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Managing Water in the West

Klamath River Basin Study

SUMMARY REPORT

December 2016

U.S. Department of the Interior
Bureau of Reclamation

State of California
Department of Water Resources

State of Oregon
Water Resources Department

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

The California Department of Water Resource's mission is to manage the water resources of California in cooperation with other agencies, to benefit the State's people, and to protect, restore, and enhance the natural and human environments.

The mission of the Oregon Water Resources Department is to serve the public by practicing and promoting responsible water management through two key goals:

- to directly address Oregon's water supply needs, and
- to restore and protect streamflow and watersheds in order to ensure the long-term sustainability of Oregon's ecosystems, economy, and quality of life.

Cover photo: Mt. McLoughlin and Klamath Lake in the Klamath Basin Area. Photo by Regional Photographer Winetta Owens.

Klamath River Basin Study Summary Report

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Bureau of Reclamation

In Partnership with:

California Department of Water Resources
Oregon Water Resources Department

Disclaimer

The Klamath River Basin Study was funded jointly by the Bureau of Reclamation (Reclamation), the State of California Department of Water Resources, and the State of Oregon Water Resources Department, and is a collaborative product of the Klamath River Basin Study Technical Working Group. The purpose of the study is to assess current and future water supply and demand in the Klamath River Basin and to identify a range of potential strategies to address projected imbalances. The study is a technical assessment and does not provide recommendations or represent a statement of policy or position of Reclamation, the Department of the Interior, California Department of Water Resources, or Oregon Water Resources Department. The study does not propose or address the feasibility of any specific project, program, or plan. Nothing in the study is intended, nor shall the study be construed, to interpret, diminish, or modify the rights of any participant under applicable law. Nothing in the study represents a commitment for provision of Federal funds beyond this technical assessment.

Executive Summary

The Klamath River Basin has a history of complex water management issues dating back more than a century. In large part, this is due to the competing needs of the various water users, irrigation diversions, and the construction and operation of dams, which have altered the natural flow and nutrient and sediment regimes in the river and have inhibited passage of migratory fish.

The Bureau of Reclamation (Reclamation), in partnership with non-federal cost-share partners, the California Department of Water Resources (CDWR) and the Oregon Water Resources Department (OWRD), conducted the Klamath River Basin Study (Basin Study). The Basin Study takes a comprehensive approach to evaluate historical and projected future water supply and demand over the entire watershed. It identifies a range of adaptation strategy concepts to determine which have the greatest potential benefit for reducing climate change impacts and meeting water users' needs.

The Basin Study Summary Report Executive Summary (ES) provides a description of the study approach and tools used to evaluate climate change impacts on the watershed, the development of adaptation strategy concepts, and evaluation of results.

Klamath River estuary.

The information presented in this report was developed in conjunction with basin stakeholders and is intended to inform and assist stakeholders by identifying potential future scenarios for long term planning. The analyses provided in this report reflect the use of best available datasets and data development methodologies at the time of the study. It is important to acknowledge the uncertainties inherent within projecting future planning conditions for water supply and demand. For example, projections of future climate, population, water demand, and land use contain uncertainties that vary geographically and temporally depending on the model and methodology used. Trying to identify an exact impact at a particular place and time remains difficult, despite advances in modeling efforts over the past half-century. Accounting for these uncertainties, Reclamation and its stakeholders used a scenario planning approach that encompasses the estimated range of future planning conditions. More detailed information about uncertainties related to each part of the study is available in the Klamath River Basin Study Full Report.

The Klamath River Basin

The Klamath River Basin extends from the headwaters north of (and including part of) Crater Lake National Park in Oregon (OR) to its outflow at the Pacific Ocean in Requa, California (CA) (figure ES-1). It is divided into distinct upper and lower basins, each with very different climates, hydrologic regimes, and water needs.

The lower basin, in the Pacific Coast Range, receives roughly 70 percent more annual precipitation than the upper basin. The upper basin, in the rain shadow of the Pacific Coast Range, has more than four times the irrigated acreage of the lower basin. Table ES-1 below summarizes notable Klamath River Basin management interests. These often compete for finite water supplies and can create imbalances, which are difficult to resolve.

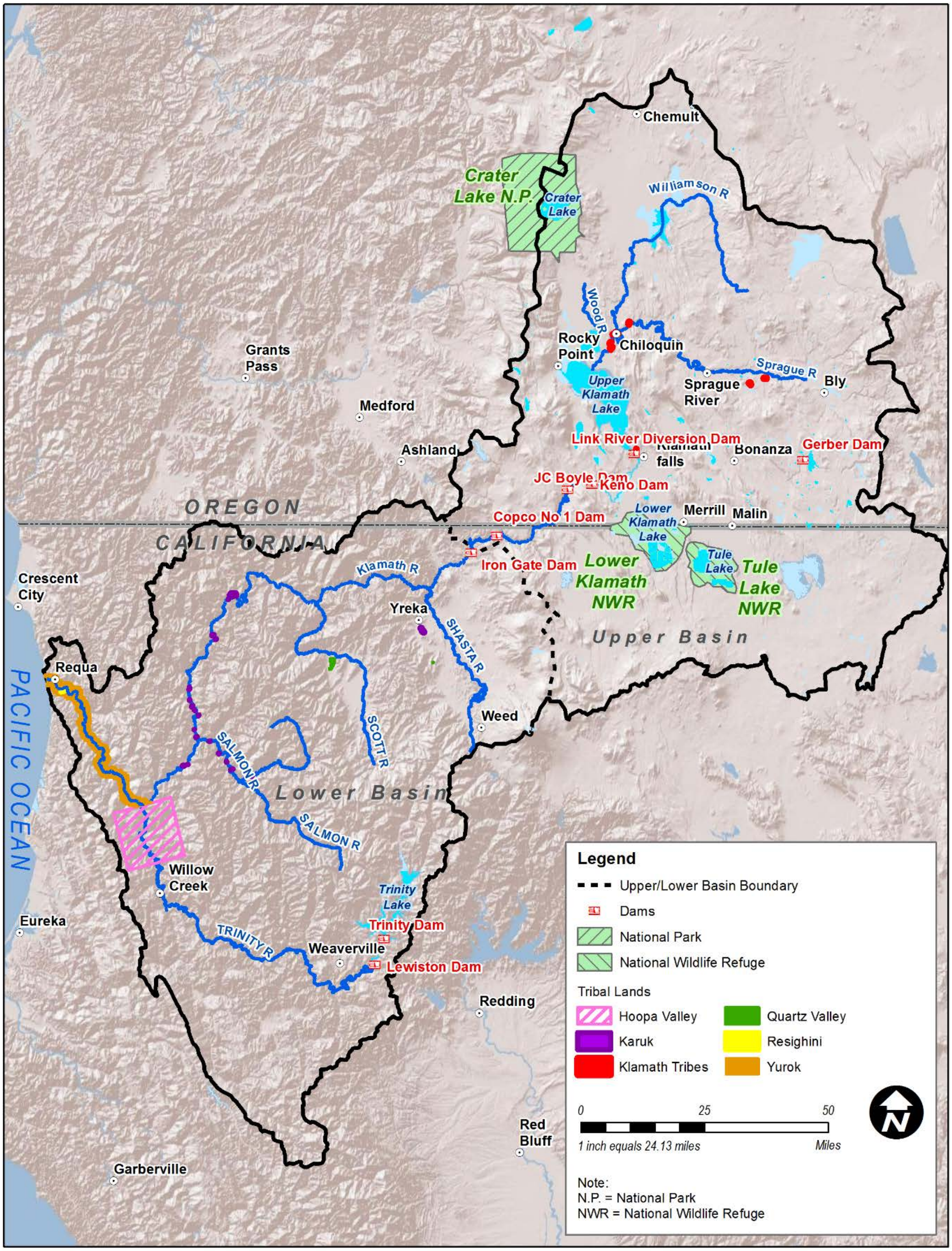

Figure ES-1.—Map of the Klamath River Basin.

