BUREAU OF RECLAMATION

Klamath River Basin

SECURE Water Act Section 9503(c) Report to Congress

U.S. Department of the Interior

March 2021

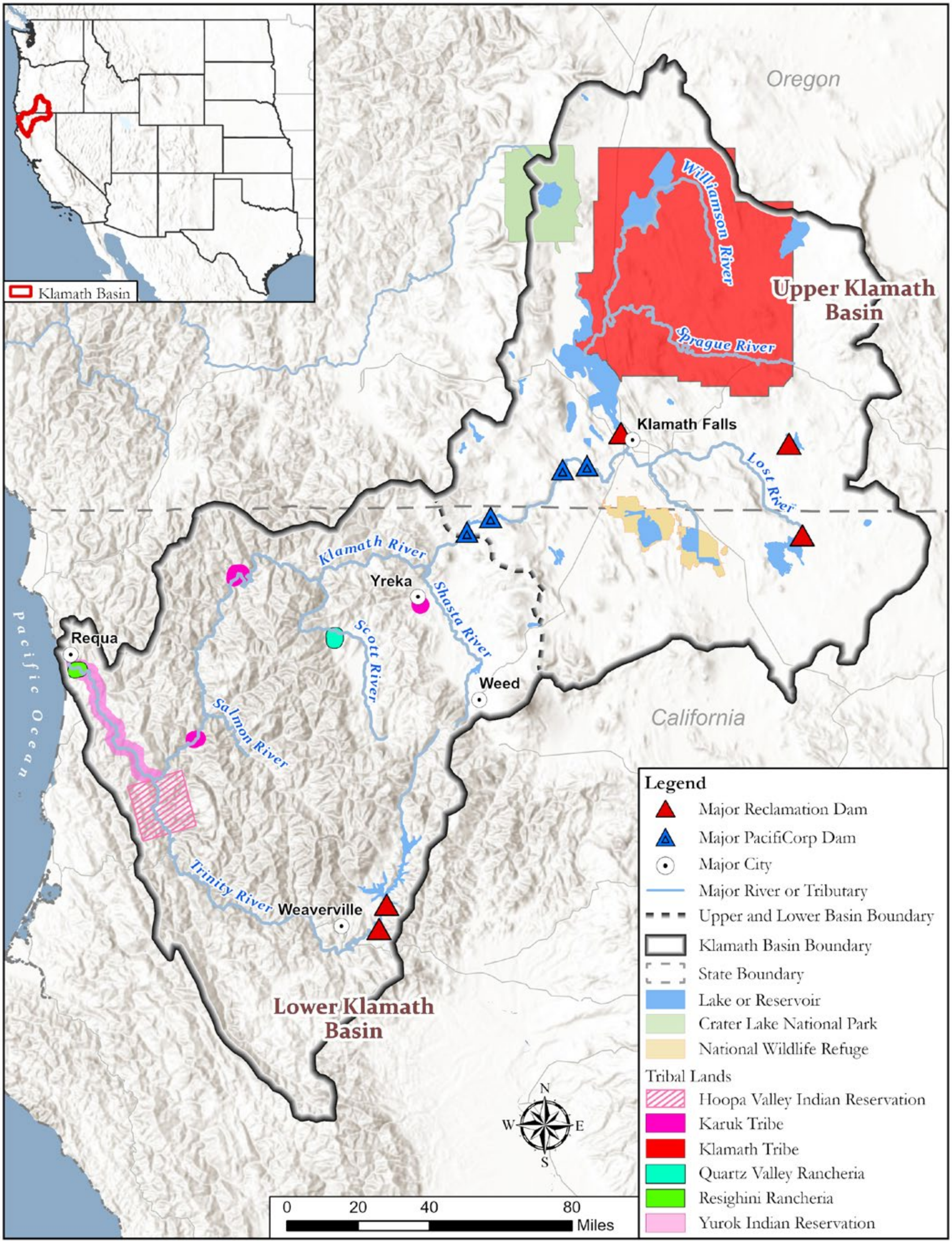
Mission Statements

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
Basin Study	Klamath River Basin Study
CDWR	California Department of Water Resources
cfs	cubic feet per second
CMIP5	Coupled Model Intercomparison Project Phase 5
CT	central tendency
ET	evapotranspiration
HD	hot-dry
HW	hot-wet
KAF	thousands of acre-feet
MWAT	maximum weekly average temperature
NOAA Fisheries	National Oceanic and Atmospheric Administration National Marine Fisheries Service (formerly NMFS)
NWR	National Wildlife Refuge
OWRD	Oregon Water Resources Department
Reclamation	Bureau of Reclamation
SECURE Water Act	Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WD	warm-dry
WW	warm-wet


Klamath Basin
Oregon
California
Upper Klamath Basin
Lower Klamath Basin
Williamson River
Sprague River
Lost River
Klamath Falls
Klamath River
Shasta River
Scott River
Salmon River
Trinity River
Yreka
Requa
Weed
Weaverville
Pacific Ocean
Legend
Major Reclamation Dam
Major PacifiCorp Dam
Major City
Major River or Tributary
Upper and Lower Basin Boundary
Klamath Basin Boundary
State Boundary
Lake or Reservoir
Crater Lake National Park
National Wildlife Refuge
Tribal Lands
Hoopa Valley Indian Reservation
Karuk Tribe
Klamath Tribe
Quartz Valley Rancheria
Resighini Rancheria
Yurok Indian Reservation
N
W
E
S
0
20
40
80
Miles

Klamath River Basin Setting

States:

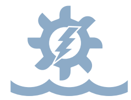

California

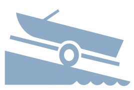

Oregon

Major Water Uses:


Agriculture


Flood Control


Hydropower


Recreation


Fish and Wildlife Habitat


Tribal Treaty Rights

River Basin Area: 15,700 square miles

River Length: 254 miles

Major Rivers/ Tributaries:

- Shasta
- Scott
- Salmon
- Trinity

Notable Reclamation Facilities:


Clear Lake Dam


Gerber Dam


Lewiston Dam


Link River Dam


Trinity 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/

Reclamation s Klamath Project has historically included approximately 254,000 acres of land, providing water to approximately 1,400 farms. Principal crops raised include alfalfa, irrigated pasture, small grains, and potatoes (Getty Images).

SECTION 1

Water Management Challenges

The Klamath River Basin has a history of complex water management challenges dating back more than a century. In large part, these challenges relate to the competing needs of the various water users; irrigation diversions; and the construction and operation of dams, which have altered the natural flow, nutrient, and sediment regimes in the river and inhibited passage of migratory fish. Existing management challenges include the Klamath River Basin's interstate geographical boundaries, potential removal of dams, and remaining unadjudicated water rights. These challenges have all contributed to difficulties in meeting water demands for agricultural, environmental, recreational, hydropower, and Tribal (treaty rights) uses. To address these challenges, the Bureau of Reclamation (Reclamation) and non-Federal cost share partners, including the California Department of Water Resources (CDWR) and the Oregon Water Resources Department (OWRD), collaborated to develop the Klamath River Basin Study (Basin Study) (Reclamation, 2016 [Basin Study]) presented in this document.

Basin Overview

The Klamath River Basin has an area of approximately 15,700 square miles. It is the second largest watershed in the State of California after the Sacramento River. Approximately 60 percent of the watershed is public land. It supports a wide range of habitats for numerous fish and wildlife species in addition to supplying water for agricultural, hydropower, Tribal, recreational, municipal, industrial, and domestic uses. The watershed is strongly influenced by the Cascade and Siskiyou mountains, which create two distinct climates—an arid climate in the upper basin, generally east of the mountains, and a maritime climate in the lower basin. The dividing line between the upper and lower basins is approximately located at Iron Gate Dam on the Klamath River.

Each basin has very different climates, hydrologic regimes, and water needs. The lower basin has historically received about 70 percent more precipitation annually than the upper basin. However, the upper basin has more than four times the irrigated acreage of the lower basin. The upper portion of the basin covers approximately 38 percent of the watershed, but contributes only 12 percent of the entire watershed's annual flow. The lower portion of the basin covers approximately 62 percent of the watershed, yet contributes 88 percent of the watershed's annual flow. The primary tributary inflows to the Klamath River are located in the Lower Klamath River Basin and include the Shasta, Scott, Salmon, and Trinity Rivers.

The Klamath River Basin extends from its headwaters north of Crater Lake National Park in Oregon to its outflow into the Pacific Ocean in Requa, California. Major water bodies include Crater Lake, Upper Klamath Lake, Tule Lake, and Trinity Lake.

