Concentration Pathway
Reclamation	Bureau of Reclamation
RMJOC	River Management Joint Operating Committee
SECURE Water Act	Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act
SWE	snow water equivalent
TDG	total dissolved gas
USACE	U.S. Army Corps of Engineers
EPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
WaterSMART	Sustain and Manage America's Resources for Tomorrow


CANADA
Pacific Ocean
Montana
Washington
Idaho
Oregon
Nevada
Utah
Wyoming
Grand Coulee
Hungry Horse
Kalispell
Spokane
Ephrata
Lower Granite Dam
Missoula
Yakima
Bonneville
Portland
Pendleton
Bend
Boise
Idaho Falls
Anderson Ranch
Twin Falls
Columbia River
Yakima River
Deschutes River
Snake River
Flathead River
Legend
Major Reclamation Dam
Non-Reclamation Dam
Major City
Lake or Reservoir
Columbia River Basin
International Border
Canadian Province
Major River or Tributary
State Boundary
0 75 150 300 Miles
N S E W
Columbia River Basin

Columbia River Basin Setting

States and Provinces:

Idaho · Montana · Nevada · Oregon · Utah · Washington · Wyoming · British Columbia

Major Water Uses:

Agriculture · Municipal and Industrial · Flood Control · Hydropower · Recreation · Navigation · Fish and Wildlife Habitat

River Basin Area: 258,000 square miles

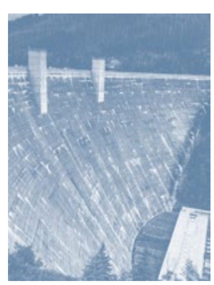
River Length: 1,243 miles

Major Rivers/ Tributaries:

- Columbia
- Snake
- Willamette
- Kootenai
- Flathead/ Pend Oreille
- Deschutes
- Yakima

Notable Reclamation Facilities:


Grand Coulee Dam


Hungry Horse Dam

Contents

ABOUT

This basin report is part of the 2021 Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act Report to Congress, prepared by the Bureau of Reclamation in accordance with Section 9503(c) of the SECURE Water Act of 2009, Public Law 111-11. The 2021 SECURE Water Act Report follows and builds upon the first two SECURE Water Act Reports, submitted to Congress in 2011 and 2016. The report characterizes the impacts of warmer temperatures, changes to precipitation and snowpack, and changes to the timing and quantity of streamflow runoff across the West.

The 17 Western States form one of the fastest growing regions in the Nation, with much of the growth occurring in the driest areas. The report provides information to help water managers address risks associated with changes to water supply, quality, and operations; hydropower; groundwater resources; flood control; recreation; and fish, wildlife, and other ecological resources in the West.

To see all documents included in the 2021 SECURE Water Act Report to Congress, go to: https://www.usbr.gov/climate/secure/

In a rare scene at Hungry Horse Dam in Montana, water is released through the outlet works due to heavy precipitation over the winter and spring.

SECTION 1

Water Management Challenges

Water management and infrastructure in the Columbia River Basin relies heavily on the ability of mountain snowpack to behave much like a reservoir; storing water in the form of snow during the winter and releasing it in the spring and summer as demand for water increases. With warming temperatures increasing the amount of precipitation that falls as rain instead of accumulating in snowpack, water managers will need to address issues such as earlier and larger peak runoff and lower summer flows. These changes have the potential to limit operational flexibility and the ability to meet competing operational objectives, such as water supply, flood control, water quality, hydropower, and fish and wildlife needs.

Basin Overview

The Columbia River is the fourth largest river in North America and the largest river in the Pacific Northwest, draining roughly 260,000 square miles and traveling more than 1,240 miles from its headwaters in the Rocky Mountains to its confluence with the Pacific Ocean. The Columbia River Basin spans seven states (Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming) and one Canadian province (British Columbia). Geography in the region is diverse and includes mountainous headwaters, deserts and dry plateaus towards the interior, and rainforests near the coast. There are many tributaries to the Columbia also discussed in this report (e.g., Snake River, Willamette River, Deschutes River, Yakima River).

The river is the lifeblood of the region, supplying water for municipal, industrial, and agricultural sectors; producing renewable, reliable, and low-cost hydropower; supporting a large recreation and tourism industry; and providing crucial habitat for fish and wildlife, including Endangered Species Act (ESA)-listed salmon and steelhead. Managing the river system to meet these diverse needs is a highly coordinated effort. Within the Columbia River Basin, the Bureau of Reclamation (Reclamation) works with numerous partners on a variety of water resource management and planning activities. These partners include other Federal agencies; State government departments (e.g., departments of water resources, ecology, and fish and wildlife/game in Idaho, Montana, Oregon, and Washington); Tribes; local entities; and water users.

Compared to other large river basins with multi-year reservoir storage capacity, the Columbia River Basin storage capacity is relatively small, comprising the capacity to hold less than 30 percent of the annual runoff. Average annual runoff from the basin totals approximately 200 million acre-feet per year, while reservoir storage in the basin totals approximately 55 million acre-feet (Hyde, 2010).

Of the more than 250 dams and reservoirs in the basin (USACE, 2012) Reclamation manages over 61[1] dams with a combined active capacity of more than 18 million acre-feet. In addition to the Columbia Basin Project and Grand Coulee Dam located on the mainstem of the Columbia River, Reclamation reservoirs are primarily concentrated in the headwaters of the Flathead River basin, Snake River basin, Yakima River basin, and Deschutes River basin.

Over the last 5 years, Reclamation has collaborated with States, public utilities, water control districts, other agencies (Bonneville Power Administration, U.S. Army Corps of Engineers, etc.), and internal and external researchers to address these water management challenges and to develop innovative solutions in the Columbia River Basin. Examples include the following:

Development of Drought Contingency Plans (see *Building Resilience to Drought* section below)

- North Santiam Watershed
- Washington State Department of Ecology
- Public Utility District No. 1 of Whatcom County, Washington

Evaluation of subbasin-specific conservation and water management alternatives

- Upper Deschutes River Basin Study
- Crooked River Reservoir Operations Pilot Study

Generation of basin-wide climate change datasets

- River Management Joint Operating Committee (RMJOC) RMJOC-II Climate Change Study

Development of new tools and technology to address emerging needs (see Section 4 of this document, *Innovations*).

[1] This number includes transferred and reserved works. Transferred works are those facilities owned by the United States, but with contractual responsibility of the operation and maintenance transferred to local irrigation districts. Reserved works are those facilities owned by the United States and operated and maintained by Reclamation.

Water Supply

The Columbia River Basin provides water for over 8 million people and irrigation to support multibillion-dollar agricultural regions. It has been estimated that over 6 percent of the annual runoff in the Columbia River Basin is diverted to irrigate approximately 7.8 mi ion acres of agricultural land. Of those acres, Reclamation's storage reservoirs are used to supply 4.3 million acres throughout the region, which contributes to the regional economy. In the most recent water use study by the U.S. Geological Survey (Dieter et al., 2018), Idaho alone ranked second in the Nation in terms of total volume of irrigation withdrawals, coming behind only California.

Flood Risk Management

Of the 55 million acre-feet of total storage, the Columbia River Basin has approximately 44 million acre-feet of authorized flood storage, including approximately 20.5 million acre-feet of storage behind the Columbia River Treaty dams in British Columbia, Canada. Flood risk management in the basin is a coordinated effort between Reclamation, the U.S. Army Corps of Engineers (USACE), Bonneville Power Administration (BPA), and BC Hydro in Canada.