Table ES-1.—Summary of Klamath River Basin Management Interests

Topic	Description
Agricultural water use	Agricultural irrigation uses about 98% of the total human consumptive water use in the Klamath River Basin. Agricultural water users include Reclamation's Klamath Irrigation Project (Klamath Project), individual and irrigation district users, and out-of-basin transfers such as the Central Valley Project in the case of the Trinity sub-basin.
Environmental needs	The Klamath River Basin supports three fish species that are listed under the Endangered Species Act (ESA), including the shortnose and Lost River suckers and the Southern Oregon Northern California Coast (SONCC) Evolutionarily Significant Unit (ESU) coho salmon.
Interstate watershed management	The Klamath River Basin spans parts of both Oregon and California. Since these States have different regulations for surface and groundwater use, they collaborate on various water management activities.
Removal of Klamath River dams	Two agreements for the removal of four dams in the Basin (Iron Gate, Copco 1, Copco 2, and J.C. Boyle) provide key benefits to irrigators and fisheries: an amended Klamath Hydroelectric Settlement Agreement (KHSA) and the 2016 Klamath Power and Facilities Agreement.
Recreational uses	Reaches of the Klamath River and several tributary rivers, are classified as "wild," "scenic," and "recreational" under both the National and California Wild and Scenic River Systems.
Tribal treaty rights	The United States must provide sufficient water to sustain and protect Indian Trust Assets, including hunting, gathering, and fishery purposes.
Water management and water rights	The Klamath River Basin is over-appropriated. Water rights adjudication is complete for several tributaries, but the mainstem Klamath River has not been fully adjudicated.
Water storage	The Klamath River Basin contains several storage reservoirs; however, there is no carryover storage to alleviate stresses from multi-year droughts.
Hydropower production	The mainstem Klamath River dams and dams on the Trinity River provide hydropower.
Water quality	Several water quality regulations have been adopted and others are in development. Temperature requirements for listed species have been identified.

Since 2001, groundwater pumping in the basin has increased, particularly within and near the Klamath Project, owned and operated by Reclamation, as a way of reducing imbalances in water supply and demand. This is because water managers in the Klamath River Basin have experienced frequent difficulty in meeting the range of water needs in the basin over the past several decades. Various agreements help guide water management. For example, the 2013 National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) "Biological Opinions on the Effects of Proposed Klamath Project Operations from May 31, 2013, through March 31, 2023, on Five Federally Listed Threatened and Endangered Species" outlines water supply priorities in the following order:

The broad operational priorities for the Upper Klamath Basin are: (1) ESA[1] compliance, (2) meeting contractual obligations to Klamath Project irrigators, and (3) providing water to the Lower Klamath NWR[2] when ESA and contractual obligations have been met.

Models were used in this Basin Study to simulate historical conditions. Operational changes have occurred throughout history; use of a model allows for simulation of historical hydrologic conditions under current river operations rules, as defined by the 2012 Biological Assessment and associated 2013 Biological Opinion (BiOp). The use of models also provides a benchmark for comparison of historical conditions against future projected conditions considering both population growth and climate change. Historical Basin Study model simulations identified some existing imbalances. These are listed below.

Historical Water Supply and Demand Imbalances

The following bullets summarize water supply and demand imbalances identified in the Klamath Basin based on historical model results. Water years 1970-1999 were used to represent the historical time period for the study. Although this historical time period does not include the recent past, in which numerous dry years have occurred, it does include a range of hydrologic conditions spanning wet and dry years. Current operations were used to develop the historical model. Modeling current operations under a range of hydrologic conditions from 1970-1999 allows for greater understanding of how current operations are affected by different hydrologic conditions. The imbalances explored in this study include fulfillment of water delivery targets and exceedance of river water temperatures above the level considered suitable for salmon.

- Model-simulated average annual deliveries to Klamath Project irrigators are estimated to meet about 93 percent of full delivery volume of 390,000 acre-feet per year (AFY) (using data from water years 1970-1999 [Fiscal Years of October 1969 – September 1999]).

- Model-simulated average annual deliveries to the Lower Klamath National Wildlife Refuge (LKNWR) are estimated at 24,500 AFY.

- The model-simulated maximum weekly average temperature (MWAT) during the summer in the Klamath River at Klamath, CA, was about 76 degrees Fahrenheit (F) (using data from water years 1970-1999), exceeding the classification of “poor” habitat suitability under the Southern Oregon/Northern California Coast (SONCC) Evolutionary Significant Unit (ESU) coho salmon recovery plan (NMFS, 2012).

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1 Endangered Species Act.
2 National Wildlife Refuge.

Projected Climate Changes

Fallowed Farmland in Upper Klamath Basin.

Climate projections from general circulation models (GCM) are the best available estimates of future climate conditions.

GCM projections were used to generate a number of equally likely climate change scenarios to inform analysis as part of the Basin Study. Five climate change scenarios span the range of projected equally likely future temperature and precipitation: warm-wet (WW), warm-dry (WD), hot-wet (HW), hot-dry (HD), and central tendency (CT).

Figure ES-2 summarizes projected changes in climate, water supply and demand, and the maximum river water temperature in the Klamath River by 2070 for the CT scenario based on the most recent set of GCM projections, termed coupled model intercomparison project (CMIP)5. The CT scenario generally indicates the middle of the range of future scenarios. It is **not** a "most likely" scenario. The CT climate change scenario suggests that the Klamath River Basin may be warmer and slightly wetter in the future, compared to a historical baseline period (water years 1970-1999).

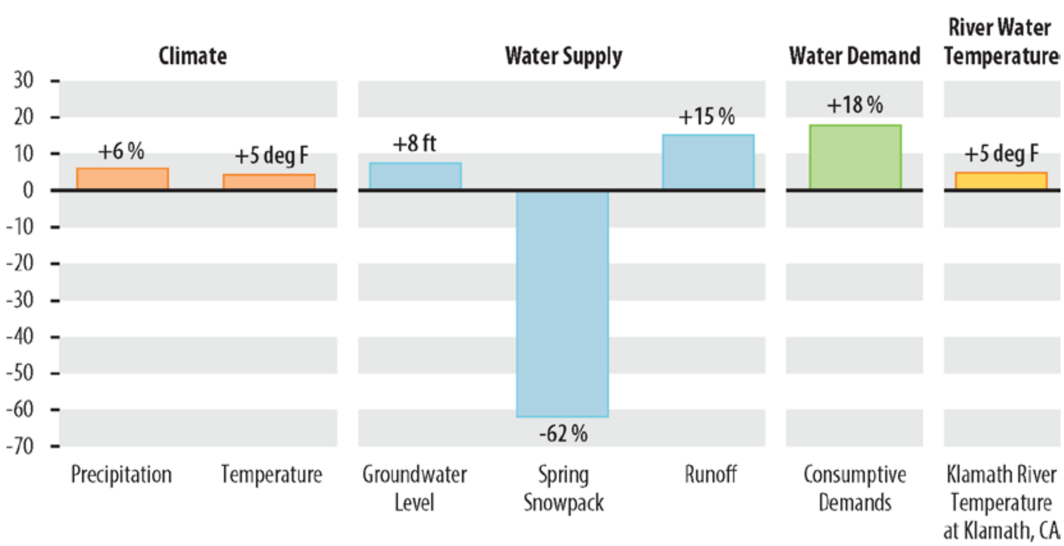

Figure ES-2.—Summary of projected changes for the 2070s for the CMIP5 central tendency climate change scenario.

Although the CT scenario suggests wetter conditions overall, the basin may have drier summers, along with higher temperatures in all seasons. Existing water management challenges may increase due to substantially less spring snowpack and changes in seasonal runoff timing, despite slightly higher groundwater levels and more annual runoff. In addition, the CT scenario suggests that water demands will increase, as will Klamath River temperatures. The challenges for fish and wildlife, as well as for irrigators in the upper Klamath River Basin, are illustrated by the following conclusions identified in the Basin Study.

Projected Water Supply and Demand Imbalances from Climate Change Alone

As described above in “Historical Water Supply and Demand Imbalances,” challenges already exist in the Klamath Basin for meeting water needs. Using the same measures, the impacts of climate change on water supply and demand imbalances, including river temperatures, are summarized below.

- Model-simulated average annual deliveries to Klamath Project irrigators range from an increase of 3 percent to a decrease of 12 percent by the 2070s, based on the range of equally likely CMIP5 climate change scenarios.

- Model-simulated average annual deliveries to the LKNWR decrease 35 percent to 65 percent, from the historical modeled average volume of 24,500AFY, by the 2070s, under the range of equally likely CMIP5 climate change scenarios. These modeled projected decreases are based on current river operations rules as defined by the 2012 Biological Assessment and associated 2013 BiOp.

- The model-simulated MWAT in the Klamath River at Klamath, CA, increases by 4 to 8 degrees F by the 2070s under all climate change scenarios. Increasing temperatures further exacerbate summer habitat suitability according to the SONCC ESU coho salmon recovery plan.

Incorporating Population Growth

The Basin Study future water demand assumes a population growth rate of less than one percent per year through the 2070s. This assumption is based upon county population projections published by California and Oregon, as well as available municipal water plans. Though this growth rate is relatively low, by 2070 the Klamath Basin population will have increased by about 28 percent above its 2010 population level.

Adaptation Strategy Concepts

The following five adaptation strategy concepts were applied to the future projected conditions to determine which would potentially assist in reduction of water supply and demand imbalances (figure ES-3). They address issues related to water supply, demand, management of flows, and temperature.