The Klamath River begins south of Upper Klamath Lake near the City of Klamath Falls, Oregon. The mean annual flow of the Klamath River is about 12.9 million acre-feet per year. The primary tributaries to the Klamath River above Upper Klamath Lake include Wood River to the north, Williamson River to the north, Sprague River to the east, and inflows from the eastern flank of the Cascades. Some reaches of the river and its tributaries are classified as wild or scenic under Federal and California State law. The Klamath River contains six mainstem dams, including Link River Dam, Keno Dam, J.C. Boyle Dam, COPCO No. 1 Dam, COPCO No. 2 Dam, and Iron Gate Dam. Tribal lands within the Klamath River Basin include the Hoopa Valley, Karuk, Klamath, Quartz Valley, Resighini and Yurok reservations. Mean annual precipitation in the basin ranges from as little as 10 inches at lower elevations in the Upper Klamath River Basin to more than 70 inches in the mountains to the west. About two-thirds of the precipitation falls as snow between October and March. Historical runoff in the Klamath River Basin is highly variable from year to year. Since 1900, temperatures in the Pacific Northwest have increased by 1.8°F (degrees Fahrenheit), which is 50 percent greater than the global average. Further, the Klamath River Basin, like the Western United States overall, has experienced a general decline in spring snowpack, reduction in the amount of precipitation falling as snow in the winter, and earlier snowmelt runoff between the mid- and late-20th century. Over the next 50 years, the Klamath River Basin is projected to experience continued warming, as well as increased winter and decreased summer precipitation.

Figure 1. Algae blooms in the summer lead to low dissolved oxygen and create lethal conditions for the endangered shortnose and Lost River suckers (Getty Images).

Groundwater is an important water source for fish, wildlife, irrigators, and residents throughout the watershed and, in particular, the Upper Klamath River Basin and Scott and Shasta Valleys. Many irrigators depend on groundwater to supplement surface water supplies during drought years. The City of Klamath Falls, which is the primary population center in the Upper Klamath River Basin and has a population of about 21,000, is entirely supported by groundwater.

Located in the Upper Klamath River Basin, Reclamation's Klamath Project was authorized in 1905. The Klamath Project has historically included approximately 254,000 acres of land. It provides water to approximately 1,400 farms covering about 200,000 acres, as well as about 27,000 acres of irrigable lands in the Lower Klamath and Tule Lake National Wildlife Refuges (NWR). Principal crops raised include alfalfa, irrigated pasture, small grains, and potatoes. The value of these crops combined with others grown in the area is estimated to be approximately $204 million.

The historical estimated total consumptive use of water in the Klamath River Basin is about 2 million acre-feet per year (Reclamation, 2016 [Basin Study]). Wetland and reservoir evaporation and transpiration account for 60 percent of these consumption uses while agricultural irrigation (39 percent), along with municipal, industrial and rural domestic use (1 percent), consume the remaining water supply. Additional water uses that are primarily non-consumptive include instream flow needs and lake levels that provide sufficient water to sustain and protect Indian Trust Assets, including sufficient water to meet treaty rights such as hunting, gathering, fishery, and cultural purposes.

The Klamath River is home to numerous resident and migrating fish species. Resident fish include the shortnose *(Chasmistes brevirostris)* and Lost River suckers *(Deltistes luxatus)* which reside in the Upper Klamath River Basin. During the summer, large blooms of the blue-green algae lead to low dissolved oxygen and lethal conditions in the Upper Klamath Lake for these endangered sucker species (**Figure 1**). Spring Chinook *(Oncorhynchus tshawytscha)*, fall Chinook, and coho salmon *(Oncorhynchus kisutch)*, as well as steelhead *(Oncorhynchus mykiss)*, spawn in reaches of the Klamath River and its tributaries. Despite efforts to manage water temperature and fish hatcheries to maintain populations, coho salmon were listed as threatened in the Klamath River Basin under the Endangered Species Act.

The Upper Klamath River Basin is a part of the Pacific Flyway where hundreds of thousands of migrating birds stop to rest (**Figure 2**). The Lower Klamath and Tule Lake NWRs, located in the Upper Klamath River Basin of Oregon and California, encompass approximately 46,700 and 39,100 acres, respectively. Mean annual water use for the Lower Klamath and Tule Lake NWRs was approximately 124,000 and 95,900 acre-feet, respectively, including precipitation and water deliveries (Reclamation, 2016 [Basin Study]).

Figure 2. The Upper Klamath River Basin in Oregon is a part of the Pacific Flyway where hundreds of thousands of migrating birds stop to rest (Getty Images).

Summary of Studies in the Klamath River Basin

- Groundwater Simulation and Management Models for the Upper Klamath Basin, Oregon and California (Gannett et al., 2012)
- California Water Plan Update 2013 (CDWR, 2014)
- West Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections (Reclamation, 2015)
- Klamath River Basin Study (Reclamation, 2016 [Basin Study])
- West Wide Climate Risk Assessments: Hydroclimate Projections (Reclamation, 2016 [Hydroclimate Projections])

A canal headworks on Upper Klamath Lake in Klamath Falls, Oregon.

SECTION 2

Analysis of Impacts to Water Resources

Impacts to water and related resources in the Klamath River Basin were evaluated in the Klamath River Basin Study (Reclamation, 2016 [Basin Study]) by developing scenarios characterizing a wide range of potential changes in climatic and socioeconomic conditions in the 21st century. These scenarios are not intended to be predictions of future conditions, but rather to characterize future uncertainties in order to improve the analysis of potential impacts, development of adaptation strategies, evaluation of performance measures, and characterization of tradeoffs. To accomplish these objectives, scenarios were developed for future time horizons of 2030 and 2070 from ensembles of climate projections that bracket the range of potential futures, from less to more warming and drier to wetter conditions. A total of five climate scenarios were developed to represent future climate conditions that are warm-wet (WW), warm-dry (WD), hot-wet (HW), hot-dry (HD), and a central tendency (CT) (Reclamation, 2011).

Key findings related to historic and Coupled Model Intercomparison Project Phase 5 (CMIP5) projected changes in temperature, precipitation, snowpack, runoff, streamflow, evapotranspiration (ET), and sea level rise are presented below. 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.

Temperature – In the Klamath River Basin, average annual temperature varies considerably with cooler temperatures at higher elevations along with a cooling trend from west to east. The historical basinwide mean annual temperature varies from almost 41°F in the Upper Klamath River Basin to about 46°F near the coast. There has been about a 1°F increase since the mid-20th century. It should be noted that historical climate has not changed steadily through the 20th century. Basin average temperature has increased from the 1970s through the rest of the century, following an approximate 40-year period of relatively steady temperatures. Relative to the historic climate (1950 to 1999), temperatures are likely to continue to increase during the 21st century. Warming is projected to increase by about 2°F in the early-21st century, 3°F at mid-century, and more than 4.5°F with a potential range from 2.5°F to 10°F by the end of the century.

Precipitation– In the Klamath River Basin, precipitation increases with elevation and has a generally decreasing trend from west to east. It occurs primarily in the late fall and winter months and varies considerably between years. The seasonality of precipitation in the Klamath River Basin is typical of coastal watersheds where the winter season experiences the greatest precipitation—about 18 inches per year ranging from about 10 inches in the Upper Klamath River Basin to 22 inches near the coast. Since the 1950s, there has been a general trend toward increased precipitation (2 percent). Basin annual precipitation has fluctuated considerably during the past century, but has been relatively steady from the 1940s through the rest of the 20th century. During the 21st century, projected changes in basinwide annual precipitation include an increase of about 2 percent by mid-century to about 5.5 percent by the end of the century, with a potential range of between a 2 percent decrease to a 6 percent increase.

Snowpack, Runoff, and Streamflow– In the Klamath Mountains and the Cascade Range (**Figure 3**), winter precipitation may accumulate temporarily as snowpack, which, when it melts in the spring, may either runoff or infiltrate into the ground. Watershed ET reduces infiltrated soil moisture, which contributes to the reduction in runoff, streamflow and groundwater recharge. Starting in the 20th century, widespread decreases in springtime snowpack were observed consistently across the lower elevations of the Western United States. Snowpack losses tend to be larger at low elevations because rising temperatures cause more precipitation to occur as rainfall instead of snow at these relatively warmer lower elevations. Rising temperatures have also caused the snowpack to melt earlier in the spring, causing a shift in the timing of runoff and streamflow. Historical trends in spring (April 1) snowpack and runoff include declines of 41 percent and 6 percent respectively. The decline in runoff was roughly comparable to the increase in evapotranspiration during the historical period. Compared with the historical period (1950 to 1999), basinwide snowpack projections, as measured by snow water equivalent, indicate declines in April 1 snow water equivalent of roughly 30 to 40 percent by the 2030s and close to 60 percent by the 2070s.