Water Quality

Water temperature and total dissolved gas (TDG) are the primary water quality concerns associated with dam and reservoir operations in the Columbia River Basin. Water temperature concerns range from water that is potentially too cold in the headwaters, to elevated summer temperatures that may impact ESA-listed fish lower in the system. According to the U.S. Environmental Protection Agency (EPA)-approved temperature standards established by Idaho, Oregon, Washington, the Confederated Tribes of the Colville Reservation, and the Spokane Tribe of Indians, all or parts of the

Columbia River and lower Snake River have been identified as "impaired waters." The EPA recently released water temperature Total Maximum Daily Loads for these rivers (EPA, 2020). Water passing over dam spillways or other outlet works, whether for the purpose of passing fish or for necessary flood releases, has the potential to entrain air as it plunges into the spillway basins, causing elevated TDG levels that can be lethal for fish.

Hydropower

Over 400 hydropower dams in the northwest (including the 31 major Federal dams comprising the Columbia River System provide 60 to 70 percent of the electrical needs in the region. The inexpensive and renewable electricity provided by the hydropower system has attracted large technology companies to build energy-intensive data centers in the region. In contrast to other renewable energy sources like wind and solar that are subject to daily variations in weather conditions, hydropower is able to provide a continual power source. As more solar and wind power come online, there will be an increased need for operational flexibility of hydropower facilities to help balance power supply to meet demand. Historically, the winter months have been the period with the greatest power system reliability concerns; however, population growth and increased use of air conditioning across the region is creating an emerging concern for reliability during the summer months as well **(Figure 1)**.

Fish and Wildlife

The ESA requires agencies to ensure that their actions are not likely to jeopardize the continued existence of a listed species and that they do not result in the destruction or adverse modification of habitat designated as critical to its conservation. Reclamation currently operates according to several biological opinions (including those on the Columbia River System; the Lewiston Orchards Project; and the upper Snake, Deschutes, Tualatin, and Umatilla Rivers) to ensure compliance with its ESA obligations. In the upper Snake River basin, Reclamation operates its facilities to provide up to 487,000 acre-feet of additional flow (called flow augmentation) in the spring and summer annually for out-migrating juvenile salmonids in the lower Snake and Columbia Rivers (NOAA Fisheries, 2008).

As part of the Columbia River System Biological Opinion, the Federal Action Agencies (BPA, USACE, and Reclamation) coordinate on an array of activities aimed at improving health and survival of listed fish at all stages of their lifecycle (NOAA Fisheries, 2020 and USFWS, 2020). The agencies are working on an updated ESA consultation to improve conditions for listed fish that include several specific strategies (BPA, Reclamation, and USACE, 2020). These include activities such as habitat restoration, improvements to fish passage, and predation management. To date, billions of dollars have been invested in these activities.

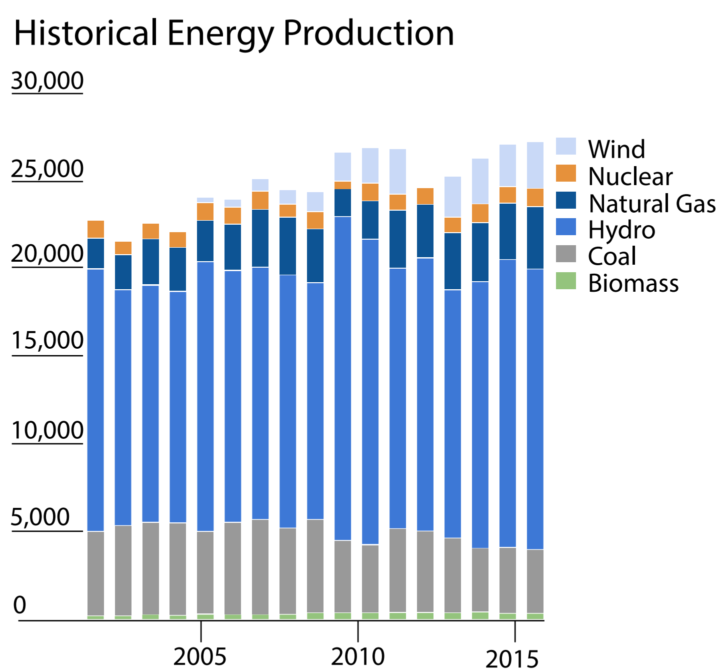


Figure 1. Total energy produced each year in the Pacific Northwest by type (NPCC, 2020).

Note: "Hydro" stands for "Hydropower".

Summary of Studies in the Columbia River Basin

- River Management Joint Operating Committee (RMJOC) RMJOC-II Climate Change Study (RMJOC-II, 2018 and RMJOC-II, 2020)
- Upper Deschutes River Basin Study (Reclamation, 2019)
- Crooked River Reservoir Operations Pilot Study (Reclamation, 2018 [Crooked River])
- North Santiam Watershed Drought Contingency Plan (North Santiam, 2018)
- Washington State Drought Contingency Plan (WSDE, 2018)
- Public Utility District No. 1 of Whatcom County, Washington Drought Contingency Plan (WPUD, 2019)

An irrigation pivot supplying water from Reclamation s Minidoka Project to a field in eastern Idaho.

SECTION 2

Analysis of Impacts to Water Resources

The most comprehensive study on potential climate change impacts in the Columbia River Basin is the second edition of the River Management Joint Operating Committee's (RMJOC) RMJOC-II Climate Change Study (RMJOC-II, 2018 and RMJOC-II, 2020). This study used 10 Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5), two downscaling techniques, two emission scenarios, and two hydrologic models to develop 160 possible streamflow future conditions. For a detailed explanation of climate projections relied on by Reclamation, please refer to Reclamation's 2021 West-Wide Climate and Hydrology Assessment, Section 2.1, and for a discussion of associated uncertainties, please refer to Section 9.1. Basin-wide study results describing temperature, precipitation, snowpack, and runoff are described below:

Temperature

Temperatures in the Columbia River Basin have been rising in recent decades and projections indicate even greater warming going into the future. According to the recent RMJOC-II Climate Change Study, temperatures have risen 1.5°F (degrees Fahrenheit) since the 1970s and are projected to increase another 1 to 4°F by the 2030s. If current emission trends continue, projections indicate warming of 4 to 10°F by the 2070s. **Figure 2** illustrates the average annual daily maximum projected temperatures over the Columbia River Basin.

Average annual daily maximum temperature across Columbia River Basin and Pacific coastal drainages (avg. across 10 models)

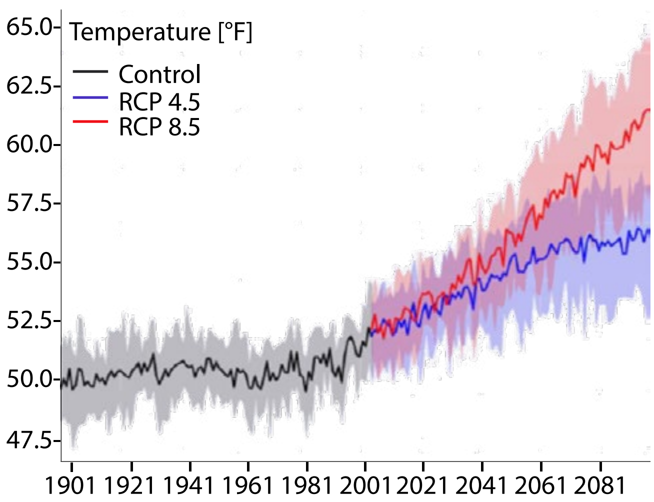


Figure 2. Average annual daily maximum temperatures, and 10th and 90th percentile temperatures, for the ten Global Climate Models (GCMs) in the River Management Joint Operating Committee (RMJOC) RMJOC-II Study for the Columbia River Basin and Pacific coastal drainages in Washington and Oregon. For Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 from 1901 to 2100. The 20th century period (shown in black and gray) is the control period for each GCM and is used to evaluate performance. The GCM time series are also bias-corrected based upon the comparison of the latter half of the control simulation to a reference dataset.