	Quantify water for possible future storage
	Reduce agricultural demands throughout the basin
	Increase inflows to Upper Klamath Lake
	Test whether changes in upstream tributary flow or temperature have a greater effect on Klamath River water temperature at Klamath, CA, which is located near the mouth of the Klamath River
	Reduce water temperatures in the Shasta and Scott tributary rivers, through the addition of groundwater, to lower Klamath River water temperature at Klamath, CA

Figure ES-3.—Klamath River Basin Study adaptation strategy concepts.

Performance Measures and Key Findings

Performance measures were used to evaluate historical and future water supply vulnerabilities, and to facilitate the comparison of adaptation strategy concepts in their potential to reduce identified imbalances in water supply and demand. The performance measures, identified in accordance with the Basin Study Framework guidance document (Reclamation 2009c) and described in the Methods System Reliability Analysis, below, include:

- Water deliveries
- Hydroelectric power resources
- Recreational resources
- Ecological resources
- Water quality resources
- Flood control

Using these performance measures, the Klamath River Basin Study Technical Working Group (TWG) identified the potential of the adaptation strategy concepts to reduce projected water supply and demand imbalances expected with future climate and population conditions in the Klamath River Basin. Figure ES-4 lists key findings of the results of the Basin Study. Reclamation and the non-federal cost share partners (CDWR and OWRD) comprised the TWG.

	Substantial surface water may be available for storage in the future due to reduction in snowpack and projected changes in precipitation timing and volume.
	In parts of the basin where water deliveries are driven by agricultural demand, model results show that reducing agricultural demands results in noticeable increases in streamflow downstream. However, within Reclamation's Klamath Project, deliveries are based on available water in Upper Klamath Lake and forecasted seasonal inflow due to the guidelines in the 2012 BA and 2013 BO. Therefore, a reduction in agricultural demands within the Klamath Project does not lead to substantial changes in seasonal Klamath Project water supply. If deliveries within the Klamath Project were based solely on agricultural demand, then it is likely that a reduction in these demands would have a greater impact on streamflow and hydropower in the Klamath River.
	Increasing inflows to Upper Klamath Lake has the greatest ability to reduce climate change impacts in the basin, but these changes are still modest.
	Reducing water temperatures in Klamath River tributaries has a greater ability to reduce mainstem Klamath River temperatures at Klamath, CA, than does changing tributary flow patterns, but the effect is not strong.
	While reducing water temperature in the Shasta and Scott Rivers by about 7 degrees Fahrenheit is not sufficient to substantially impact Klamath River temperatures at Klamath, CA, it could provide needed cool water refugia for juvenile coho salmon in the Shasta and Scott Rivers during summer months.

Figure ES-4.—Summary of key findings.

Acronyms and Abbreviations

AFY	Acre-feet per year
Basin Study	Klamath River Basin Study
BiOp	Biological Opinion
CA	California
CDWR	California Department of Water Resources
CMIP	Coupled Model Intercomparison Project
CT	Central Tendency
ES	Executive Summary
ESA	Endangered Species Act
ESU	Evolutionary Significant Unit
F	Fahrenheit
ft	foot/feet
GCM	General Circulation Model
HD	Hot-dry
HW	Hot-wet
KBRA	Klamath Basin Restoration Agreement
KHSA	Klamath Hydroelectric Settlement Agreement
Klamath Project	Klamath Irrigation Project (Reclamation)
LKNWR	Lower Klamath National Wildlife Refuge
M&I	Municipal and Industrial
MODFLOW	3-D Finite-Difference Groundwater Model (USGS)
MWAT	Maximum Weekly Average Temperature
NIWR	Net Irrigation Water Requirement
NMFS	National Marine Fisheries Service
NWR	National Wildlife Refuge
OR	Oregon
OWRD	Oregon Water Resources Department
Reclamation	Bureau of Reclamation
RBM	River Basin Model
SECURE	Science and Engineering to Comprehensively Understand & Responsibly Enhance (Federal)
SONCC	Southern Oregon/Northern California Coast
TWG	Technical Working Group
U.S.	United States
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WD	Warm-dry
WW	Warm-wet

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Summary Report

Introduction

The Klamath River Basin supports habitats for numerous fish and wildlife species and supplies water for agriculture, hydropower, recreation, and tribal, municipal, industrial, and domestic uses. This Klamath River Basin Study (Basin Study) builds upon existing collaborations and recent work conducted throughout the Klamath River Basin to demonstrate how climate change may affect both environmental and human water uses in the basin. It also identifies management strategies with the potential to improve future water security.

The Klamath River Basin faces complex water management challenges. These challenges come from the settlement history of the basin, and its climatic and hydrologic characteristics. Interest groups in the basin work together in various combinations to find solutions to the basin's water management challenges.

Klamath River Basin Setting

The Klamath River Basin encompasses:

- 6 national wildlife refuges
- 1 national park
- 2 national monuments
- 2 federal irrigation projects
- 5 national forests

Its lands are managed by five Federal agencies, six federally recognized Tribes, two States, and numerous local and private organizations. The river has six dams while retaining large sections of wild and scenic designations.

Examples of these efforts include:

- The Trinity River Restoration Program.—Established in 2000 by a Record of Decision as an adaptive water management program. Partners include Federal, State, local, and tribal government agencies. Restoration work began in 2004 (Department of the Interior, 2000).

- The Klamath Basin Monitoring Program.—Coordinates water quality monitoring and research throughout the Klamath River Basin. Participating organizations include Federal, State, local, and tribal Government agencies, non-governmental organizations, universities, land trusts, private firms, and other stakeholders.

- Tribes, basin stakeholders, and interest groups worked together to develop the Klamath Basin Restoration Agreement (KBRA) and companion Klamath Hydroelectric Settlement Agreement (KHSA) in 2012 with the goal of restoring Klamath River Basin fisheries and sustaining local economies. The agreements include actions to improve water supply reliability, fund watershed restoration activities, revitalize economics in the basin, and remove four dams in the upper Klamath River. The KBRA has terminated because Federal authorizing legislation was not enacted. However, an amended KHSA and a 2016 Klamath Power and Facilities

Agreement maintain a path for removal of the dams, restoring the watershed, and providing benefits to irrigators.

- Tribes, the Bureau of Reclamation (Reclamation), U.S. Fish and Wildlife Service (USFWS), and National Marine Fisheries Service (NMFS) have worked together to reduce impacts of Reclamation's Klamath Irrigation Project (Klamath Project) on the natural river system and to aid in the recovery of threatened and endangered fish species. Resulting documents, including the 2012 Biological Assessment (Reclamation, 2012) and the 2013 joint Biological Opinion (BiOp; NMFS and USFWS, 2013) outline an operation plan to decrease stress on threatened and endangered species in the basin while allowing Reclamation to operate the Klamath Project to meet authorized contractual obligations.

Wheat farming in the Upper Klamath Basin.

This Basin Study incorporates both existing modeling tools and data developed by the collaborating agencies, and tools and data developed specifically for the Basin Study. For example, an existing groundwater model developed by the United States Geological Survey (USGS) was used to evaluate impacts on groundwater levels and recharge to streams. In addition, an existing river temperature model, also developed by the USGS, was used to evaluate impacts on the Klamath River temperature at Klamath, California (CA). A tool developed specifically for the Basin Study is the water management model – based on the RiverWare river system modeling software – that simulates managed river conditions and reservoir storage over time.

Purpose and Objectives

The purpose of the Basin Study is to evaluate current and projected future water supply and demand, and to collaborate with stakeholders in the region to identify and evaluate potential adaptation strategy concepts that may reduce identified imbalances. The Basin Study builds upon established stakeholder collaborations and published studies in its approach. The adaptation strategy concepts considered in the Basin Study allow for greater understanding of what types of options have the greatest ability to address supply and demand imbalances that are projected to increase in the future. Implementation of adaptation strategy concepts evaluated by the Basin Study and presented in the report would require further evaluation and cooperation at multiple levels, including local communities and land managers within the basin.

Authorization

The Federal Science and Engineering to Comprehensively Understand & Responsibly Enhance Water Act of 2009 (SECURE Water Act) and Secretarial Order 3297 established the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program. The WaterSMART Program authorizes Federal water and related resources management agencies to work with State and local water managers to pursue and protect sustainable water supplies, and plan for future climate change by providing leadership and technical assistance for the efficient use of water. The Basin Study Program is part of the Department of Interior's WaterSMART Program and was developed to address twenty-first century water supply challenges, including climate change and increased competition for limited water supplies.

Partner and Stakeholder Involvement

The Basin Study was guided by a Technical Working Group (TWG), which received input from stakeholders (figure 1). Reclamation and the non-federal cost share partners (California Department of Water Resources (CDWR) and Oregon Water Resources Department (OWRD)) comprised the TWG. The TWG was the primary decision-making body for the Basin Study. Tribes, interested organizations and individuals (including Federal, State, and local agencies), water use organizations, and non-profit groups were asked to provide input throughout the Basin Study process.