Due to warming, more winter precipitation will occur as rainfall. This change is projected to cause an increase in basinwide runoff of about 10 percent by the 2030s, increasing to about 15 percent by the 2070s. However, these increases are largely confined to the north coast drainage. The Upper and Central Klamath River Basin may experience declines of up to 5 percent by the end of the century. The changes in runoff timing are reflected in streamflows in the Klamath River and its tributaries. Overall, there is a slight increase in mean annual flow with an increase in winter flows (December through March) accompanied by a decrease in the April through

Figure 3. The Lower Klamath National Wildlife Refuge is part of the Klamath Basin National Wildlife Refuge Complex that also includes Klamath Marsh, Tule Lake, Clear Lake Reservoir, and Upper Klamath (Getty Images).

September flows. As a result, the irrigation season return flow is projected to decrease by about 40 percent, with a range of 14 percent to 64 percent.

In the Klamath River Basin, groundwater is an important water source for fish, wildlife, irrigators, and residents. Groundwater provides cool, late summer streamflows for fish that sustain populations at critical times for spawning and rearing. In addition, some irrigators depend on groundwater to supplement surface water supplies during low precipitation years and drought periods. Other irrigators, along with many domestic users, depend solely on groundwater supplies.

The highest recharge to groundwater occurs along the western boundary of the Upper Klamath River Basin on the eastern slopes of the Cascade Mountains. Prior to about 2000, natural recharge regularly replenished groundwater aquifer storage. However, since 2001, the basin has experienced increased groundwater pumping, particularly within and near the Klamath Project. This increased groundwater pumping is in response to the reduced availability of surface water supplies due to required instream flows in the Klamath River established for fish species listed under the Endangered Species Act (**Figure 4**).

Projected changes in precipitation in the basin will affect recharge to groundwater in the future. Therefore, projections of groundwater recharge correspond closely with projections of future precipitation. Projected recharge is expected to increase by about 8 percent over the Upper Klamath River Basin by the 2070s, with a range from a decrease of 12 percent to an increase of 23 percent. Groundwater levels are simultaneously projected to increase by about 8 feet on average, with a range from a decrease of 7 feet to an increase of 26 feet. Projected increases in groundwater elevation are greater for the mountainous parts of the basin, with little expected change in the farmed interior parts of the basin.

Sea Level Rise – Global and regional sea levels have been increasing steadily over the past century and are expected to continue to increase throughout this century. Over the past several decades, sea level measured at tide gauges along the California coast has risen at a rate of about 6.7 to 7.9 inches per century (Cayan et al., 2009). Projections for the Washington, Oregon, and California coasts north of Cape Mendocino indicate that sea level is projected to change between a decrease of 2 inches (sea-level fall) and an increase of 9 inches by 2030, between a 1 inch decrease and a 19 inch increase by 2050, and between an increase of 4 to 56 inches by 2100 (NRC, 2012). These increases in sea level will directly impact existing aquatic habitats supporting the shellfish, smelt and salmon fisheries traditionally used by native American Tribal and other communities located in the coastal and estuarine regions of the Pacific Coast.

Figure 4. Historically, the Klamath River was the third most productive river for salmon in the continental United States (Getty Images).

Resources Category	Performance Measure	Location(s)	Measure Details
Water supplies	Total Klamath Project supply	Klamath Project	Calculated under 2013 Biological Opinion operating criteria. Compare result with full season Klamath Project supply of 390,000 acre-feet.
	Total Upper Klamath Lake seasonal supply	Upper Klamath Lake	End-of-February storage plus actual March through September inflow at Upper Klamath Lake
	Mean annual tributary flow	Shasta River; Scott River	Mean annual flow at U.S. Geological Survey (USGS) gages (USGS 11517500 Shasta River near Yreka; USGS 11519500 Scott River near Fort Jones)
Hydroelectric power resources	Hydropower production	Sum of J.C. Boyle power, COPCO 1 power, COPCO 2 power, Iron Gate power	Mean annual hydropower production summed over these facilities [1]
	Volume of spill	J.C. Boyle, COPCO 1, Iron Gate	Mean annual spill volume based on water year [1]
	Frequency of spill	J.C. Boyle, COPCO 1, Iron Gate	Mean number of spill days per water year at these facilities[1]
Recreational resources	Mean fishing days per year	Various mainstem Klamath River reaches	Mean number of days per year that flows are within acceptable ranges for select river reaches
	Mean boating days per year	Various mainstem Klamath River reaches	Mean number of days per year that flows are within acceptable ranges for select river reaches
Ecological resources	Salmonid success	Shasta River; Scott River	Flow thresholds throughout the year [2]
	Delivery to refuge	Lower Klamath National Wildlife Refuge	Mean annual water delivery to refuge [3]
	Pool elevation	Clear Lake Reservoir; Gerber Reservoir	Minimum elevation thresholds [4]
Water Quality	Water temperature	Klamath River	Maximum weekly average temperature
Flood control	Frequency of flood control release	Upper Klamath Lake	Mean number of days per year that flood control releases are made from Upper Klamath Lake [5]
	Mean annual flood control release volume	Upper Klamath Lake	Mean annual volume of flood control releases from Upper Klamath Lake [5]
	Date of seasonal peak flow	J.C. Boyle, COPCO 1, Iron Gate	Mean date of the center of mass of the annual flow volume (by water year) at select locations [1]

Table 1. Resource categories and performance measures.

1 Source: PacifiCorp

2 Source: McBain and Trush, 2014

3 Source: Klamath Basin National Wildlife Refuge Complex

4 Source: Klamath Basin Area Office

5 Source: Reclamation, 2012

Risk and Reliability Analysis

To evaluate the effects of potentially changing water supplies and demands, a system risk and reliability analysis was performed for the Klamath River Basin Study (Reclamation, 2016 [Basin Study]). The analyses were performed using the Klamath River Basin RiverWare model which was developed to encompass the entire watershed including tributaries of Upper Klamath Lake, the Lost River system, and major Klamath River tributaries, such as the Shasta River, Scott River, Indian Creek, Salmon River, and Trinity River. The model also included representation of eight reservoirs: Upper Klamath Lake, Clear Lake Reservoir, Gerber Reservoir, Lake Ewauna, J.C. Boyle Reservoir, COPCO 1 Reservoir, COPCO 2 Reservoir, and Iron Gate Reservoir. For the water quality analysis, an existing river temperature model, River Basin Model-10 (Perry et al., 2011) was used to simulate water temperatures in the mainstem Klamath River from the Link River to the mouth near Requa, California.

A framework was designed to evaluate resource categories described in the Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act. For each resource category, one or more performance measures were developed based on input from stakeholders and resource managers in the basin to evaluate historical and future vulnerabilities to meeting water needs in the basin, and to facilitate the comparison of adaptation strategies. The resource categories and performance measures are presented and described in **Table 1**.

Using the Klamath River Basin RiverWare and River Basin Model-10 models, simulations were performed to characterize historical and projected future changes in each of the performance measures. The assessment of future impacts was focused on two future time horizons: the 2030s (represented by the mean from 2020 to 2049) and the 2070s (represented by the mean from 2060 to 2089) and included characterization of uncertainty represented by the five climate scenarios (WD, HD, HW, WW and CT).

The following section summarizes the results by resource category and performance measure.

Water Supply

To evaluate the ability of the Klamath River Basin to supply water to meet human needs, the Basin Study analysis focused on four measures: the percent of full irrigation water supply to the Klamath Project (from April through September), the mean annual sum of End-of-February Upper Klamath Lake storage plus actual March through September Upper Klamath Lake inflow (**Figure 5**), mean annual flows in the Shasta River near Yreka, and mean annual flows in the Scott River near Fort Jones.

Total Klamath Project supply – Over water years 1970 to 1999, historical hydrology enables an annual average of 93 percent of full Klamath Project irrigation supply under current operating criteria, assuming a maximum supply of 390,000 acre-feet. For both 2030 and 2070, the CT scenario indicates little to no change with other scenarios ranging from an increase of 3 percent (WW) to a decrease of 12 percent (HD).

Total Upper Klamath Lake seasonal supply – On average over water years 1970 to 1999, the sum of End-of-February storage plus March to September inflows at Upper Klamath Lake was about 1.38 million acre-feet. For both 2030 and 2070, the CT scenario indicates little to no change with other scenarios ranging from an increase of 12 percent (WW) to a decrease of 13 percent (HD).

Figure 5. Link River Dam, west of Klamath Falls, Oregon, regulates elevations within Upper Klamath Lake and flow from the reservoir into the Klamath River. This reservoir is the principal source of water for the Klamath Project.

Mean annual tributary flow – Over water years 1970 to 1999, the total water supplies in Shasta and Scott Rivers without irrigation demands were simulated to have mean annual flows of 188 cubic feet per second (cfs) and 669 cfs, respectively. For the 2030 and 2070 periods, the CT scenario projects the mean annual flows in the Shasta River to increase by about 4 percent (2030) to 6 percent (2070), with a range of a 15 percent decrease (HD) to 20 percent increase (WW) by the 2070 time period.