The historical period is shown in black, while two different future emission scenarios are shown in blue and red (Representative Concentration Pathway (RCP) 4.5 (lower emission scenario) and RCP 8.5 (higher emission scenario), respectively). Current emission trends are most closely following the RCP 8.5 scenario (red).

The amount of warming will vary with geography and season. The interior parts of the basin are expected to experience the greatest warming, while the coastal areas are expected to experience the least. For example, in the Deschutes River basin (a subbasin of the Columbia in central Oregon), temperature increases of 2.5 to 6.1°F are projected to occur by the 2060s. In Washington State, the largest increases in temperature (5.4°F by the 2050s) could occur during the summer, while smaller increases (4.5°F by the 2050s) could occur during the winter.

Precipitation

Trends in precipitation for the Columbia River Basin are less certain, but RMJOC-II Climate Change Study results suggest a trend towards increased annual precipitation going into the future. The Upper Deschutes River Basin Study found that, in the Deschutes River basin, median changes in precipitation amount to an increase of approximately 5 percent (the full range is a decrease of 3 percent to an increase of 11 percent) by the 2060s. **Figure 3** illustrates the annual projected precipitation over the Columbia River Basin. The historical period is shown in black, while two different future emission scenarios are shown in blue and red (RCP 4.5 and RCP 8.5, respectively).

In terms of seasonal changes to precipitation, study results from the RMJOC-II Climate Change Study, Washington State Drought Contingency Plan, and Upper Deschutes River Basin Study suggest that the increase in precipitation will occur primarily during the already-wet winter months, while the dry summer months are projected to become drier.

Average precipitation across Columbia River Basin and Pacific coastal drainages (avg. across 10 models)

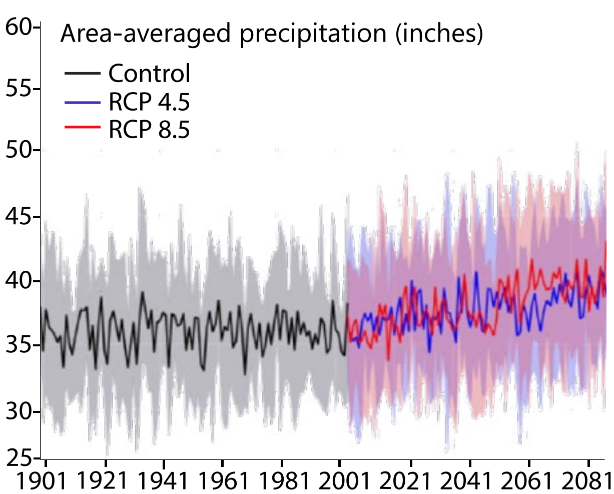


Figure 3. Average annual precipitation, and 10th and 90th percentile precipitation, for the ten Global Climate Models (GCMs) in the River Management Joint Operating Committee (RMJOC) RMJOC-II Study for the Columbia River Basin and Pacific coastal drainages in Washington and Oregon. For Representative Concentration Pathway (RCP) 4. 5 and RCP 8.5, from 1901 to 2100 (1901 to 2004 as the historical period). The 20th century period (shown in black and grey) is the control period for each GCM and is used to evaluate performance. The GCM time series are also bias-corrected based upon the comparison of the latter half of the control simulation to a reference dataset.

Snowpack

Rising temperatures in the Columbia River Basin are projected to cause an increase in the proportion of precipitation that falls as rain, rather than snow. This will result in a trend towards declining snowpack in the mountainous regions of the basin going into the future (RMJOC-II, 2018). **Figure 4** illustrates the projected changes in snow water equivalent (SWE)—the amount of water stored in snowpack. The first column in each panel of Figure 4 illustrates the distribution of snowpack for the historical period in millimeters of SWE. The three panels to the right illustrate the percent change in SWE for the 2030s, 2050s, and 2080s. The top row shows results using RCP 4.5, and the bottom row shows results using RCP 8.5.

Runoff

The combination of changes to temperature, precipitation, and snowpack will result in changes to the magnitude and seasonality of runoff. The RMJOC-II Study notes that by the 2030s, fall and winter flows are likely to be higher, spring peak runoff is likely to occur earlier, and low summer flow periods are likely to last longer. The study also notes the potential for these changes to be greatest in the Snake River basin. In the snowmelt-dominant basins of the Cascade Mountains, snowmelt is expected to occur 3 to 4 weeks earlier by the middle of the 21st century. Studies in the Deschutes River basin had similar findings of earlier runoff and higher winter and spring runoff volumes.

Columbia River Basin Snow Water Equivalent Projections

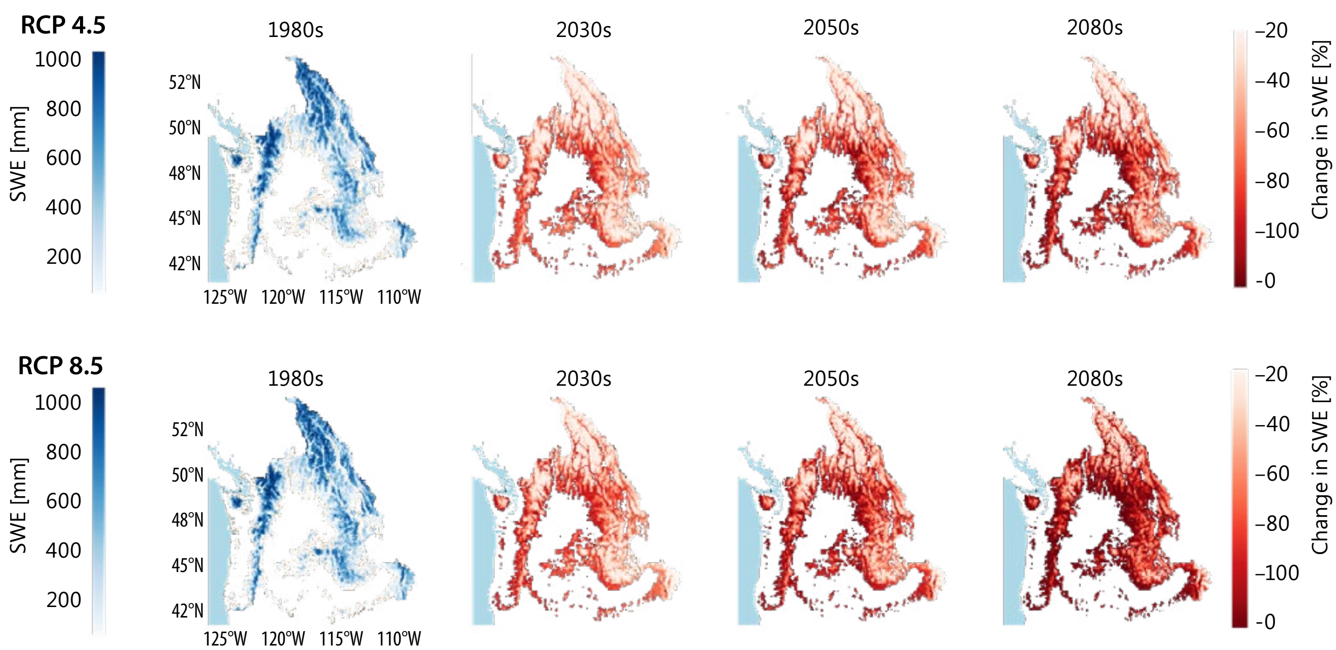


Figure 4. Columbia River Basin snow water equivalent in the 1980s, and average snow water equivalent changes by the 2030s (2020 to 2049), 2050s (2040 to 2069), and 2080s (2070 to 2099) on April 1, for the 10 Global Climate Models (GCMs) using Representative Concentration Pathway (RCP) 4.5 (top) and RCP 8.5 (bottom). Results downscaled using the Bias Corrected Spatial Disaggregation (BCSD) method (RMJOC-II, 2018).