The TWG conducted Basin Study outreach through public meetings and workshops in 2013 through early 2016. This process allowed for collaborations on data and modeling tools that greatly improved the study. Stakeholders and other interest groups not directly involved with the study development also assisted in a review of the Basin Study Report as a way of ensuring a transparent and collaborative Basin Study process.

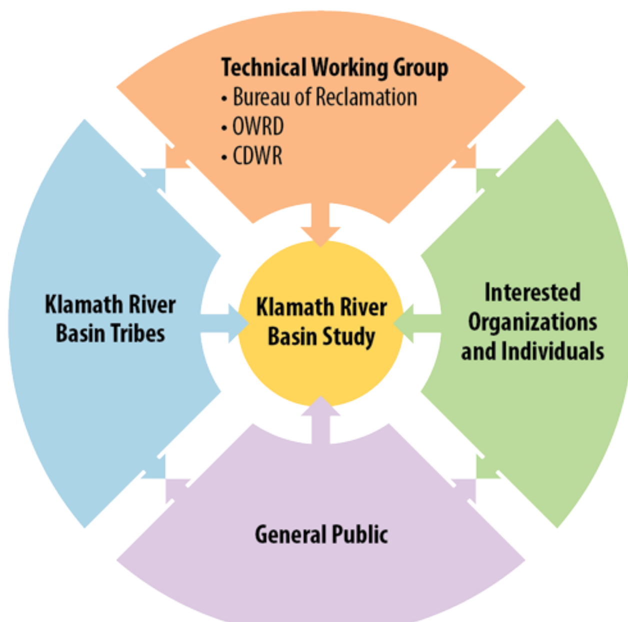


Figure 1.— Basin Study stakeholder involvement.

Basin Study Approach

The primary components and approach of the Basin Study are illustrated in figure 2. These include an assessment of current and future water supply, an assessment of current and future water demand, an analysis of climate change impacts on managed water in the basin (termed “system reliability analysis”), and analysis of how adaptation strategy concepts may reduce imbalances in water supply and demand identified through the system reliability analysis.

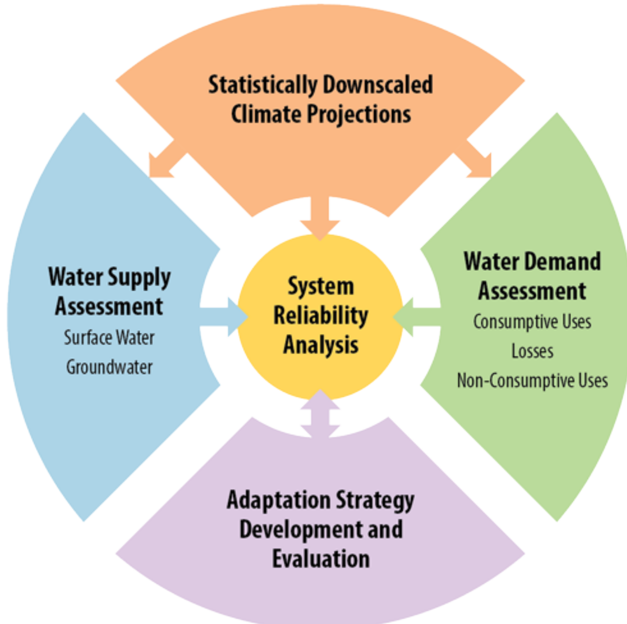


Figure 2.—Primary components and approach of the Basin Study.

Future climate conditions are represented using statistically downscaled climate projections that are developed by climate modeling centers around the world. Basin studies and other similar climate change studies rely on these projections to estimate a range of possible future conditions. For this Basin Study, the TWG used a combination of projections from the past two assessments by the Intergovernmental Panel on Climate Change. The projections from the two assessments are termed coupled model intercomparison project (CMIP)3 and CMIP5, with the CMIP5 being the most recent set of projections.

The Basin Study summarizes climate change impacts on the Klamath River Basin using both CMIP3 and CMIP5 to highlight any possible differences between the sets of projections. The Basin Study focuses on two future time periods for analysis, a near-term future time period (2030s) and a long-term future time period (2070s). In order to balance the number of future scenarios, while also capturing a range of potential future conditions, the study incorporates five climate change scenarios for each future time period. Each climate change scenario is an equally likely estimate of future conditions. Together, these climate change scenarios allow for evaluation of climate change impacts on hydrology and managed water in the basin.

The water supply assessment considers a range of variables including surface runoff, groundwater levels, snowpack, and soil moisture. Assessment of these variables draws from modeling of surface and groundwater using historical climate and future climate scenarios. The water supply assessment also uses information based on tree rings, which may give information about past climate conditions over the last 600 years or more. Scenarios based on tree rings are compared to historical model-simulated conditions, which are based on relatively short gaged records of 100 years or less, to give a broader context of past climate.

The water demand assessment incorporates consumptive uses such as demand for agricultural, municipal, industrial, and rural domestic uses; loss of water through lake and reservoir evaporation; and evapotranspiration from area wetlands. Information generated by the water demand assessment, along with information generated by the water supply assessment, is incorporated into an analysis of system reliability.

Members of the Karuk Tribe fishing in the Klamath River.

The system reliability analysis evaluates both the historical and future water supply and demand conditions using a water management model. The water management model was developed using RiverWare, a river system modeling tool for both short- and long-term watershed planning. The Klamath Basin RiverWare model incorporates current river operations rules as defined by the 2012 Biological Assessment and associated 2013 BiOp. The model simulates managed river conditions and reservoir storage over time and allows for comparison of future scenarios with historical model-simulated conditions. The model also allows for exploration of adaptation strategy concepts that may reduce imbalances in water supply and demand.

In the Basin Study, the TWG developed a broad set of adaptation strategy concepts that encompass a range of individual strategies identified by past studies and stakeholder input. These adaptation strategy concepts allow for greater understanding of what types of strategies have the greatest ability to reduce water supply and demand imbalances that may increase due to climate change. Together, all of these described components constitute the Basin Study.

Projections of Future Conditions

The assessment of potential climate change impacts on the Klamath River Basin required developing a set of scenarios of projected future water supply and demand conditions, accounting for future climate and population growth. This scenario-based approach allows for a greater understanding of vulnerabilities in the basin.

The Basin Study, consistent with other completed and ongoing basin studies throughout the western United States, uses climate projections from general circulation models (GCMs) to generate a number of climate change scenarios. The climate projections for the Klamath River Basin suggest a warmer future (no projections suggest cooling may occur) with a range of drier to wetter conditions, compared to a historical baseline period (water years 1970-1999). The climate change scenarios developed for the Basin Study encompass this range of potential futures, from less to more warming and less wet to wetter conditions. Because current science does not favor any individual projections, all developed climate change scenarios are considered equally likely future conditions. Using this approach, five climate change scenarios span the range of projected future temperature and precipitation. These scenarios are characterized as:

- warm-wet (WW)
- warm-dry (WD)
- hot-wet (HW)
- hot-dry (HD)
- central tendency (CT)

For each of these five scenarios there are two types of model results: one based on CMIP3 projections and one based on CMIP5 projections, as described above. A comparison of CMIP3 and CMIP5 projections indicates a similar range of projected precipitation, but the CMIP5 projections show the upper basin to be not as wet and the lower basin to be wetter compared with the CMIP3 projections. In addition, CMIP5 projections of temperature indicate more warming than CMIP3 projections.

With incorporation of both CMIP3 and CMIP5 climate change scenarios, there are ten scenarios each for two future time periods (the 2030s and 2070s). The 2030s scenario represents average future climate conditions over a thirty-year time period for water years 2020-2049 (October 2019 – September 2049). The 2070s scenario represents average future climate conditions over a thirty-year time period for water years 2060-2089 (October 2059 – September 2089). Model-simulated future conditions are compared against a historical baseline to evaluate projected changes.

The historical baseline for the Basin Study is defined as water years 1970-1999 (October 1969 – September 1999). Figure 3 conceptually illustrates historical and future scenarios and shows that there is generally greater uncertainty in future projections moving further into the future. Tree ring data was used in the Basin Study to determine how the historical baseline period compares with a much longer historical period of about 600 years. However, tree ring data was not directly used as input to the Basin Study models.