Hydroelectric Power

To evaluate historical conditions and future impacts on hydroelectric power production, the analysis focused on the following measures: mean annual hydropower production (summed over J.C. Boyle Dam, COPCO 1 Dam, COPCO 2 Dam, and Iron Gate facilities); mean annual spill volumes at J.C. Boyle, COPCO 1, and Iron Gate Dams; and mean annual days with spill at the same three dams.

Hydropower production – Over the water years 1970 to 1999, the combined mean annual hydropower production of the J.C. Boyle Dam, COPCO 1 Dam, COPCO 2 Dam, and Iron Gate facilities was simulated to be about 26,700 megawatts. For the 2030 and 2070 periods, the CT scenario projects the mean annual hydropower production to diminish slightly by 3 percent (2030) and 6 percent (2070) (**Figure 6**). The production ranged from a maximum decline of 15 percent (2070) to a slight increase of 4 percent (2030 and 2070) in the HD and WW scenarios, respectively.

Volume of Spill – Over the water years 1970 to 1999, mean annual spill volumes at J.C. Boyle, COPCO 1, and Iron Gate Dams were simulated to be 163, 186, and 534,000 acre-feet, respectively. For the 2030 and 2070 periods, the CT scenario projects the mean annual spill volumes to increase by about 97 percent (2030) to 109 percent (2070) at J.C. Boyle Dam with the increase ranging from 54 percent (HD) to 257 percent (HW).

At COPCO 1 Dam, the CT scenario projects the mean annual spill volumes to increase by about 88 percent (2030) to 101 percent (2070) with the increase ranging from 8 percent (HD) to 213 percent (HW). At Iron Gate Dam, the CT scenario projects the mean annual spill volumes to increase by about 28 percent (2030) to 29 percent (2070) with a range of a 14 percent decrease (HD) to a 78 percent increase (HW).

Spill Days – Over the water years 1970 to 1999, mean annual days with spill at the three dam facilities were simulated to be on the order of one third of days in a year for J.C. Boyle Dam, about 12 percent of days per year for COPCO 1 Dam, and about 45 percent of days for Iron Gate Dam. For the 2030 and 2070 periods, the CT scenario projects the mean annual spill days to increase by about 82 percent (2030) to 92 percent (2070) at J.C. Boyle Dam with a range of 48 percent (HD) to 139 percent (HW). At COPCO 1 Dam, the CT scenario projects the mean annual spill days to increase by about 2 percent (2030) to 20 percent (2070), with a range of a 12 percent decrease (HD) to a 46 percent increase (HW). At Iron Gate Dam, the CT scenario projects the mean annual spill days to decrease by about 20 percent (2030) to 21 percent (2070) with a decrease ranging from 2 percent (WW) to 28 percent (WD).

Figure 6. Mean annual hydropower production for the Klamath Project will decrease slightly by 3 percent by 2030 and by 6 percent by 2070 in the central tendency scenario.

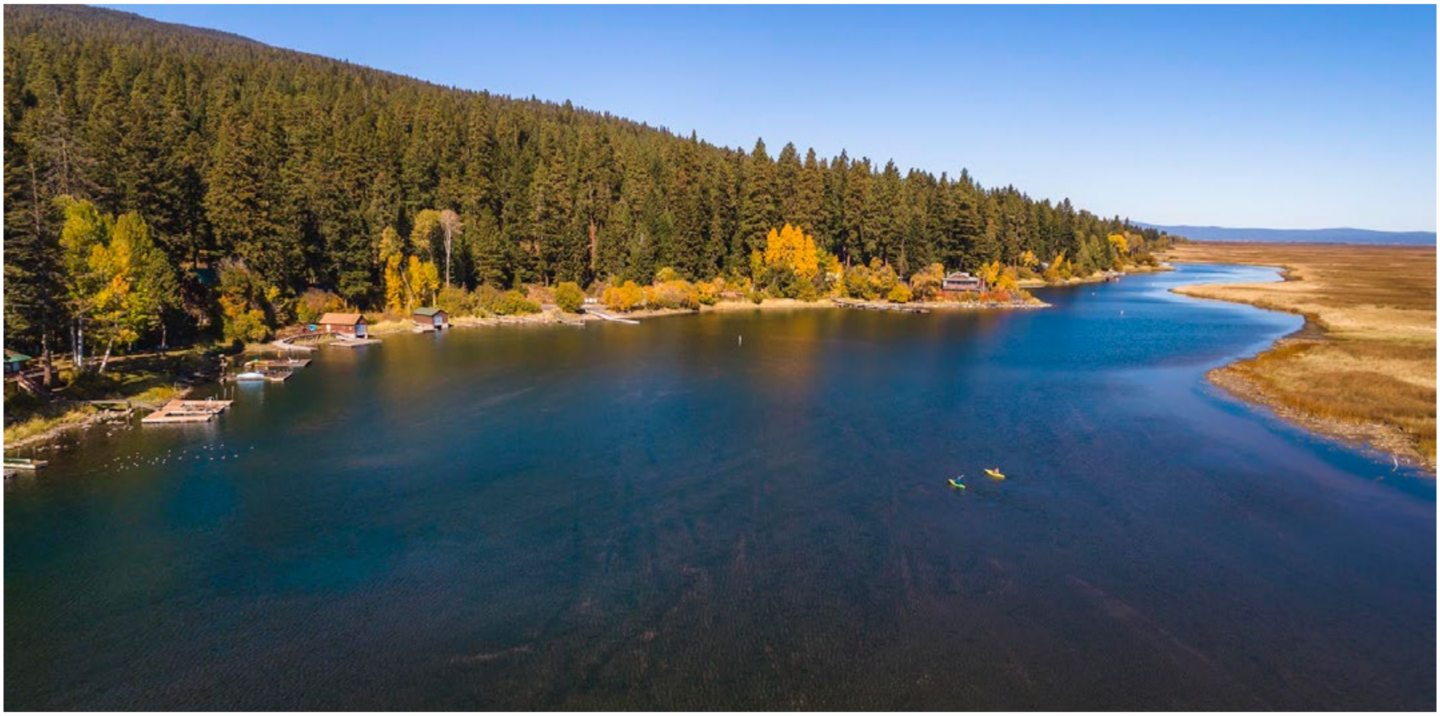


Figure 7. Recreational facilities like campgrounds and trails have drawn many tourists annually into the area. River reaches between J.C. Boyle Dam in Oregon and Iron Gate Dam in California, as well as below Iron Gate Dam, are major destinations for commercial and private whitewater rafting and kayaking (Reclamation, 2016 [Basin Study]) (Getty Images).

Recreation

Recreation impacts were evaluated by computing the mean annual number of days when flows in seven selected Klamath River, Scott River, and Trinity River reaches fell within recommended ranges of flow for fishing and boating (**Figure** 7).

Fishing days – For the 1970 to 1999 historical period, more days fell within the recommended range for fishing than for river boating. The CT scenario projects that mean annual fishing days will have little change except for the Hells Corner reach where there was about a 15 percent increase in both the 2030 and 2070 periods.

Boating days – The CT scenario projects the mean annual boating days will have little change in Scott and Trinity Rivers in both the 2030 and 2070 periods. However, significant declines occurred in the Hells Corner (20 percent to 30 percent) and Boyle reaches (6 percent to 13 percent). In these reaches, declines occurred in all scenarios except the WD and WW which had slight increases (1 percent to 5 percent) respectively in the Boyle Reach during the 2070 period.

Ecological Impacts

Ecological impacts were evaluated by computing the mean annual number of days where flows in the Scott and Shasta Rivers met or exceeded recommended flow thresholds for dry year conditions recommended by McBain and Trush (2014). Ecological impacts were also simulated by computing the mean percent of full demand supplied to the Lower Klamath NWR and minimum pool elevations in Clear Lake Reservoir and Gerber Reservoir for protection of the shortnose and Lost River suckers.

Salmonid success – Over the water years 1970 to 1999, the frequency of meeting dry year fish targets on the Scott and Shasta Rivers was simulated to 70 percent and 56 percent of the days, respectively. The CT scenario indicated a slight decrease (0 percent to 1 percent) in the frequency of meeting the dry year flow targets. The largest declines occur in the HD scenario with decreases of 8 percent and 17 percent in the 2030 and 2070 time periods, respectively. All other scenarios had declines with the exception of the WW scenario which showed slight increases of 5 percent to 8 percent in the 2030 and 2070 time periods, respectively.