The Crooked River Pilot Study showed significantly larger peak flows in December through February and earlier peak runoff and recession, but similar baseflows through the summer months. **Figure 5** shows the range of naturalized flows at Grand Coulee Dam for the 2030s (2020 to 2049) for RCP 4.5 and 8.5. These figures demonstrate the trend towards increased winter flows, earlier runoff peaks, and lower summer flows.

Water Management Impacts

Several studies have evaluated the impacts from the potential changes to temperature, precipitation, snowpack, and runoff both at a Columbia River Basin-wide and at a more local scale (additional detail on these projects is provided in Section 3 of this document, *Potential Adaptation Strategies to Address Vulnerabilities*):

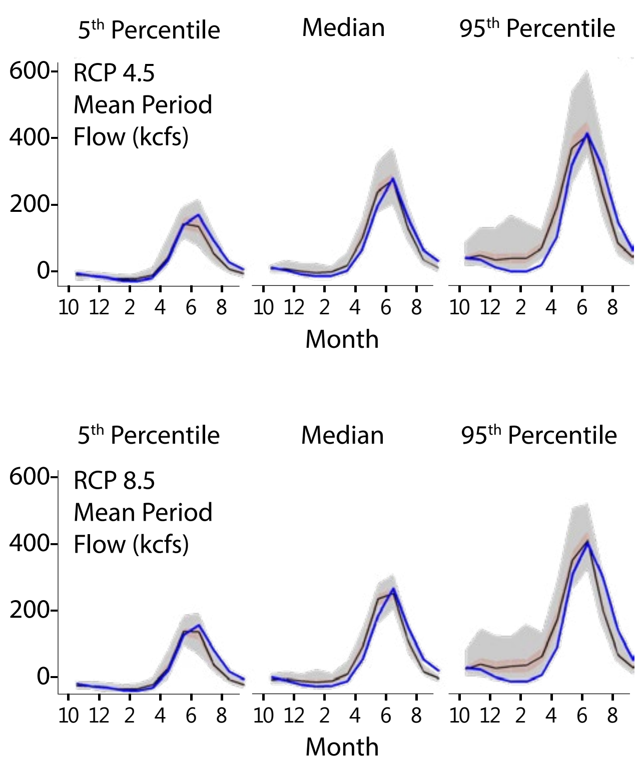
- Upper Deschutes River Basin Study
- Crooked River Reservoir Operations Pilot Study
- North Santiam Watershed Drought Contingency Plan
- Washington State Department of Ecology Drought Contingency Plan
- Public Utility District No. 1 of Whatcom County, Washington Drought Contingency Plan

Key results from these studies, along with the RMJOC-II Study, are summarized below:

Water Delivery

Lower summer snowmelt runoff will increase the reliance on stored water for irrigation in many parts of the basin. Shifts in runoff timing, lengthening growing seasons, and greater reliance on limited water storage will increase the potential for water supply shortages throughout the agricultural portions of the basin. While

Grand Coulee Distribution of Monthly Natural Flows



Future Projections

Interquartile Range

Median

Min-Max

Modeled Historic (WY 1976-2005)

Average of Baselines

Figure 5. Distribution of the River Management Joint Operating Committee (RMJOC) RMJOC-II Study naturalized flows, by month, at Grand Coulee Dam for the 2030s time period for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 (RMJOC-II, 2018).

Note: "kcfs" represents "thousand cubic feet per second" and "WY" represents "Water Year."

the Upper Deschutes River Basin Study reports an increased likelihood of filling reservoirs in the spring, it also notes an increased reliance on stored water during the summer due to lower natural flows. Similarly, the Washington State Drought Contingency Plan recognizes the important effect that increasing rain dominance in the Yakima basin will have on summer water supplies. Agriculture in the Yakima Valley currently relies on snowmelt to satisfy a significant portion of growing season irrigation demand. With declining snowpack and earlier runoff, Yakima Valley irrigators will likely look to increased deliveries from storage to meet crop requirements.

Hydropower

Warming temperatures, a shift to earlier runoff, and lower summer flows may reduce hydropower operational flexibility and the ability of the hydropower system to meet increasing demands. Recent studies suggest that warming temperatures will result in increased summer energy demand (due to increased need for air conditioning and a longer air conditioning season) and decreased winter energy demand (due to decreased need for winter heating) (BPA et al., 2020; RMJOC, 2018). However, hydrologic changes could result in increased generation capability during the winter and early spring months, but reduced generation capacity during the late-summer periods. This has important potential implications for reliability and the occurrence of power shortages going into the future.

Flood Risk Management

Reclamation reservoirs in the Pacific Northwest Region range from coastal (fed primarily from rainfall) to alpine (fed primarily from snowmelt); however, most of Reclamation's reservoirs are located in the transitional zone (receiving a mixture of rain and snow as their primary water source and with average winter temperatures near the freezing threshold). Projects in these mixed rain-and-snow basins are projected to exhibit the largest increase in flood risk due to a combination of warming and increased winter precipitation. The increased potential for rain-on-snow events could result in more frequent large runoff events during the winter months.

Figure 6. Looking forward, hydrologic modeling shows a trend at Grand Coulee Dam towards increased winter flows, earlier runoff peaks, and lower summer flows. These trends have the potential to lead to drought, increased wildfires, and water scarcity and water quality issues.

Flood risk management requirements are unique to each project or reservoir system and were developed using individual historical datasets, risk assumptions, flood-protection criteria, and rule-curve development techniques. While many of the reservoirs' operating criteria were developed to account for a wide range of natural variability, operating rules will need to be examined and potentially modified to ensure their adequacy for any changes brought by climate change. Similarly, water supply and runoff forecast methods used across the basin may also need to be examined and modified for climate change influences. In the Crooked River watershed (within the Deschutes River basin), the variability in the rain-snow transitional zone during the snow accumulation period has historically made water supply forecasts challenging and uncertain. As more watersheds throughout the basin trend towards mixed rain-snow dominance, this is likely to become the case for an increasing number of reservoir systems across the basin.

The Crooked River Reservoir Operations Pilot Study was conducted specifically to investigate these issues. It estimated the potential impacts of climate change flood control operations on the Crooked River and identified adaptation strategies for flood control operations. The wetter climate change scenario resulted in an additional 22 days of flows above flood stage (the elevation in the river at which flooding occurs) and increased potential for surcharge (water stored above the spillway elevation) compared to the current condition. The study also indicated the need for deeper and longer-duration reservoir drawdowns and larger reservoir discharges for flood protection.

Fish and Wildlife

The Columbia River Basin provides important habitat to a variety of fish and wildlife. Climate change is projected to have an array of interrelated and cascading ecosystem impacts, many of which are primarily associated with increases in air and water temperatures and changes to the timing and magnitude of river flows.

2015 Water Rights Curtailment in Washington State

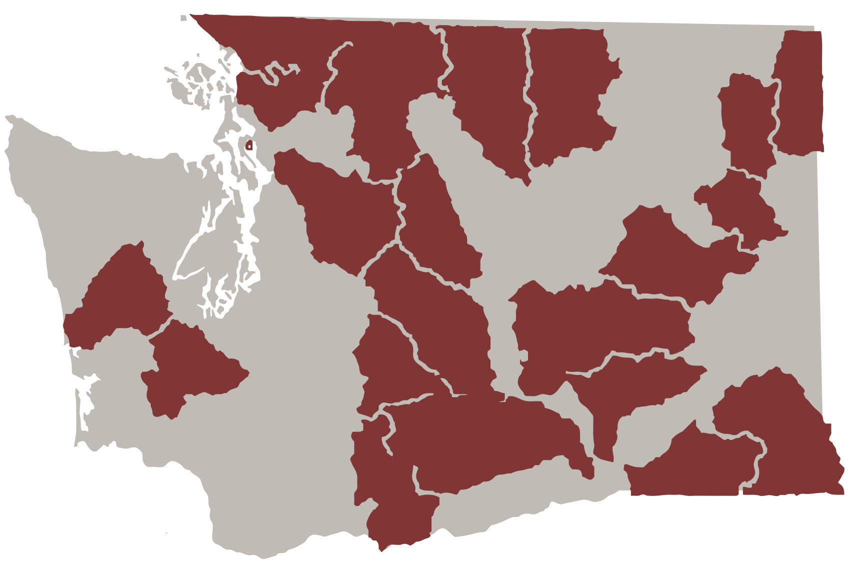


Figure 7. Water Resource Inventory Areas where water rights were curtailed in the 2015 drought.