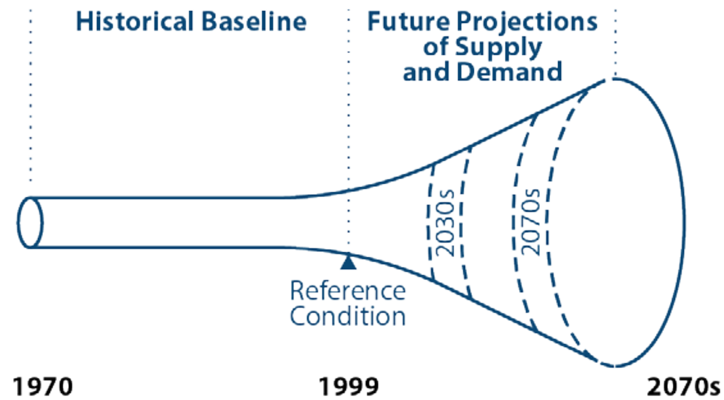


Figure 3.—Future projections of supply and demand.

Projected future water supply and demand both incorporate future climate change scenarios. Projected future water demand also incorporates projections of future population growth. It is anticipated that the Klamath River Basin will not experience the same development pressures as other parts of California and Oregon. For example, the California State Water Plan projects a population increase of 21 percent to 92 percent in urban areas from 2006 to 2050, depending on the location (CDWR, 2013). The Oregon State Integrated Water Resources Strategy (OWRD, 2012) projects a 63 percent increase in population statewide by 2040. In comparison, the Klamath River Basin population is expected to increase by only about 28 percent from 2010 to 2070, based on county population projections published by the two States as well as available municipal water plans. Therefore, a single growth scenario based on Klamath River Basin population projections is used to represent municipal and rural domestic water demands.

Methods for Water Supply Assessment

The water supply assessment consists of evaluation of historical climate and hydrologic trends as well as analysis of future conditions. It relies on independent models of surface and groundwater hydrology. For surface water hydrology, the Basin Study incorporates results from the Variable Infiltration Capacity (VIC) model. The VIC model was used to support Reclamation's West-Wide Climate Risk Assessment (Reclamation, 2011; Reclamation, 2016). It requires daily precipitation, maximum and minimum temperatures, and wind speed as inputs to simulate snowpack, soil moisture, evapotranspiration, runoff, and streamflow.

For the Basin Study, the TWG computed historical trends in water balance variables over water years 1950-1999 using VIC model simulations. The analysis of model-simulated historical trends is longer than the historical baseline period used for analysis of climate change impacts (water years 1970-1999). A longer time period is advantageous for historical trend analysis because it is more likely to represent changes due to climate change, as opposed to changes due to natural variability that occur over shorter time periods. Similar to historical simulations, future climate change scenarios were input into the VIC model to quantify water balance variables throughout the basin. Future simulations are compared to historical baseline simulations to evaluate climate change impacts.

To establish how the variability in climate over the last 50 years compares with the past 600 hundred years, tree ring data was analyzed to identify wet periods and droughts. This information, along with future climate change scenarios, helps to determine the likelihood of more or less severe wet periods and droughts in the future.

The TWG analyzed the effects of historical and future climate change scenarios on groundwater in the upper Klamath River Basin as part of the Basin Study, using an existing MODFLOW finite-difference groundwater model developed by Gannett et al. (2012). The historical simulation period for this modeling effort is water years 1970 – 2004. Output from the VIC surface hydrology model was used as input to the groundwater model. The groundwater model simulates groundwater levels and discharge of groundwater to streams, among other variables. A common historical baseline period of water years 1970-1999 was used for analysis of climate change impacts on groundwater and surface water to accommodate the differing time periods of available historical model data.

The TWG also analyzed groundwater hydrology for the Scott and Shasta Valleys using a regression-based approach, similar to that taken by Reclamation (2013) in the Santa Ana Watershed Basin Study. The groundwater modeling tool is based on a computed relationship between historical basin-average groundwater elevations and historical precipitation, streamflow, and water demand. The historical time period used for analysis is calendar years 1980 to 1999 due in part to the availability of historical groundwater elevation data, but also to maintain as much consistency as possible with other modeling components (e.g. MODFLOW and VIC models). Projections of future groundwater elevation may be simulated using this estimated historical relationship along with future precipitation, streamflow, and water demand inputs.

The water supply assessment relies on results from all of these modeling tools to provide a comprehensive evaluation of surface and groundwater hydrology.

Methods for Water Demand Assessment

Water demands are typically associated with one or more water uses that can be consumptive or non-consumptive. Consumptive water use results in a loss of water from the supply system, often associated with human activities. The water demand assessment consists of analysis of the primary consumptive demands in the basin, which include:

- Agricultural demands
- Municipal and Industrial (M&I) demands

- Rural domestic demands
- Evaporation from reservoirs
- Evapotranspiration from wetlands

The assessment of future water demands incorporated climate change scenarios, projected population growth throughout the basin, and static land use patterns defined by 2009 cropping data. The methods used to compute the agricultural demands are similar to those used by Reclamation's West-Wide Climate Risk Assessments (Reclamation, 2014).

The Basin Study M&I demands are based on water use estimates from available municipal water plans for the primary population centers in the basin. The countywide United States Geological Survey (USGS) National Water Availability and Use Program data was used in conjunction with other sources to compute rural domestic water demands. For future scenarios, M&I and rural domestic demands were determined based on projected population growth and changes in landscape irrigation due to climate change. The percent of M&I and rural domestic water use for landscape irrigation was fixed at average historical levels.

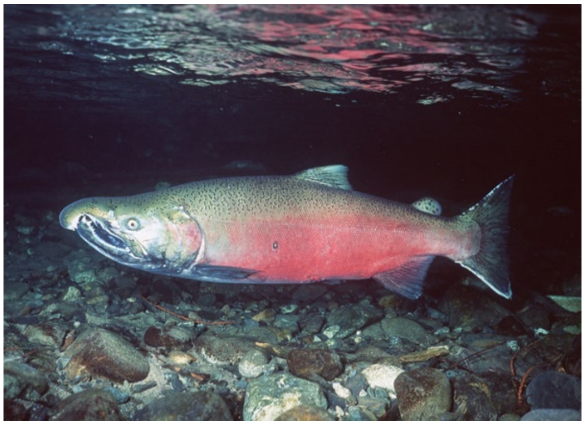
The Basin Study quantifies historical and future evaporation for eight lakes and reservoirs throughout the basin. The methods used to compute reservoir evaporation are similar to those used by Reclamation's West-Wide Climate Risk Assessment (Reclamation, 2014).

Wood River delta wetland.

In the Basin Study, the TWG also evaluated historical and projected future evapotranspiration from wetlands, given that emergent wetlands encompass over 340,000 acres in the Klamath River Basin. The Basin Study includes estimates of evapotranspiration based on existing peer-reviewed studies of water use by wetlands. The number of wetland acres was assumed to stay the same for future wetland evapotranspiration estimates.

Non-consumptive Demands

There are additional water demands in the basin that are not considered consumptive. These demands include environmental uses, tribal uses,



ESA protected Southern Oregon/ Northern California coast coho salmon.

hydropower production, and recreational uses. Environmental demands such as the need for adequate water quality to support fish and wildlife were evaluated as part of the system reliability analysis using a water temperature model. The water temperature model relies on managed river flows, climate, and water temperature inputs, linking it closely with the Klamath Basin RiverWare model.

Tribal domestic and industrial water uses were incorporated into the M&I and rural domestic use categories in the water demand assessment. Additional water uses that are primarily non-consumptive include instream flow needs and lake levels to support hunting, trapping, gathering, and other cultural practices. Availability of water for these uses was evaluated in the system reliability analysis.

Water Supply Assessment

The assessment of historical and projected surface water supply encompasses the entire Klamath River Basin. The general approach for assessing historical surface water supply is to evaluate how historical climate has influenced the quantity, timing, and form of water across the landscape. The water supply assessment involves analysis of both surface water and groundwater resources, including quantification of historical trends and projections based on future climate change scenarios for the 2030s and 2070s. In this Summary Report, results are presented from analysis of the CMIP5 CT climate change scenario, with corresponding ranges presented across all equally likely CMIP3 and CMIP5 scenarios.

With respect to surface water, the assessment focuses on projected changes in:

- spring snowpack (on April 1, when it is typically deepest)
- annual runoff
- irrigation season runoff (April to September)
- droughts and wet periods identified through tree ring analysis

The majority of groundwater use in the Klamath River Basin occurs in the upper basin, and the Scott and Shasta Valleys. Therefore, the assessment of historical and projected groundwater supply focuses on these three groundwater basins in the watershed. In addition, groundwater supplies have been important as a source for reducing existing water supply and demand imbalances, particularly in drought years. The TWG collaborated with researchers at the USGS to implement an existing MODFLOW groundwater model encompassing the upper Klamath River Basin upstream of Iron Gate Dam.

With respect to groundwater, the assessment focuses on projected changes in:

- groundwater recharge
- groundwater discharge to rivers
- overall changes in groundwater elevations throughout the major groundwater use areas

Historical Water Supply

Precipitation in the upper basin of the Klamath River is 70 percent less, on average, than it is in the lower basin (figure 4). The watershed is influenced by the geography of the Cascade and Siskiyou Mountains, which creates two distinct climates: an arid climate in the upper basin, generally east of the mountains; and a wetter climate in the lower basin. Figure 4 also shows mean annual temperatures across the basin.