Delivery to refuge – Over the water years 1970 to 1999, mean annual deliveries to the Lower Klamath NWR were simulated to be about 24,600 acre-feet. For future deliveries, all scenarios indicated declines in the amount of refuge water delivered. In the CT scenario, deliveries were about 43 percent lower in both 2030 and 2070. Declines ranged from a minimum of 21 percent to 36 percent in the WW scenario in 2030 and 2070, respectively, and to a maximum of 52 percent to 55 percent in the HD scenario in the 2030 and 2070 time periods, respectively.

Pool elevation – Frequency of meeting minimum recommended pool elevations in Clear Lake Reservoir (4520.6 feet) and Gerber Reservoir (4798.1 feet) were simulated for the historical and projected future climate scenarios. In all cases, the minimum pool elevations were met or exceeded.

Water Quality

Water quality impacts were simulated by the River Basin Model-10 for each scenario to determine the maximum weekly average temperature (MWAT) in the mainstem Klamath River. The MWAT is the highest 7-day moving average of the daily mean river temperature. Historical conditions and climate change impacts were evaluated by computing the mean MWAT across the simulation period at the Klamath River near Klamath and comparing values with those recommended in the Southern Oregon/ Northern California Coast Coho Salmon Recovery Plan (**Table 2**) (NOAA Fisheries, 2012).

Maximum Weekly Average Temperature – The MWAT fell within the "poor" classification for all years of all scenarios. In the CT scenario, the MWAT increased by 4°F in the 2030s and 5°F in the 2070s. In the other scenarios, MWAT ranged from an increase of 3°F in the WW (2030) to 8°F in the HW (2070) scenarios.

Maximum Weekly Average Temperature (MWAT) Classification	Temperature Range (degrees C)	Temperature Range (degrees F)
Poor	> 17.6	> 63.68
Fair	16 -17	60.8 - 62.6
Good	15 -16	59 - 60.8
Very Good	< 15	< 59

Table 2. Maximum weekly average temperature recommendations from the Southern Oregon/Northern California Coast Coho Salmon Recovery Plan (NOAA Fisheries, 2012).

Flood Control

Flood control in the Klamath River Basin and projected future changes were evaluated for two types of measures: flood control releases from Upper Klamath Lake, and the date of seasonal peak flow at the major mainstem Klamath River dams (J.C. Boyle, COPCO 1, and Iron Gate). For the analysis conducted in the Klamath River Basin Study, flood control rules at Upper Klamath Lake (**Figure 8**) were defined by the 2013 Proposed Action for Klamath Project Operations (Reclamation, 2012). Flood control releases from Upper Klamath Lake were computed as the flow releases beyond those required to meet Klamath Project deliveries and environmental needs. However, it is acknowledged that the RiverWare model simulations generally indicate greater flows coming from the Lost River basin, thereby resulting in less demand by the Klamath Project for Upper Klamath Lake water. This result may contribute to the seemingly high percentage of days of flood control release from Upper Klamath Lake. Greater flows from the Lost River basin may also explain some of the higher Keno Dam inflows in the winter. The date of seasonal peak flow was computed as the average date by which half of the annual flow volume has passed through the dam.

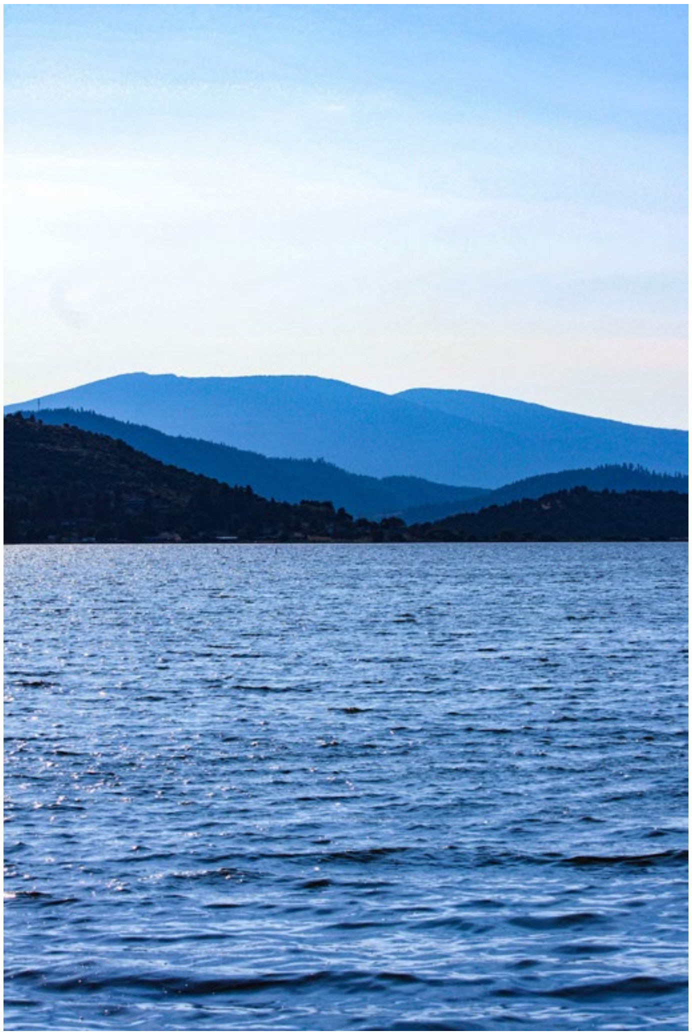


Figure 8. Upper Klamath Lake in Oregon.

Panorama of Klamath Mountains in northwestern California (Getty Images).

Frequency of Upper Klamath Lake Flood Control Releases – Analysis for water years 1970 to 1999 showed that the frequency of flood control releases from Upper Klamath Lake was approximately 44 percent of days. In the CT scenario, the frequency of flood control releases decreased slightly in both 2030 (5 percent) and 2070 (6 percent) time periods. In the other scenarios, the maximum decrease occurred in the HD scenario by 13 percent (2030 time period) and by 17 percent (2070 time period). Only in the WW scenario were there slight increases of 5 percent and 4 percent in the 2030 and 2070 time periods, respectively.

Mean Annual Flood Control Releases Volume – Analysis for water years 1970 to 1999 showed that the mean annual flood control release volume was approximately 224,000 acre-feet. In the CT scenario, the flood control release volume increased by 33 percent and 39 percent in the 2030 and 2070 time periods, respectively. In the other scenarios, the maximum increases of 63 percent and 100 percent occurred in the HW scenario in the 2030 and 2070 time periods. Slight decreases occurred in the HD (4 percent) and WD (1 percent) scenarios in 2030 which became slight increases of 11 percent and 13 percent in the 2070 time period.

Date of seasonal peak flow – Analysis for water years 1970 to 1999 showed that seasonal peak flow at J.C. Boyle, COPCO 1, and Iron Gate Dams ranged from early- to mid-April. For the 2030s, the CT scenario indicates a shift toward earlier in the year by up to 1 week at COPCO 1 Dam and Iron Gate Dam, while for the 2070s the projected change for the CT scenario is about 7 to 10 days earlier. The maximum shift toward earlier seasonal peak flow was 17 days for the HW scenario in the 2070 time period. In general, projected changes in the date of seasonal peak flow at J.C. Boyle Dam are less substantial than at the other two locations with projected changes ranging from 1 to 4 days later for the 2030s, and 4 days earlier to 3 days later for the 2070s, depending on the scenario.

Lower Klamath National Wildlife Refuge in Oregon (Getty Images).

SECTION 3

Potential Adaptation Strategies to Address Vulnerabilities

Adaptation strategies for the Klamath River Basin were developed to address vulnerabilities identified in the historical and projected risk and reliability assessment. An initial literature review identified about 50 published reports and other documents relevant to the SECURE Water Act resource categories in the Klamath River Basin. In addition to this literature review, the Basin Study team completed outreach to Klamath River Basin agency representatives, Tribal representatives, stakeholders, and residents through conference calls, attendance at water supply management and planning meetings in the basin, and public outreach. During this process, 185 adaptation strategies were identified.

To identify the most relevant, a screening process was employed. First, the strategies were grouped in five categories: increase water supply, decrease demand, modify operations, governance and implementation, and miscellaneous. Once the proposed strategies were organized into general categories, they were evaluated and screened in a staged analysis effort. These evaluation measures were developed by Reclamation in consultation with the non-Federal partners based on a previous stakeholder outreach process (Klamath Water and Power Agency, 2013) that resulted in wide acceptance of their use for the screening of the water management actions. Reclamation and the non-Federal partners applied these screening criteria to arrive at representative strategies that encompass the collective goals of the criteria including:

- **Verifiable, durable, and implementable benefits to align water supply and demand for the Klamath River Basin–** Strategies performing well under this criterion are expected to provide a measurable water supply increase.
- **Consistency with legal and regulatory requirements –** Strategies that performed well under this criterion had no identified legal and regulatory issues.
- **Affordability –** Strategies performing well under this criterion had low investment costs and/or low long-term operations and maintenance costs.