These include increased stress on fisheries that are sensitive to a warming aquatic habitat; increased risk of watershed vegetation disturbances due to increased fire potential; shifts in the geographic range of various species; impacts on migration timing; and effects on the distribution and abundance of pests and pathogens in ecosystems. The potential for increased runoff, increased releases for flood risk management, and increased spill during the winter months may increase the number of days that the total dissolved gas concentrations exceed established thresholds. This was the case in the Crooked River Reservoir Operations Pilot Study, where climate change conditions increased the number of days with TDG levels over 120 percent.

Occurrence of Extreme Events

The Columbia River Basin has experienced extreme low- and high-water events since 2015, which could be attributed to changing climate conditions. Throughout Washington, 2015 is highlighted as an example of drought in many basins. Smaller basins like the Boise and Umatilla Rivers have both experienced high-water events in 2017, 2019, and 2020.

Extreme Dry Conditions

Conditions during the 2015 water year provide a good case study of potential climate impacts to water resources in dry years. Despite near-normal precipitation across the basin, warmer than normal temperatures (5.1 to 7.6°F above average) resulted in a record-low snowpack, increased runoff during the winter months, and earlier snowmelt. With less snowpack available to sustain streamflow and soil moisture into the warmer months, the Northwest experienced severe drought, water scarcity and water quality issues, and the most severe wildfire season in recorded history in terms of acres burned (WSDE, 2018; May, 2018) (**Figure 6**). The Washington State Drought Contingency Plan identified 2015, a drought year, as an example of new average conditions for the 21st century and documented the occurrence of widespread shortages in water supplies. In 2015, many senior water right holders had their water rights shut off for the first time in history. Agricultural losses for Washington State alone were estimated between $633 million and $773 million (May, 2018). **Figure 7** illustrates the regions in Washington where water rights were curtailed during the 2015 drought conditions.

In addition, the 2015 drought impacted recreation in the Northwest. Low water levels left popular boat ramps unusable and the State of Oregon implemented a State-wide fishing curtailment. Further, **Figure 8** illustrates an example of extreme low-flow conditions. The image is of Teanaway River in the Yakima basin in Washington State during the summer of 2015.

Teanaway River in July 2015

Figure 8. Teanaway River in Washington in July 2015. On July 9th, the Teanaway River was flowing at 8 cubic feet per second. The normal range for this particular day is between 75 to 200 cubic feet per second. With flows this low, water temperature is also a major problem. The river gage at Red Bridge Road reported water temperature of 78.8°F that day. (Photograph courtesy of Washington State Department of Ecology, all rights reserved)

The National Oceanic and Atmospheric Administration National Marine Fisheries Service's (NOAA Fisheries) 2015 Adult Sockeye Salmon Passage Report (2015 Report) (NOAA Fisheries, 2016) indicated that in 2015 losses to ESA-listed Snake River sockeye salmon *(Oncorhynchus nerka)* exceeded 95 percent in the Columbia River between Bonneville and Lower Granite Dams. NOAA Fisheries' 2015 Report documents that migration conditions during June and July of 2015 were detrimental to sockeye salmon as the species sustained heavy losses in the Columbia and Snake Rivers and their tributaries (NOAA Fisheries, 2016). ESA-listed Snake River sockeye salmon and Lake Wenatchee and Okanogan River sockeye salmon (Columbia River sockeye) both exhibited poorer migration survival than recent history.

The cause of high losses has been linked to river conditions, including high river temperatures during migration. During the summer of 2015, low flow conditions combined with higher than normal air temperatures (e.g., in Washington there were several warm events well above average) resulted in high stream temperatures in the Columbia and Snake Rivers, and their tributaries (Reclamation, 2018 [Lake Roosevelt]). As stated in NOAA Fisheries' 2015 Report (NOAA Fisheries, 2016), tributary temperatures in the Okanogan and Salmon Rivers were above 77°F.

The extreme climate-related conditions that occurred during 2015 prompted several new investigations and water resource planning efforts across the basin to identify drought and low-water adaptation strategies and to ensure sustainable water supplies going into the future (May, 2018).

Annual (Oct-Sep) Boise River Runoff (LUC QU) Water Year 1896 to Water Year 2019

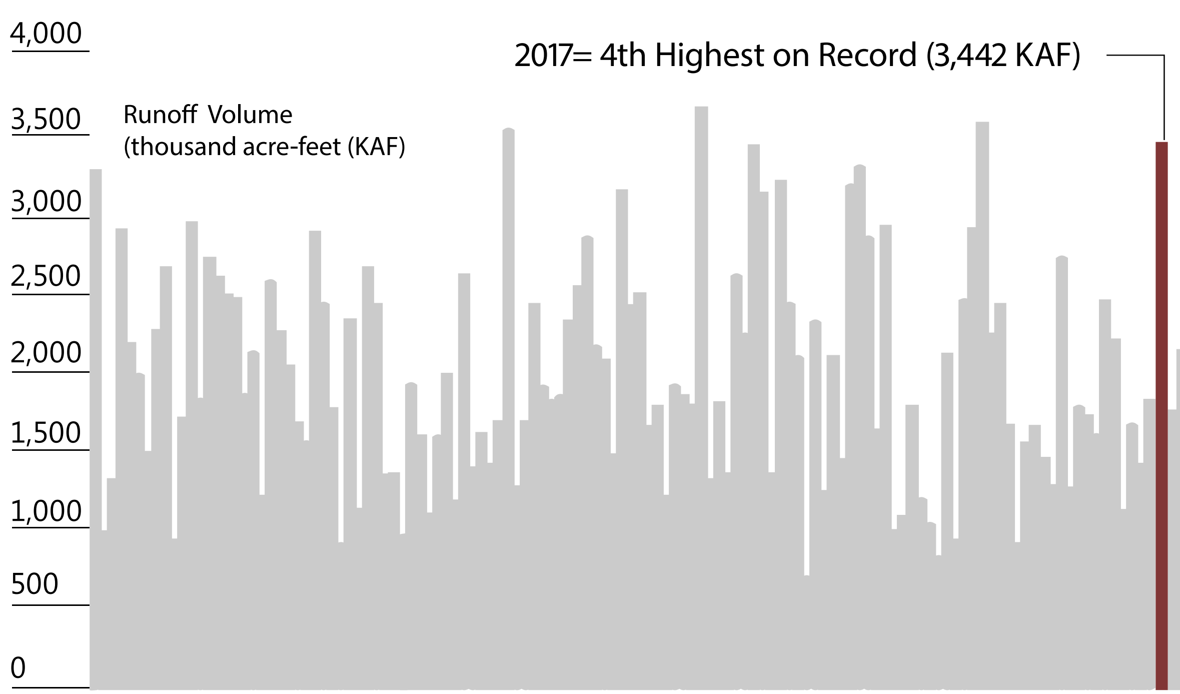


Figure 9. Annual Boise River runoff with 2017 highlighted in red showing the 4th highest runoff volume on record at 3,442 thousand acre-feet.

Figure 10. Record Boise River flood releases flooded homes in Eagle, Idaho and led to the evacuation of residents.

Figure 11. Many sections of the Boise, Idaho Greenbelt pathway were inundated by the Boise River flood releases.