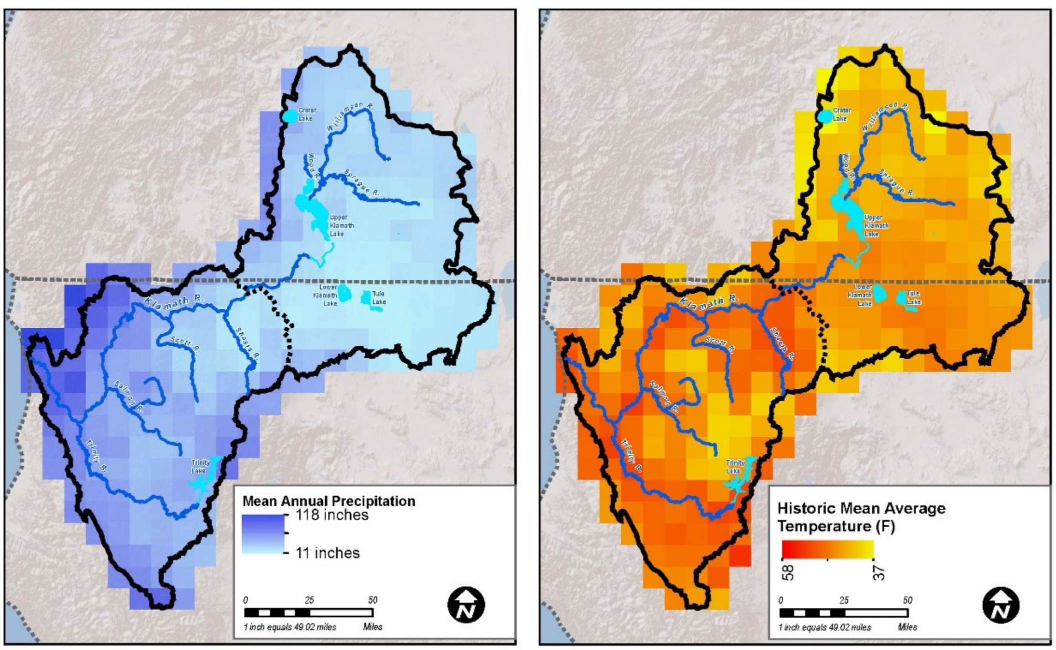


Figure 4.—Historical mean annual precipitation (water years 1950-1999) and historical mean annual air temperature (1950-1999).

Surface waters originate as precipitation in the form of snowfall or rain. This precipitation percolates into the soil. Some is utilized by vegetation and some evaporates, with the remainder flowing through subsurface soil to streams and rivers, or penetrating into deep groundwater tables. Air temperature greatly influences evapotranspiration to the extent water is available.

When soils are saturated, water drains into the river system. Water is stored in the snowpack, groundwater basins, or reservoirs. Snowpack storage in the Klamath River Basin is critical because the basin's existing reservoirs currently do not have the capacity to store the snowpack volume if it were to come as rain.

Historically, precipitation in the Klamath River Basin has fluctuated substantially from year to year. Historical trends in annual precipitation and temperature between 1950 and 1999, computed from VIC model simulations performed as part of the Basin Study, have shown increases of 2 percent in precipitation and one degree F in temperature. Historical trends in spring (April 1) snowpack and runoff over the same period include declines of 41 percent and 6 percent, respectively. In the upper basin, dry season (April to September) runoff declined 18 percent during this historical period (1950-1999).

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. Through natural groundwater discharges and the addition of pumped groundwater to streams, it provides cool, late summer streamflows to sustain fish at a critical time for spawning and rearing. Some irrigators use groundwater as a supplement when surface water supplies do not fully meet irrigation needs. Other irrigators depend solely on groundwater supplies. In addition, the City of Klamath Falls – the primary population center in the upper Klamath River Basin with a population of about 21,000 – is entirely supported by groundwater.

The assessment of historical groundwater supply in the upper Klamath River Basin relies, in part, on previous work by Gannett et al. (2007, 2012). The upper Klamath groundwater basin spans about 8,000 square miles upstream of Iron Gate Dam. Gannett et al. (2007) estimated that groundwater recharge from precipitation comprises about 20 percent of the total precipitation in the upper Klamath River Basin. The exact percentage varies spatially and temporally. The highest recharge to groundwater occurs along the western boundary of the upper Klamath River Basin on the eastern slopes of the Cascade Mountains, while the lowest recharge amounts are in the central and southern parts of the basin.

Prior to about 2000, natural recharge regularly replenished groundwater aquifer storage in the upper basin. Since 2001, the upper basin has experienced increased groundwater pumping, particularly within and near the Klamath Project. This is due, in part, to the reduced availability of surface water supplies as instream flows are required for Endangered Species Act (ESA) listed fish species. A water bank program has purchased varying quantities of groundwater to supplement surface water supplies in 10 of the past 13 years (2003 to 2015) in order to meet ESA and other wildlife needs, further depleting groundwater supplies.

Statistical models of the Shasta and Scott Valleys in the lower basin were developed as part of the Basin Study using existing data from CDWR for 1980 to 1999. These models indicated declines of about 20 feet in groundwater elevations during the late 1980s and early 1990s in the Shasta and Scott Valleys, corresponding with lower precipitation and streamflow during that period.

Future Water Supply

Projections of future precipitation show a range of possibilities. The complete range of equally likely scenarios spans from a 10 percent decrease of average annual precipitation to a 16 percent increase by the 2070s. Figure 5 shows an average annual precipitation increase of about 6 percent under the CMIP5 CT scenario for that time period. All scenarios of future temperature indicate that warming ranges from 3 to 8 degrees F by the 2070s (4.5 degrees F for the CMIP5 CT scenario). Although the change in future precipitation is less certain, high confidence in warming temperatures suggests that the balance of rainfall and snowfall will continue to shift toward more rain in the future.

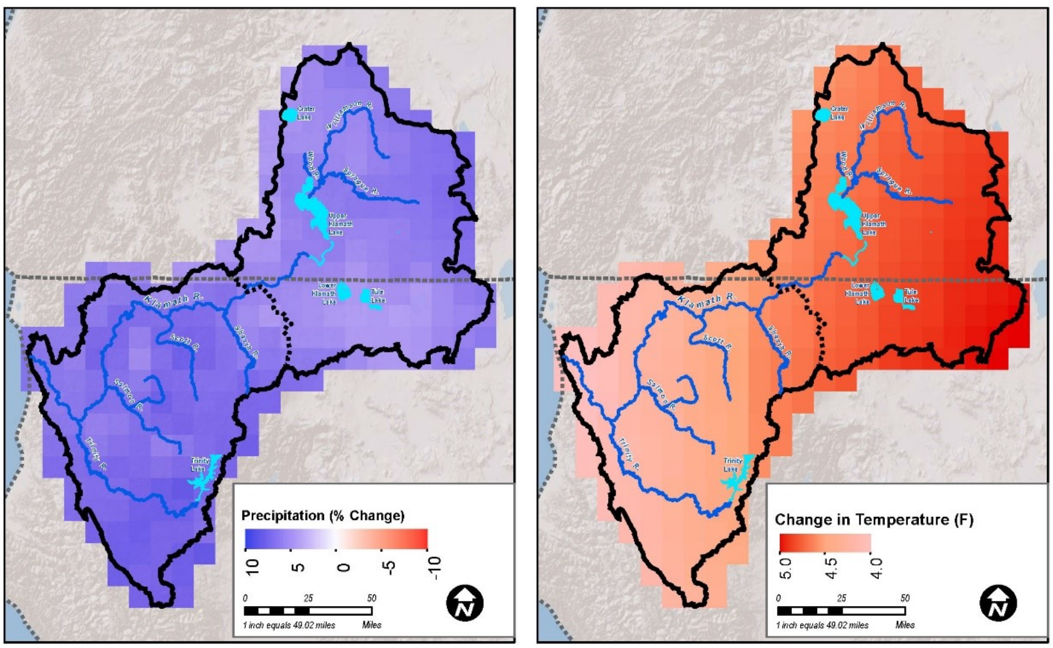


Figure 5.—Changes in precipitation (%) and temperature (F) for the 2070s for the CMIP5 central tendency scenario.

The Klamath River Basin water supply assessment does not specifically include analysis of projected changes in extreme precipitation events (e.g. floods) likely to result from climate change. However, the climate change scenarios developed in the Basin Study implicitly capture extreme values – to the extent that they can be captured – by the GCM data that informs the scenarios. In addition, the focus of the water supply assessment is on the watershed's overall seasonal water supply, which is most relevant to Basin Study partners and stakeholders.