- **Flexibility –** Strategies performing well under this criterion allowed for implementation to be adjusted over time with infrastructure that could be moved or have its operations modified.
- **Protection of water rights –** Strategies performing well under this criterion had no effect on existing water rights and neighboring surface and groundwater availability.
- **Environmental and third-party impacts and benefits –** Strategies performing well under this criterion had no effect on environmental resources or impacts on water quality and other associated resources.

Figure 9 illustrates the process for identifying, screening, and evaluating adaptation strategies to result in the five adaptation strategy concepts explored through the Klamath River Basin Study.

The adaptation strategy screening process resulted in the identification of five strategy concepts that were carried forward for evaluation. Strategies within the governance and implementation category and miscellaneous category did not generally lend themselves to be evaluated quantitatively using the Basin Study models. Strategies in these two categories were documented for future consideration.

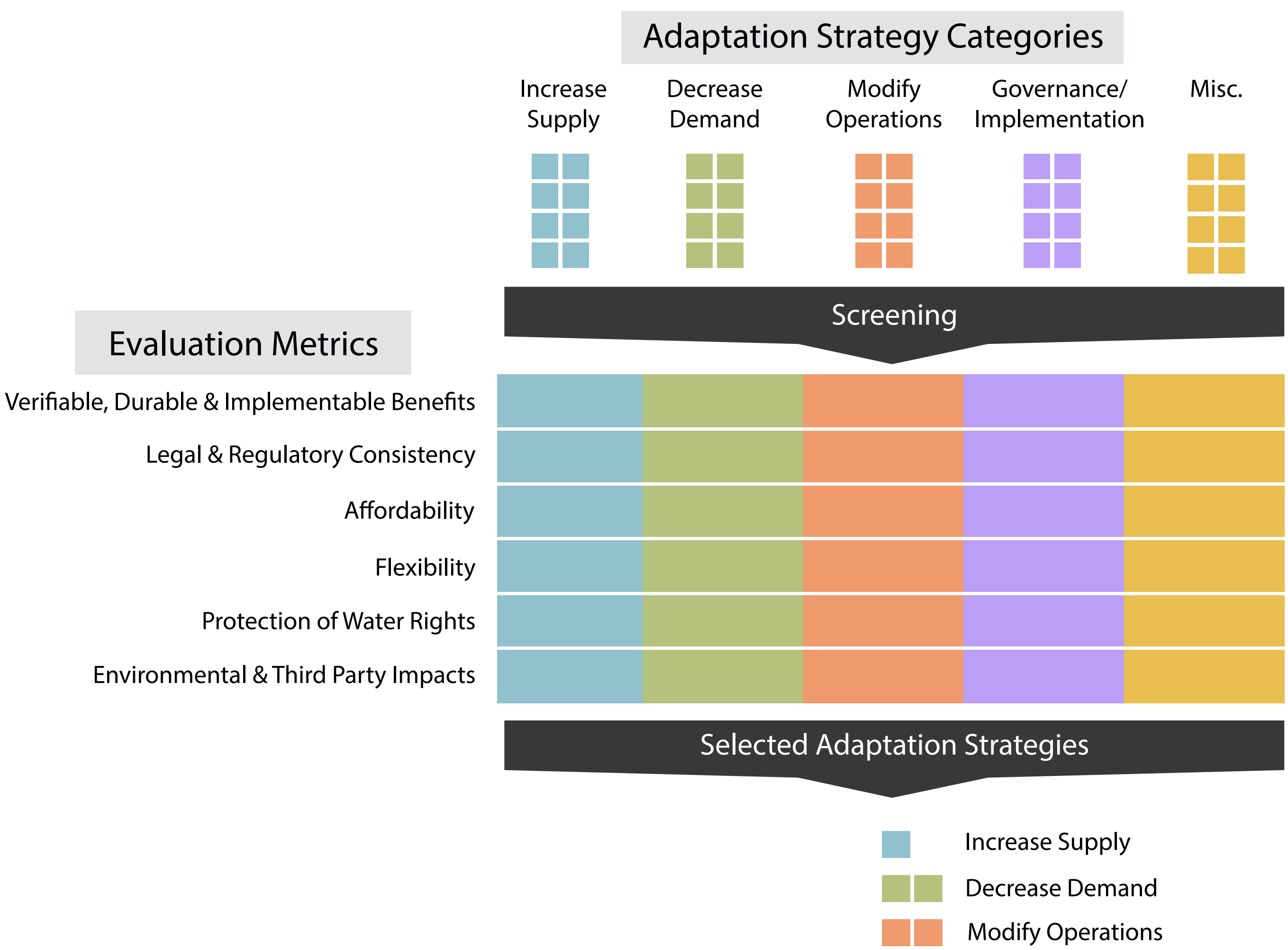
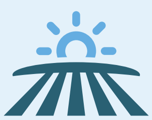


Figure 9. Adaptation strategy concept evaluation and screening.

The Klamath River Basin RiverWare model and the River Basin Model-10 water temperature model were modified as needed to simulate the performance of four potential water management actions associated with the three remaining adaptation strategy concepts. Model simulations using the five projected future scenarios provided results that could be evaluated according to system reliability measures. Key findings from these simulations are summarized in **Figure 10**.

The three representative measures described in the system reliability analysis were simulated to evaluate: the average Klamath Project supply (April through September), average annual water deliveries to Lower Klamath NWR, and average annual MWAT.

Increase Supply - Additional Water Storage Capacity – According to model simulations, substantial surface water may be available for storage in the future due to the shift from snowmelt runoff to rainfall runoff, as well as projected changes in precipitation timing and volume. Due to limited Upper Klamath Lake storage and current operational constraints, alternative storage opportunities could be explored.

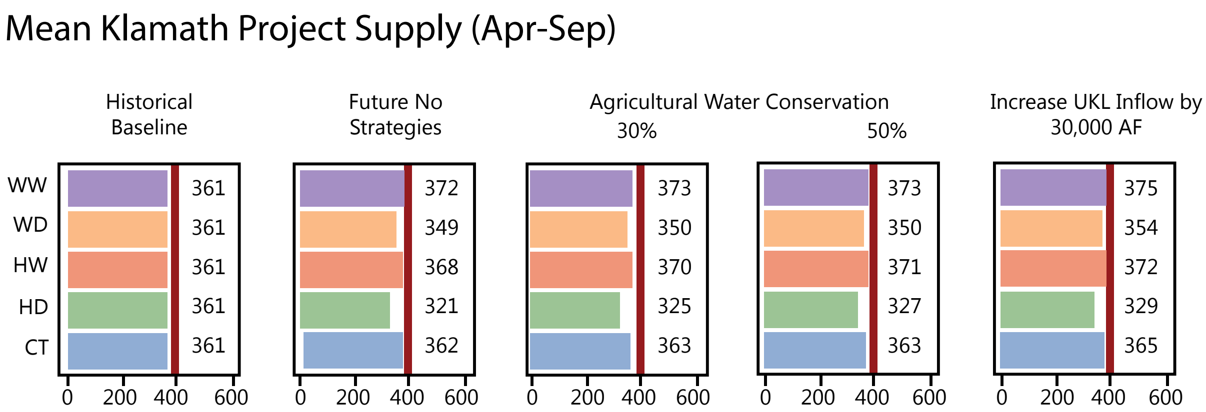


Decrease Demand - Agricultural Water Conservation – Reductions in agricultural demand in the Klamath Project are not projected to cause substantial changes in average seasonal Klamath Project supply. This result is in part due to operational rules under Biological Opinions issued by NOAA Fisheries and USFWS. However, cutting agricultural demand in half in other parts of the Klamath River Basin outside of the Klamath Project does result in noticeable increases in streamflow further downstream in the basin and, as a result, increased Klamath River hydropower production.

Decrease Demand - Additional Supply to Upper Klamath Lake – Additional inflow to Upper Klamath Lake of 30,000 acre-feet per year is the adaptation strategy concept that shows the greatest promise for reducing water supply and demand imbalances in the Klamath River Basin. Still, this additional inflow does not have substantial impact on seasonal Klamath Project supply, primarily because of operating criteria under Biological Opinions issued by NOAA Fisheries and USFWS.

Modify Operations - Tributary Water Temperature Reduction and Sensitivity of Simulated Water Temperature to Changes in Flow and Climate – These two adaptation strategy concepts illustrate that Klamath River temperature at Klamath, California is much more sensitive to changes in tributary temperature than to changes in flow. Changes to managed flows on Link River, Shasta River, Scott River, and Trinity River did improve river water temperatures slightly. However, these results show that effort spent to reduce mainstem Klamath River temperatures should focus on reducing tributary water temperature rather than modifying river operations.