For example, to mitigate the effects of the drought in the Yakima basin, irrigators, conservation groups, and State and Federal agencies worked together on a strategy to redirect water from the Yakima River through irrigation canals to seven different tributaries. This redirected water served to increase flows in the tributaries and support salmon runs and riparian habitat during the extreme drought conditions.

Extreme Wet Conditions

Future climate analysis has indicated the potential for a general increase in precipitation, which could increase runoff. The region is already experiencing some of these changes as there have been several notable high-water events in tributary basins throughout the region since 2015. While different than drought, these high-water conditions present an equally important set of challenges for water managers.

For instance, during 2017, the Boise River drainage in southwest Idaho received 135 percent of normal snowpack and 150 percent of normal water year precipitation. As a result, the Boise River saw an annual (October through September) runoff of 184 percent of normal (3,442,000 acre-feet), the fourth highest annual runoff in the period of record dating back to 1896 **(Figure 9)**.

In order to manage the runoff, water managers maintained flows downstream of the Boise River reservoir system through the City of Boise, the largest population center in Idaho, above the flood stage of 7,000 cubic feet per second for 101 days. This effort was further complicated by cooler and wetter weather that resulted in lower-than-normal irrigation diversions from the river.

High flows on the Boise River resulted in the flooding and displacement of residents situated close to the river **(Figure 10)**, caused damage to the popular Greenbelt walking and biking path that runs through the City of Boise **(Figure 11)**, and caused other nuisance flooding on properties adjacent to the river **(Figure 12**). The high flows also delayed the onset of the popular recreational river floating season. Peak regulated discharge through the city reached 9,250 cubic feet per second in early June. Without the water storage provided by the reservoir system, peak water discharge through the city would have reached 24,100 cubic feet per second in early May and flood impacts would have been devastating to the cities along the river, including Boise.

Figure 12. High flows on the Boise River.

Another example of the detrimental effects of extreme water conditions is in northeast Oregon. The Umatilla River basin experienced two significant runoff events in the back-to-back years of 2019 and 2020. During the 2019 event, torrential rain fell within the Umatilla River basin during two separate storms in early April 2019. The watershed above the system's only on-channel reservoir—McKay Reservoir (located on McKay Creek, a tributary of the Umatilla River)—produced the highest monthly inflow in the record dating back to 1928 **(Figure 13)**. This event was challenging to forecast due to uncertainty in location, timing, and magnitude of the precipitation for both water managers and the National Weather Service. The regional water operations team was proactive in March and early April to release water to increase space in McKay Reservoir before the event to minimize flooding downstream of the reservoir. Impacts would have been far greater without the proactive water regulation provided by the reservoir. The event caused damage to numerous homes and farmland along McKay Creek.

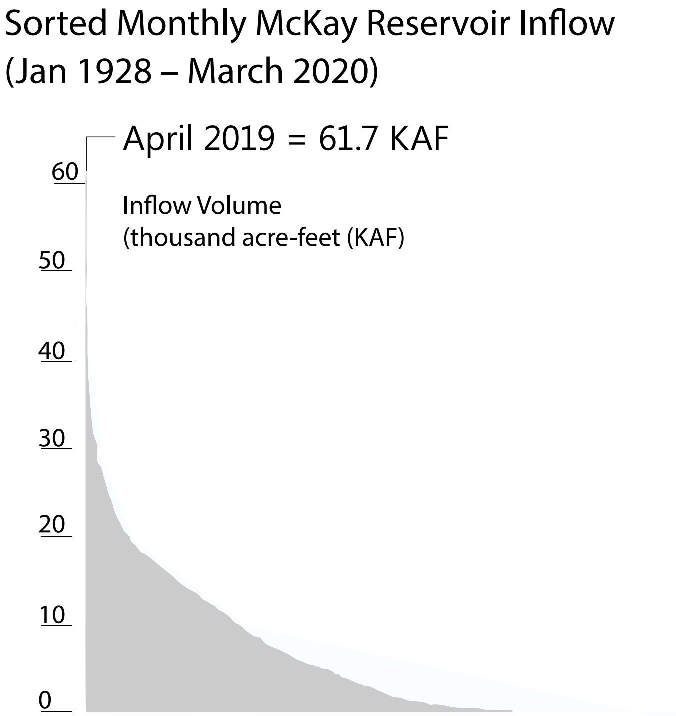


Figure 13. Monthly inflow volume to McKay reservoir sorted from largest to smallest.

In February 2020, a similar event struck the area again. For this event, McKay Reservoir had more space to capture the runoff, and the runoff from the storm was directed more towards the larger Umatilla River than McKay Creek. There were no impacts along McKay Creek below the reservoir. However, on the portion of the Umatilla River without any dams, the event again resulted in damage to homes and farmland and, this time, damage to a section of Interstate 84 that runs along the river **(Figure 14)**. In addition, notably, this event resulted in the loss of a human life. The monetary cost of the damage during this event was estimated to be $4.8 million in the City of Pendleton, Oregon alone. Examples of extreme wet conditions highlighted here show the importance of improving forecasting tools to aid water managers in meeting the many purposes of Reclamation's projects, including flood risk management.

Figure 14. Interstate 84 near Echo, Oregon during the 2020 high flow event from the Umatilla River. (Photograph courtesy of Oregon Office of Emergency Management, all rights reserved)

A scenic view of the Deschutes River in Oregon. The Upper Deschutes River Basin Study, completed in 2019, evaluated a range of potential approaches to address water supply and demand imbalances in the river, and to improve instream conditions.

SECTION 3

Potential Adaptation Strategies to Address Vulnerabilities

In recent years, Reclamation collaborated with stakeholders on the completion of several investigations of climate change adaptation strategies. These studies have identified and evaluated approaches and strategies to address future water supply and demand imbalances (Upper Deschutes River Basin Study), update flood control operations and water supply forecasting methods (Crooked River Reservoir Operations Pilot Study), and improve drought resilience and response actions (Drought Contingency Plans).

Developing Better Stakeholder Relations Using Science

The Upper Deschutes River Basin Study was a collaboration between Reclamation and the Deschutes Basin Board of Control with funding from the Oregon Department of Water Resources. The study brought together a wide-range of stakeholders with diverging interests including irrigators, city managers, and conservation groups. The study evaluated a range of potential approaches to address water supply and demand imbalances and improve instream conditions for endangered species like the Oregon Spotted Frog (**Figure 15**). It allowed stakeholders to gain a better understanding of likely future conditions through modeling the various conditions.

Figure 15. The Oregon Spotted Frog *(Rana pretiosa)* is listed as endangered under the Endangered Species Act. Much of the work in the upper Deschutes River basin is centered around improving habitat for the Oregon Spotted Frog while meeting other demands for water.

The study produced a large amount of scientific information, models, and data that can be used to evaluate water situations in the basin. Additionally, and more importantly, the study created relationships between stakeholders and formed a collective understanding of the physical processes in the system. The benefit of these relationships has become apparent in subsequent studies and has led to successful discussions about solutions to complex and often competing needs.

Adapting to Changing Conditions in Real-Time

As the effects from climate change begin to manifest in real-time, reservoir operators need to understand potential adaptations that will continue to allow them to operate safely. The Crooked River Reservoir Operations Pilot Study investigated a range of possible improvements to reservoir operations under five different climate change scenarios. The Crooked River reservoirs use a combination of dynamic flood rule curves (defined water storage space requirements depending on the time of year and the forecasted runoff) and volume forecasts (an estimate of the potential amount of runoff in a flood season) to determine the amount of space needed in the reservoir to capture the runoff and minimize the risk of downstream flooding (**Figure 16**).