Changes in surface water supply (2070s) for the CT scenario (with the range of equally likely scenarios in parentheses)

- *Average annual precipitation: +6% (-10% to +16%)*
- *Average annual temperature: +4.5 degrees F (+3 degrees F to +8 degrees F)*
- *April 1 Snowpack: -62% (-38% to -86%)*
- *Irrigation season runoff (April-September): -40% (-14% to -64%)*
- *Drought magnitudes and duration could decrease, according to tree ring analysis*

Surface Water

Projected climate change impacts to surface water include changes in both the timing of runoff and form of precipitation. Runoff timing is defined as the date when half of the runoff volume has already occurred. More winter precipitation is expected to fall as rain instead of snow. This could cause runoff timing to shift up to one month earlier by the 2030s (shifts from April to March) and two months earlier by the 2070s (shifts from April to as early as February). Figure 6 illustrates projected changes in spring snowpack (defined here as average snowpack on April 1), which drives seasonal peak runoff.

Average annual runoff is projected to increase by about 15 percent for the CMIP5 CT scenario, with a range from a decrease of 6 percent to an increase of 39 percent across all equally likely scenarios (refer to figure ES-2). Despite a possible increase in annual runoff, irrigation season runoff (April to September) is projected to decrease about 40 percent by the 2070s for the CMIP5 CT scenario, with a range of decreases from 14 percent to 64 percent in all equally likely scenarios. This may be due in part to shifting seasonal streamflow patterns.

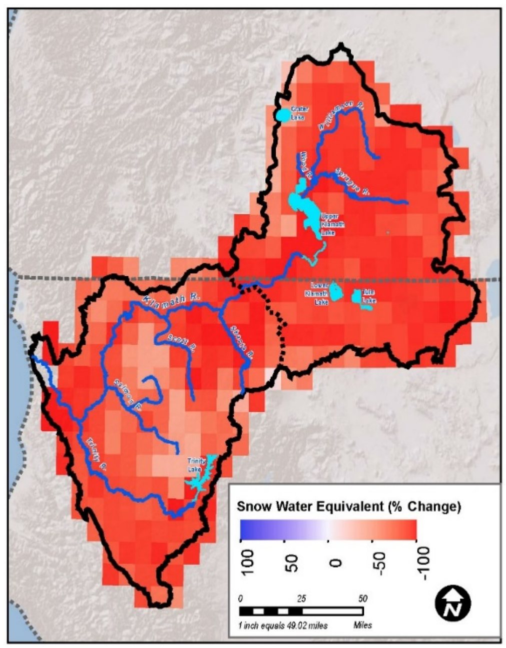


Figure 6.—Change in April 1 snowpack for the 2070s for the CMIP5 central tendency projection.

The seasonality of streamflow, and in particular summertime low flow in this region, is of interest to water managers since there is often limited supply for numerous competing demands during low flow periods. The variability of flow also affects river ecosystem function.

Analysis of historical tree ring data indicates that the frequency of wet periods and droughts may be similar for the 2030s and 2070s compared with the historical baseline; however, the magnitude and duration of wet periods and droughts may decrease. Further, several climate change scenarios point to somewhat wetter conditions on an average annual basis in the Klamath River Basin. The differing projections based on these methods of analysis highlight the uncertainty in determining future precipitation and the benefit of incorporating multiple types of analysis.

Recent work by Malevich et al. (2013) in the upper Klamath River Basin, which looks at tree ring records over the past 1,000 years, suggests that recorded history has not captured the full range of drought magnitude and duration experienced by the region over the last millennium.

Groundwater

For the upper basin, climate change scenarios and results from the surface water analysis inform projections of groundwater levels and recharge. In order to focus on the impacts of climate change alone, <u>the water supply assessment **does not** evaluate impacts of changing demands (i.e. pumping) on groundwater.</u>

Precipitation changes in the basin could affect future groundwater recharge rates. Therefore, projections of groundwater recharge correspond closely with projections of future precipitation. For the CMIP5 CT scenario, recharge is expected to increase by about 8 percent in the upper Klamath River Basin by the 2070s, with a range from a decrease of 12 percent to an increase of 23 percent across all equally likely scenarios.

For the CMIP5 CT scenario, groundwater levels are projected to increase by about 8 feet on average, with a range from a decrease of 7 feet to an increase of 26 feet across all equally likely scenarios. 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.

Changes in groundwater supply (2070s) for the CT scenario (with range of equally likely scenarios in parentheses)

Upper Klamath Basin

- *Groundwater recharge from precipitation:*
  +8% (-12% to +23%)
- *Groundwater levels:*
  +8 ft (-7 ft to +26 ft)
- *Groundwater discharge to streams: +2% in Lost River and +12% in Sycan region of the Sprague River (-7% to +41%)*

Shasta/Scott Valleys

- *Shasta groundwater levels:*
  +25 ft (+5 ft to +43 ft)
- *Scott groundwater levels:*
  and + 23 ft (+8 ft to +42 ft)

Projected groundwater trends also include changes in mean annual groundwater discharge to rivers and streams. Basin-wide groundwater discharge to rivers and streams is projected to increase by a range of just under 2 percent in the Lost River to about 12 percent in the Sycan Region of the Sprague River headwaters, according to the CMIP5 CT scenario for the 2070s. The full range of changes across all equally likely scenarios ranges from a decrease of 7 percent to an increase of 41 percent, with both ends of that range occurring in the Sycan Region. Projected discharge increases to streams are greatest for headwater areas and lowest for the basin's interior.

Consistent with the results for the upper basin, the projected monthly groundwater elevations for the Scott and Shasta sub-basins for the 2030s and 2070s may be higher than the historical baseline, not considering changes in groundwater use beyond that associated with population growth. Projected increases in groundwater levels correspond with projected increases in precipitation. The projected changes are also within or close to the historical fluctuations in groundwater elevation in the two basins, on the order of 20 feet for both basins (see text box above).

Water Demand Assessment

The assessment of historical and projected water demand encompasses the entire Klamath River Basin, similar to the water supply assessment. The general approach for the water demand assessment is to focus on demands that are consumptive, in that they deplete available water in the basin for other uses. Other types of demands that rely on thresholds of streamflow or reservoir levels are evaluated through the system reliability analysis as described in the System Reliability Analysis section, below.

Historical Water Demand

Based on analyses supporting the Basin Study, total consumptive water demand for human uses in the basin is about 800,000 acre-feet per year (AFY), and about 98 percent of this demand is for agricultural irrigation (refer to figure 7). Wetland evapotranspiration and lake and reservoir evaporation make up the remaining consumptive uses in the basin and together consume about 1.2 million AFY.

Largest municipal water users in the Klamath River Basin:

- *Klamath Falls, OR*
- *Weed, CA*
- *Yreka, CA*
- *Weaverville, CA*

However, together M&I and rural domestic demands comprise only 2% of consumptive demands influenced by humans and less than 1% of total consumptive demands.

Approximately 75 percent of the M&I demand within the Klamath River Basin is from the four largest municipalities (Klamath Falls, OR; Weed, CA; Yreka, CA; and Weaverville, CA). Average annual M&I and rural domestic demands represent approximately 0.7 percent of total basin demand. Generally, rural domestic demands are less than M&I demands, except for Trinity County where estimated rural domestic demand rates are higher than M&I. Figure 7 illustrates the relative contributions of individual consumptive demands in relation to the total demand. The historical baseline scenario with respect to demands is the best estimate of current conditions, based on available data.

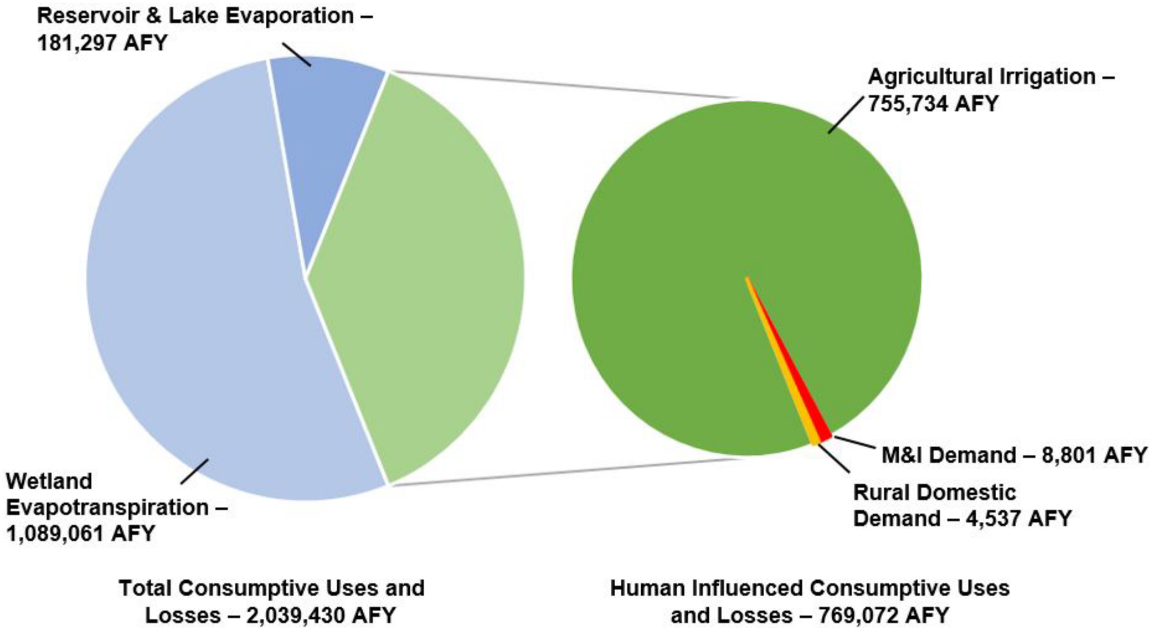


Figure 7.—Klamath River Basin estimated consumptive uses and losses for the historical baseline scenario in AFY.