Figure 10. Adaptation strategy key findings.

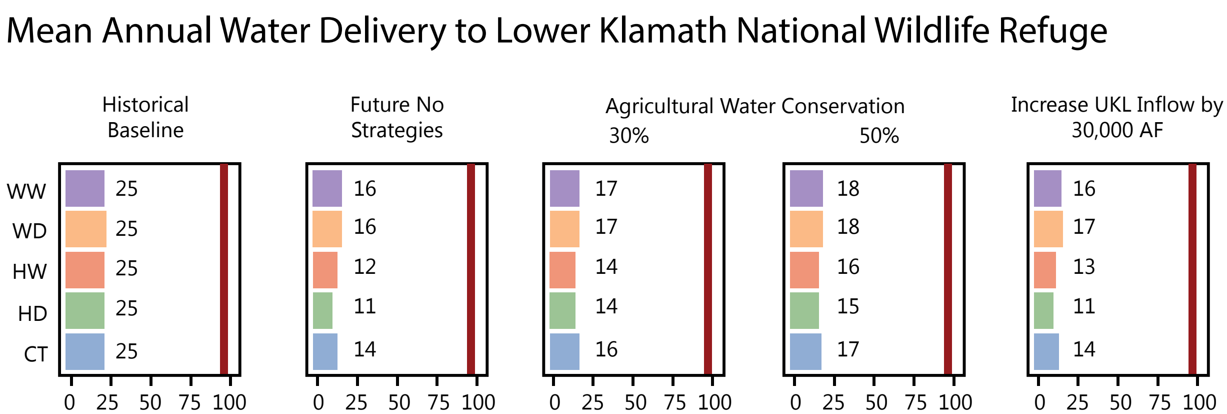


Note: Units are in thousands of acre-feet (KAF). Full seasonal supply (390,000 acre-feet) is shown as a red vertical line.
WW = Warm-Wet, WD = Warm-Dry, HW = Hot-Wet, HD = Hot-Dry, and CT = Central Tendency, AF = acre-feet

Figure 11. Historical and projected 2070s average seasonal Klamath Project supply by climate scenario with and without decrease demand adaptation strategies.

Figure 11 illustrates results for average seasonal Klamath Project supply for the historical baseline, projected future without adaptation, along with two decrease demand and one increase supply adaptation strategies. Results are shown only for those adaptation strategy concepts that potentially impact Klamath Project supply, namely agricultural conservation (reduce ET by 30 percent and 50 percent) and increased inflow to Upper Klamath Lake (add 30,000 acre-feet).

The figure shows that under both simulated historic baseline and future scenarios, the full seasonal supply is not fully met under any scenario with or without adaptation in the 2070 time period. For the CT scenario, the three adaptation strategies have seasonal supplies that are almost identical to the historic baseline and the CT future without adaptation. In general, the seasonal Klamath Project supplies are highest in the WW scenario and lowest in the HD scenario. Across the range of all climate scenarios, increasing inflows to Upper Klamath Lake by 30,000 acre-feet increases Klamath Project supply by more than the agricultural conservation measures.



Note: Units are in thousands of acre-feet (KAF). Full annual delivery to Lower Klamath National Wildlife Refuge (95,400 acre-feet) is shown as a red vertical line. UKL = Upper Klamath Lake, AF = acre-feet, LKNWR = Lower Klamath National Wildlife Refuge, WW = Warm-Wet, WD = Warm-Dry, HW = Hot-Wet, HD = Hot-Dry, and CT = Central Tendency

Figure 12. Historical and projected 2070s average annual deliveries to Lower Klamath National Wildlife Refuge by climate scenario with and without decrease demand adaptation strategies.

Figure 12 illustrates results for mean annual water deliveries to Lower Klamath NWR for the historical baseline, projected future without adaptation, along with two decrease demand and one increase supply adaptation strategies.

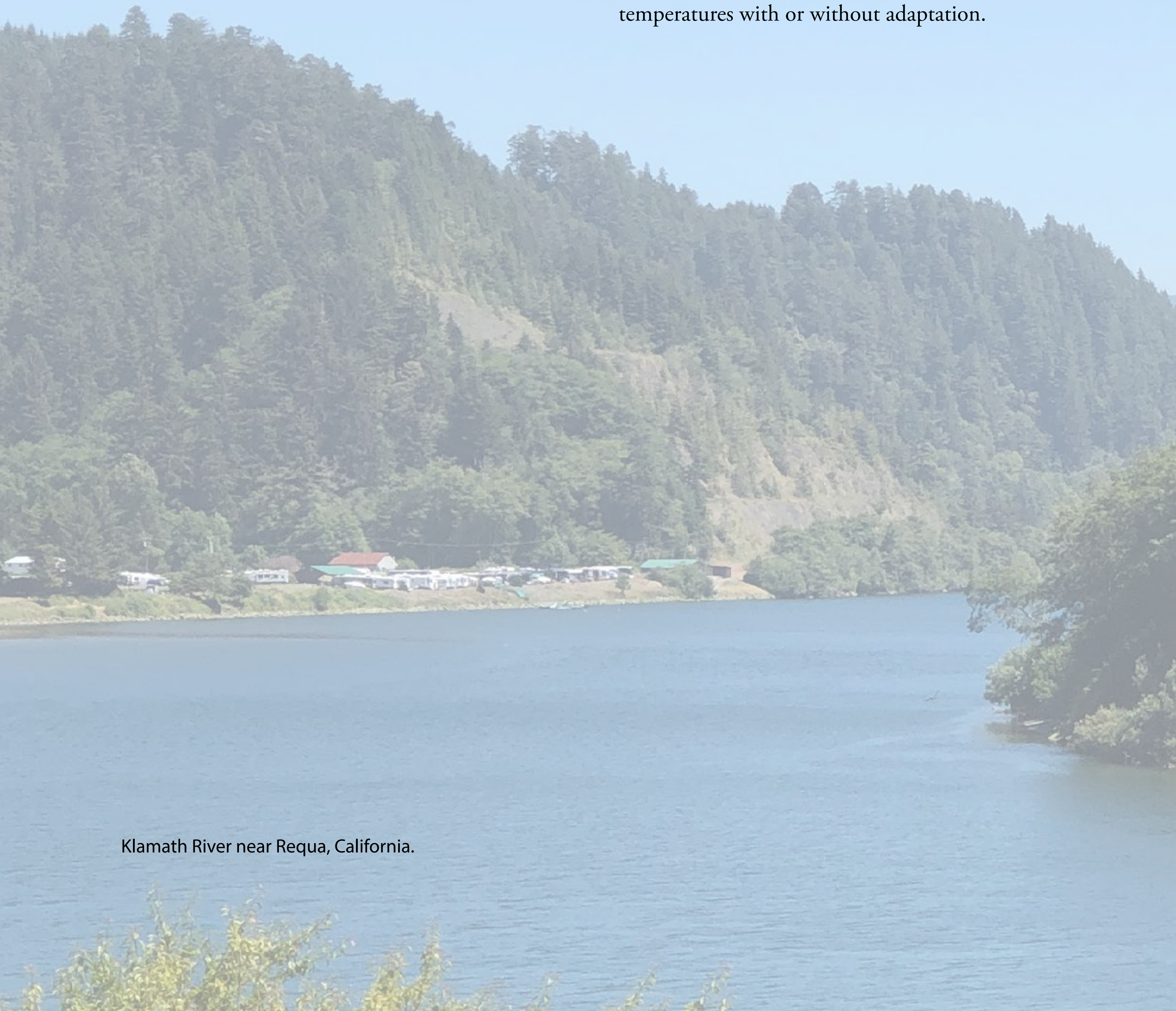
The figure shows that under both simulated historical and future scenarios, the full annual delivery to the refuge is never met. Overall, climate change negatively impacts deliveries to the refuge.

For the CT scenario, the three adaptation strategies have average annual deliveries that are less than the historic baseline and only slightly greater than the projected future without adaptation. In general, the average annual Lower Klamath NWR deliveries are highest in the WW scenario and lowest in the HD scenario. Across the range of all climate scenarios, the agricultural conservation strategies increase deliveries by more than increasing inflows to Klamath Lake by 30,000 acre-feet.

Upper Klamath Lake in Oregon is the primary source of water for Reclamation's Klamath Project.