The study developed a new dynamic rule curve that could meet flood protection requirements under the wetter 2080s climate change scenario and an additional dynamic rule curve for managing total dissolved gas concentrations downstream. A dry-year alternative operation was also developed to improve refill in years with less than average runoff conditions and it was able to capture almost 10,000 acre-feet more storage, compared to the current operation. Lessons learned from this study could help future planning in basins that experience increased flooding or drought due to a changing climate.

Figure 16. Aerial view of A.R. Bowman Dam (Prineville Reservoir) in Oregon.

Figure 17. Reclamation is working with partners to build resilience to drought through the development of Drought Contingency Plans.

Building Resilience to Drought

Another adaptation strategy in the basin includes building resilience to drought through Drought Contingency Plans, funded in part by Reclamation's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Drought Response Program: Drought Contingency Planning grants, over the last 5 years (**Figure 17**). These include the Washington State Drought Contingency Plan; Public Utility District No. 1 of Whatcom County, Washington Drought Contingency Plan; and North Santiam Watershed Drought Contingency Plan. These plans identified investigations or improvements that could begin now to improve future drought resiliency, as well as actions that can be taken during a drought to lessen the impacts.

In particular, the Washington State Drought Contingency Plan was completed by the Washington State Department of Ecology in response to the 2015 drought. The lessons learned from the 2015 drought were used to evaluate the State of Washington's current drought response plan and develop recommended improvements. Washington State Department of Ecology described challenges within its current plan structure, evaluated forecasting and monitoring techniques, and assessed drought vulnerability throughout the State.

The Bird Track Springs reach of the Grand Ronde River in Oregon has been heavily degraded by multiple historical practices resulting in poor aquatic and floodplain habitat. Reclamation, along with Federal and Tribal partners, is implementing a habitat enhancement project. One activity is the placement of large logs, as seen in this image, to help retain banks and provide habitat for fish.

Innovations

In addition to the studies described in Section 3 of this document, *Potential Adaptation Strategies to Address Vulnerabilities*, a variety of innovative projects and research have occurred within Reclamation's Columbia-Pacific Northwest Region since the 2016 SECURE Report as follows:

Helix Fish Passage (Cle Elum, Washington)

Potential increases in temperature and decreases in summer streamflow could negatively impact fish populations. Improvements to fish passage may help to mitigate those impacts. Traditionally, fish passage at high-head dams like Cle Elum Dam have consisted of staff who collect fish on the surface, and trap and haul methods that require high operation and maintenance costs. As an alternative, an innovative helix fish passage design that likens the spiral ramp in a parking garage was developed through a collaborative research effort with Reclamation's Hydraulics Lab in Denver, Colorado **(Figure 18)**. More than 15 computer-generated designs were considered. The helix configuration emerged as the most effective, while also minimizing turbidity during downstream passage, which can hurt fish.

Fish migrating downstream from the Cle Elum reservoir will enter an opened intake gate (only one out of the six different level gates will be open at a time based on water surface elevation) and will flow with the outflow water into the helix. Upon entering the helix, the fish will be transported with the water down a smooth spiral system to the base of the helix and into the bypass tunnel. Lastly, the fish and water will flow through the tunnel (approximately 1,400 feet) and into the Cle Elum River downstream of the dam. The results of this project will inform the design of other Reclamation fish passage projects of this type.

Tributary Habitat Improvements (La Grande, Oregon)

The Bird Track Springs project is a 2-mile intensive fish habitat restoration of the Grande Ronde River and has many design features that increase the groundwater connection, augment hydraulic flows at riffles, and promote summer cooling of the river through natural processes. In the past 2 years, the increased connectivity of the braided stream networks has allowed the natural floodplain to operate successfully in light of extreme high-water events on the Grande Ronde River (specifically, two 50+ year flood events in the spring of 2020 immediately following construction). Research is underway to better understand the potential for restoring thermal refuges (locations that are colder than the rest of the river) for cold-water salmonids.

Cavitation Mitigation using Air Injection (Grand Coulee, Washington)

Hydropower turbines are often required to operate at less than ideal conditions as the result of extreme reservoir levels driven by floods and drought, both of which could be exacerbated by changing climate conditions. Operating at these atypical conditions can damage the hydropower turbine. Reclamation has been conducting research to better detect damaging behaviors, such as turbine cavitation (sudden changes in pressure within the turbine) and vibration, which can be minimized using air injection. The novel use of air injection gives operators the ability to control vibration and, as a result, offers them more operational flexibility. The air injection system has been implemented on a single unit at Grand Coulee Dam to mitigate violent rough zone vortex collapse. Grand Coulee Dam now has plans to implement this technology across all units of the Third Powerhouse.

Machine Condition Monitoring (MCM) Project (Grand Coulee, Washington)

To continue delivering power under future climate conditions, Reclamation is developing better systems and tools that prevent unnecessary maintenance. In particular, the use of MCM to monitor the condition of plant equipment in real-time has the potential to significantly reduce operation and maintenance costs, increase plant availability, and preserve Reclamation's infrastructure. Several plants have already expanded the MCM system to include monitoring for rough zone, power system transients, turbine cavitation, and airgaps.

Figure 18. Helix fish passage design from Reclamation's research lab in Denver, Colorado (left) to construction at Cle Elum Dam near Yakima, Washington (right).

This monitoring prevents wear and increases maintenance intervals by reducing destructive operation of machines under adverse conditions. The MCM system's flexibility and expandability allow it to meet both current and future monitoring needs. Grand Coulee Dam was able to delay an unscheduled outage of generator G-21 in part due to data this system provided. Cost savings for this event alone are worth several million dollars. The technology has been tested at a number of Reclamation facilities and Reclamation's Science and Technology Program has funded another 3-year investigation to refine the technology.

Statistical Streamflow Forecasting Software

Water managers have identified the need for a modernized water supply forecasting tool to provide more robust analysis of forecast points, better understand forecast uncertainty, increase transparency, and improve efficiency. Reclamation's Columbia-Pacific Northwest Region and Missouri Basin Region staff are working collaboratively on developing and testing of a new forecasting software package. Next steps for the project involve continued development, testing, and validation between staff from both regions and with partners from USACE.

Upper Snake Planning Model (Idaho)

A new water resources planning model was recently developed to meet the need for more detailed water rights accounting studies in the upper Snake River basin. The new model configuration uses a linkage between a reservoir operations model (RiverWare) and the Idaho Department of Water Resources Water Rights Accounting Program.

Columbia River System Water Quality Model

The ability to model water temperature and TDG throughout the Columbia River System has emerged as a critical need for Columbia River Basin water managers. Through a collaborative effort with USACE, a system-wide model was developed to link a series of CE-QUAL-W2 and HEC-RAS models for the upper Columbia, Snake, and Clearwater Rivers down to Bonneville Dam on the lower Columbia River. The model was used to evaluate National Environmental Policy Act operational alternatives and the associated impacts on water quality.

Using System Dynamics Models to Evaluate Groundwater-Surface Water Interaction

This project will develop a system dynamics model and dashboard that will allow Reclamation staff to track the assumptions used in multiple groundwater-surface water interconnected projects occurring in different locations in large Reclamation basins. Using a test case in the Columbia Basin Project, this project will review how assumptions and changes in one part of the basin carry through to the planning and implementation of other projects in the basin. In addition, the project will explore development of a user-friendly dashboard backed by a system dynamics model that can be used by project managers and planners to track assumptions to ensure that all information is available when decisions are made.

Aerial view of Owyhee Dam in Oregon and its rare morning glory ring gate, also known as a glory hole.

SECTION 5

Next Steps

For next steps in the Columbia River Basin, Reclamation's Columbia-Pacific Northwest Region has identified the need for updated and refined modeling tools to address long-term planning needs, along with real-time operational needs. Some of these proposed efforts include the following:

Upper Snake Model RiverWare Refinement

The Upper Snake RiverWare model is a relatively new tool that combines the physical aspects of the river and reservoir system in RiverWare with the water rights accounting model used by Idaho Department of Water Resources. The combination of the two models is necessary to answer complex accounting questions, but it may not be necessary for other questions. This proposed project will develop a simplified physical RiverWare model that uses surrogates for the accounting inputs and will develop criteria for when it is necessary to use the more complex model versus the simplified model.

Model Refinement and Simplification

River-reservoir models are often developed for specific purposes and can be used over many years. The Columbia-Pacific Northwest Region has plans to review and refine a number of basin-specific models in the Boise, Deschutes, Yakima, and upper Snake River basins for future projects.

Converting Planning Models to Operations Models

This project seeks to expand capability for real-time operations by developing sophisticated modeling tools from existing planning models.

References

BPA et al., 2020	Bonneville Power Administration, Bureau of Reclamation, U.S. Army Corps of Engineers, 2020. Biological Assessment of Effects of the Operations and Maintenance of the Federal Columbia River System on ESA-Listed Species. January 2020.
Dalton, 2013	Dalton, M., P.W. Mote, and A.K. Snover, 2013. Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities. Washington, DC: Island Press. Available online at: https://cig.uw.edu/resources/special-reports/northwest-climate-assessment-report/ (last accessed July 8, 2020)
Dieter et al., 2018	Dieter, C.A., M.A. Maupin, R.R. Caldwell, M.A. Harris, T.I. Ivahnenko, J.K. Lovelace, N.L. Barber, and K.S. Linsey, 2018. Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, Available online at: https://doi.org/10.3133/cir1441 [Supersedes USGS Open-File Report 2017–1131] (last accessed July 8, 2020)
EPA, 2020	U.S. Environmental Protection Agency, 2020. Total Maximum Daily Load (TMDL) for Temperature in the Columbia and Lower Snake Rivers, May 18, 2020 TMDL for Public Comment. Available online at: https://www.epa.gov/sites/production/files/2020-05/documents/r10-tmdl-columbia-snake-temperature-final-05182020-web.pdf (last accessed July 8, 2020)
Hyde, 2010	Hyde, J.M, 2010. Columbia River Treaty Past and Future. Hydrovision July 2010.
May, 2018	May C., C. Luce, J. Casola, M. Chang, J. Cuhaciyan, M. Dalton, S. Lowe, G. Morishima, P. Mote, A. Petersen, G. Roesch-McNally, and E. York, 2018. Northwest Chapter in Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]. U.S. Global Change Research Program, Washington, DC, pp. 1036–1100. doi: 10. 7930/NCA4. 2018. CH24
NOAA Fisheries, 2020	NOAA Fisheries Service, 2020. Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Response for the Continued Operation and Maintenance of the Columbia River System. NMFS Consultation Number: WCRO 2020-00113. West Coast Region, Portland, Oregon. July 24, 2020.

NOAA Fisheries, 2016	NOAA Fisheries Service, 2016. NOAA Fisheries 2015 Adult Sockeye Salmon Passage Report. NOAA Fisheries in collaboration with U.S. Army Corps of Engineers and Idaho Department of Fish and Game. Available online at: https://archive.fisheries.noaa.gov/wcr/publications/hydropower/fcrps/2015_adult_sockeye_salmon_passage_report.pdf
NOAA Fisheries, 2008	NOAA Fisheries Service, 2008. Endangered Species Act Section 7(a)(2) Consultation Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation, Consultation for the Operation and Maintenance of 10 U.S. Bureau of Reclamation Projects and 2 Related Actions in the Upper Snake River Basin above Brownlee Reservoir.
North Santiam, 2018	North Santiam Watershed Drought Contingency Plan Task Force, 2018. North Santiam Watershed Drought Contingency Plan. Prepared by GSI Water Solutions Inc. and David Evans and Associates Inc. April 2018. Available online at: http://northsantiam.org/wp-content/uploads/NS-Drought-Contingency-Plan-Final_April_2_2018.pdf (last accessed July 8, 2020)
NPCC, 2020	Northwest Power and Conservation Council, 2020. Total energy produced each year in the Pacific Northwest by type. Northwest Power and Conservation Council, Portland, Oregon. Available online at: https://www.nwcouncil.org/energy/energy-topics/power-supply (last accessed July 8, 2020)
NPCC, 2017	Northwest Power and Conservation Council, 2017. 2017 Columbia River Basin Fish and Wildlife Program Costs Report: 17th Annual Report to the Northwest Governors. Northwest Power and Conservation Council, Portland, Oregon. Available online at: https://www.nwcouncil.org/sites/default/files/2018-4.pdf (last accessed July 8, 2020)
Reclamation, 2019	Bureau of Reclamation, 2019. Upper Deschutes River Basin Study: Water for Agriculture, Rivers, and Cities. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.
Reclamation, 2018 (Lake Roosevelt)	Bureau of Reclamation, 2018 (Lake Roosevelt). Thermal Regime of the Columbia River at Lake Roosevelt. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.
Reclamation, 2018 (Crooked River)	Bureau of Reclamation, 2018 (Crooked River). Crooked River Pilot Study. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.

RMJOC-II, 2018 — River Management Joint Operating Committee, 2018. Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies: Second Edition (RMJOC-II), Part I: Hydroclimate Projections and Analysis. River Management Joint Operating Committee: Bonneville Power Administration, U.S. Army Corps of Engineers, U.S. Department of the Interior Bureau of Reclamation. Available online at: https://www. bpa.gov/p/Generation/Hydro/hydro/cc/RMJOC-II-Report-Part-I.pdf (last accessed July 8, 2020)

RMJOC-II, 2020 — River Management Joint Operating Committee, 2020. 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. River Management Joint Operating Committee: Bonneville Power Administration, U.S. Army Corps of Engineers, U.S. Department of the Interior Bureau of Reclamation. Available online at: https://www. bpa.gov/p/Generation/Hydro/Documents/RMJOC-II_Part_II.pdf (last accessed August 31, 2020)

USACE, 2012 — U.S. Army Corps of Engineers, 2012. Columbia River Basin Dams Fact Sheet. May 4, 2012. Available online at: https://www.nwd.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/475820/columbia-river-basin-dams/ (last accessed July 8, 2020)

USFWS, 2020 — U.S. Fish and Wildlife Service (USFWS), 2020. Biological Opinion for Columbia River System Operations and Maintenance of 14 Federal Dams and Reservoirs in Washington, Oregon, Idaho, and Montana. USFWS Reference Number: 01EWFW00-2017-F-1650. Columbia Pacific Northwest Regional Office, Portland, Oregon. July 24, 2020.

WPUD, 2019 — Public Utility District No. 1 of Whatcom County Washington, 2019. Whatcom County Drought Contingency Plan. WPUD 116. 142. Prepared by: RH2 Engineering. Bellingham, Washington. Avail-able online at: https://www.pudwhatcom.org/wp-content/uploads/2019/10/WPUD-Drought-Contingency-Plan-FINAL2019.pdf (last accessed July 8, 2020)

WSDE, 2018 — Washington State Department of Ecology, 2018. Washington State Drought Contingency Plan. Publication No. 18-11-005. State of Washington, Department of Ecology, Water Resources Program, Olympia, Washington. Available online at: https://drought.unl.edu/archive/plans/Drought/state/WA_2018.pdf (last accessed July 8, 2020)

Authors

Jennifer Johnson, P.E., PhD
Darion Mayhorn

Technical Writer

Jesselyn Hamilton

Graphic Designers

Jordynn Eld
Bobby Gaytan

Contributors and Reviewers

Wendy Christensen, P.E.
Peter Cooper, P.E.
Brian Drake, P.E.
David Empel, RLA
Joel Fenolio, P.E.
Chris Runyan, P.E.
John Roache
Jon Rocha
Eric Rothwell
Roland Springer
Kirsten Strough
Richard Visser

Cover photo: A barge transports goods along the Columbia River.