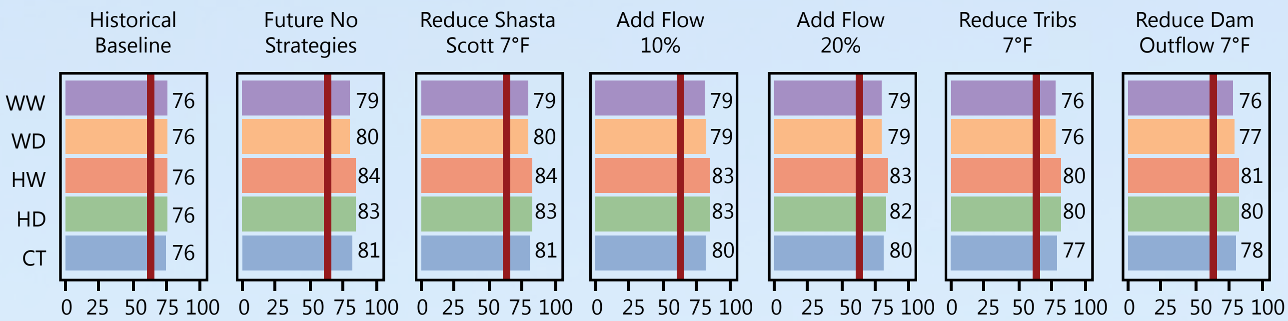
Figure 13 illustrates results for mean annual MWAT in the Klamath River at Klamath, California for the historical baseline, projected future without adaptation, along with five modify operation adaptation strategies, including three actions to reduce water temperatures by 4°C (7°F) and two actions to increase flows in the Link, Shasta, Scott, and Trinity Rivers by 10 percent and 20 percent relative to no adaptation.

For the CT scenario, all five of the adaptation strategies have MWAT temperatures that are significantly greater than the historic baseline. The "Add Flow" and "Reduce Shasta and Scott River Temperatures" adaptation strategies have MWATs that are nearly identical to the results when no adaptation strategy is used. The "Reduce Temperature in the Tributaries" and "Reduce Temperature in Dam Outflow" strategies show improvements of an approximately 3°F decrease, but still considerably exceed the poor habitat threshold. Overall, the HW scenario consistently has the highest and the WW the lowest water temperatures with or without adaptation.



Klamath River near Requa, California.

Mean Annual Maximum Weekly Average Temperature



Note: Units are in degrees Fahrenheit (°F). The red vertical line indicates the threshold of 63.7 °F, which is an indicator of poor habitat suitability. Tribs = tributaries, MWAT = maximum weekly average temperature, WW = Warm-Wet, WD = Warm-Dry, HW = Hot-Wet, HD = Hot-Dry, and CT = Central Tendency

Figure 13. Historical and projected 2070s MWAT in the Klamath River at Klamath, California by climate scenario with and without decrease demand adaptation strategies.

Baker Mcdonald, River Manager in Reclamation s Klamath Basin Area Office, points to the new modeling program being used to analyze daily distribution projections on Klamath Project agricultural diversions, and how said projections relate to historical usage patterns. Also, the current system is still being used to process and analyze data updates for daily operations model input. This data is used to prepare reporting products for stakeholder groups across the Klamath Basin.

SECTION 4

Innovations

The Klamath River Basin Study was performed to provide a comprehensive analysis of impacts to water resources with respect to climate, surface water hydrology, groundwater hydrology, and river temperature. To reach the overall objective of evaluating impacts of future change on the water resources throughout the Klamath River Basin, the Klamath River Basin RiverWare water operations model was developed to encompass the entire watershed, including tributaries of Upper Klamath Lake, the Lost River system, and major Klamath River tributaries such as the Shasta River, Scott River, Indian Creek, Salmon River, and Trinity River. The model also includes representation of eight reservoirs: Upper Klamath Lake, Clear Lake Reservoir, Gerber Reservoir, Lake Ewauna, J.C. Boyle Reservoir, COPCO 1 Reservoir, COPCO 2 Reservoir, and Iron Gate Reservoir. To represent the importance of groundwater and water temperature, the Basin Study team incorporated a groundwater model (MODFLOW) of the Upper Klamath River Basin and a river temperature model (RBM10), each developed by U.S. Geological Survey (USGS) researchers, into the modeling framework. This allowed for evaluation of important physical processes that impact water and ecological resources, namely how groundwater contributes to river flow and how changes in hydrology and operations may impact river temperature.

Besides providing tools that were used to evaluate potential future impacts to Klamath River Basin water and related resources, the Klamath River Basin RiverWare model was used to provide Reclamation's Klamath Basin Area Office with a prototype decision support tool that would allow them to consider uncertainty in future water supply and demand conditions for operational decision making. This pilot study, selected as part of the WaterSMART Reservoir Operations Pilot Initiative, provided an opportunity to improve water forecasting capabilities for the Klamath River Basin by building on the existing RiverWare model to incorporate multiple forecasts ("ensemble forecasting") of water supply and demand. The Reservoir Operations Pilot study developed a new modeling framework for incorporating new process-based ensemble forecasts (using physical models as opposed to statistical models) of water supply and irrigation water demands in the Upper Klamath River Basin, allowing water managers to consider uncertainty in the forecasts. The modeling framework is flexible to facilitate water management decisions under uncertain future climatic and hydrologic conditions, while also allowing for modification as conditions and operational policy changes.

Bald eagle at Lower Klamath National Wildlife Refuge in the Klamath Basin of southern Oregon (Getty Images).

SECTION 5

Next Steps

Reclamation continues to make advancements in water management of the Klamath River Basin through research and collaboration with partners.

Tasks Identified in Klamath River Basin Study

The Klamath River Basin Study relied on projected future conditions that were developed using existing model frameworks and inputs. Identified adaptation strategies evaluated by the Basin Study are general (i.e., not specific proposed projects) by design and are intended to identify sensitivities of the Klamath River Basin to various types of potential actions. Moving forward, a number of tasks have been identified to further enhance our understanding of climate change impacts on the Klamath River Basin.

- **Refinement of ecosystem demands and vulnerabilities –** Additional analysis of the relationship between changes in the climate; changes in the demands of aquatic, wetland, and riparian ecosystems that result from changes in the climate; and the ability to accommodate these demands with existing supplies would further support and refine the findings in this study. Also, the USGS's incorporation of developing river temperature modeling for the Trinity River could enhance our understanding of climate change impacts and implemented adaptation strategies on river temperatures.
- **Coupled groundwater/surface water model development –** Expansion of existing groundwater models for the Scott and Shasta Rivers to cover broader portions of the basin would further support the analysis completed in the Basin Study.
- **Refinement of the Reservoir Operations Pilot –** Additional refinements of the protype Klamath River Basin RiverWare model-based decision support system will help to improve confidence in the use of forecasts in the operations of the Klamath River Basin water management system. These activities should be focused on assessing and improving the skills of the water supply and demand forecasts.
- **Effects of future policy changes –** Evolving policy conditions are anticipated in the Klamath River Basin relating to future Endangered Species Act consultations and potential removal of the four mainstem Klamath River dams. Continued analysis of future policies using the Basin Study modeling framework will allow for comparisons to be made, and for greater understanding of potential climate change impacts.

Investment in Applied Science Projects

In July of 2020, Reclamation announced an initial $1.2 million investment in applied science projects for the Klamath Project. These projects will be conducted in collaboration with other Klamath River Basin agencies and stakeholders. The projects will improve partners' understanding of natural streamflows and the relationship between project operations and aquatic ecosystems in the basin (**Figure 14**).

This funding will allow Reclamation to begin several important science initiatives:

New Naturalized Flow Study – Update a 20-year-old assessment of streamflows to address shortcomings identified in the National Academy of Science's 2004 and 2007 reviews, as well as incorporate more recent data.

Lake Level Science Update – Conduct focused evaluations of emerging science in partnership with the USGS and U.S. Fish and Wildlife Service that will improve the understanding of how Upper Klamath Lake elevations affect endangered sucker fish.

Flow/Habitat Relationships in the Klamath River – Evaluate contemporary methods of data collection and habitat modeling techniques to tailor a plan to better support habitat and water flow needs of juvenile Chinook and threatened coho salmon in the Klamath River.

Salmon Model Refinement – Refine a salmon survival model in partnership with the USGS and U.S. Fish and Wildlife Service that will update the Stream Salmonid Simulator model, which is used to estimate juvenile salmon survival during their migration to the sea.

Salmon Disease and Hydrology Data Portal – Develop a process that will improve biological data management on salmon disease in the Klamath River Basin.

Collectively, these initiatives will assist with water supply forecasting, operations planning, and modeling to guide more informed decision making in the basin.

Farming amid arid terrain made possible by water deliveries from Reclamation's Klamath Project.

Figure 14. Top: Drought in the Klamath River Basin. Bottom: Lost River near Klamath Falls, Oregon and adjacent irrigated farmland.

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Cover photo: View of Klamath Lake, the largest body of fresh water by surface area in Oregon. Mt. McLoughlin is covered with snow in the background.