Other consumptive demands, including livestock water and commercial and industrial uses, comprise only 0.2 percent of the total consumptive demand. Since they make up such a small percentage of demands, these uses are not shown in figure 7 and were not further evaluated in the Basin Study.

Meeting water quality requirements is integral to water demand. As a result of natural conditions and human activities, water quality standards in the upper Klamath River Basin have not been met for many years. Water quality impairments impact the beneficial uses of water such as aesthetic and cultural values, agricultural water supply, commercial water supply, fish and wildlife habitat, potable water supply, industrial water supply, and navigation. Known or perceived concerns over health risks associated with seasonal algal toxins in the Klamath River have resulted in the alteration of traditional cultural tribal practices, such as gathering and preparation of basket materials and plants, fishing, ceremonial bathing, and ingestion of river water.

Future Water Demand

Climate change may increase demands for water throughout the basin, as crops and landscaped areas consume more water due to warming. In addition, a modest population growth rate of <1 percent to 2 percent per year for most municipalities in the basin could further increase domestic water use. All climate change scenarios suggest increases in consumptive demands, even those that suggest a wetter future, indicating that effects from warming would outweigh any potential benefit from increased precipitation in the future.

Future water demand for M&I and rural domestic uses is projected to increase approximately 17 percent basin-wide by the 2070s, considering only population growth and no climate change. When climate change scenarios are considered, basin-wide demand increases by 22 percent under the CMIP5 CT scenario for the 2070s, with a range of increases between 20 percent and 25 percent under all equally likely scenarios. Again, M&I and rural domestic demands make up about 2 percent of demands for human needs.

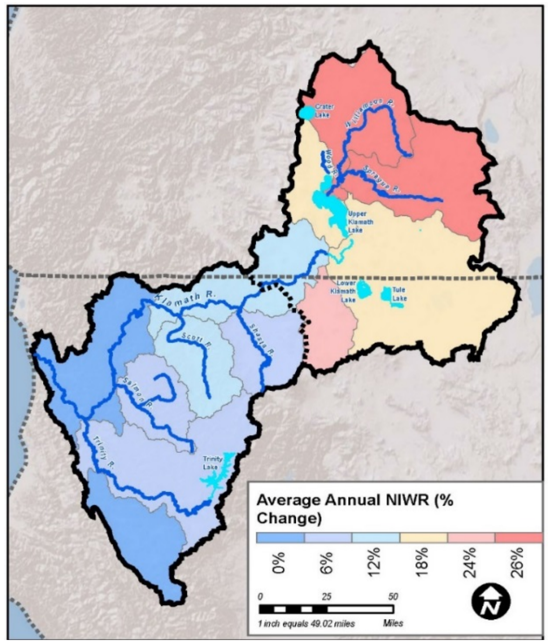


Figure 8.—NIWR by sub-basin for the 2070s.

For agricultural irrigation demands, the water consumed by crops (evapotranspiration) and the net irrigation water requirement (NIWR) are projected to increase. Under the CMIP5 CT scenario, evapotranspiration is projected to increase about 11 percent by the 2070s (with a range of +7 percent to +17 percent); NIWR is projected to increase 14 percent (with a range of +6.7 percent to +22 percent), by the 2070s (figure 8).

Although water demands are anticipated to increase to meet crop needs, crop production may also increase due to changes in timing of crop growth and harvesting. For example, alfalfa is one of the basin's dominant crops. In the future, farmers may get one additional cutting of alfalfa each year; from a historical average of two, to three by the 2070s.

Changes in consumptive water demand (2070s) for the CT scenario (with range of equally likely scenarios in parentheses)

- *Assumed basin-wide population increase: ~28%*
- *M&I and rural domestic use: +22% (+20% to +25%)*
- *Crop evapotranspiration: +10-11% (+7% to +17%)*
- *NIWR: +14% (+7% to +22%)*
- *Increase from 2 cuttings of alfalfa to 3 cuttings by 2070s*
- *Wetland evapotranspiration: +14% (+9% to +21%)*

Wetlands have been a focus of restoration efforts in the Klamath River Basin. The upper basin consisted of vast wetlands prior to agricultural development and logging. Assuming an unchanged number of wetland acres of over 340,000 acres – according to National Wetlands Inventory 2014 data (USFWS, 2014) – future water consumption (evapotranspiration) by wetlands is projected to increase 14 percent by the 2070s for the CMIP5 CT scenario (with a range of increases from +9 percent to +21 percent across all equally likely scenarios), mostly due to warming temperatures. In spite of projected increases of consumptive water use, wetlands provide a great benefit to the ecological health of the basin and improve water quality.

The Basin Study also evaluates future water losses due to reservoir evaporation. Overall, increases in evaporation are expected to be greatest during the summer months of July and August, and least during fall and winter months. However, after taking precipitation into account, future changes in reservoir evaporation differ based on location. In the upper basin, projected losses from Upper Klamath Lake display a net evaporation (evaporation minus precipitation) increase by about 5 percent by the 2070s time period for the CMIP5 CT scenario, with a range between a decrease of 9 percent to an increase of 24 percent across all equally likely scenarios. In contrast, Trinity Lake annual net evaporation decreases by about 9 percent under the same future scenario, with a range between a decrease of 44 percent to an increase of 40 percent across all equally likely scenarios. The projected decrease is likely due to the effect of increased precipitation in the region surrounding the reservoir.

System Reliability Analysis

In the system reliability analysis, the Basin Study uses information from the water supply and water demand assessments to simulate water management conditions throughout the basin and then evaluates how climate change may impact the river's ability to meet the variety of future water needs. Part of this analysis is the identification of historical and future water supply and demand imbalances. This information can be used as a point of comparison for exploration of adaptation strategy concepts that may reduce these imbalances.

Methods for System Reliability Analysis

The system reliability analysis uses the University of Colorado's RiverWare water management software for the model developed by Reclamation for the Klamath River Basin to simulate managed reservoir storage and streamflow. The Klamath Basin RiverWare model is based on current river operations rules as defined by the 2012 Biological Assessment and associated 2013 joint BiOp. Along with the Klamath Basin RiverWare model, the system reliability analysis also incorporates an existing River Basin Model (RBM)10 river temperature model, developed by the USGS (Perry et al., 2011). Use of the river temperature model provides the Basin Study a unique opportunity to explore the impacts of climate change and water management changes on Klamath River temperature.

The Basin Study TWG and basin stakeholders provided input on performance measures for evaluating historical and future system reliability. The system reliability analysis relies on these performance measures to inform water managers to what extent water needs were met historically, and how that might change in the future. A range of one to three measurements was identified for each of the six performance measures, as listed below:

1. Water Deliveries
    - Mean annual flow at USGS gages located in the Shasta River near Yreka and in the Scott River near Fort Jones
    - Water storage in the Upper Klamath Lake at the end of February plus inflow to the lake from March through September
    - Water delivered via the Klamath Project in comparison to a supply target of 390,000 AFY
2. Hydroelectric Power Resources
    - Mean annual hydropower produced at JC Boyle, Copco 1, Copco 2, and Iron Gate combined
    - Mean annual spill volume based on water year for JC Boyle, Copco 1, and Iron Gate
    - Mean number of spill days per water year at JC Boyle, Copco 1, and Iron Gate
3. Recreational Resources (fishing and boating)
    - Mean number of days per year that flows are within acceptable ranges for fishing in select river reaches
    - Mean number of days per year that flows are within acceptable ranges for boating in select river reaches
4. Ecological Resources
    - Minimum pool elevations at Clear Lake and Gerber Reservoir
    - Mean annual water delivery to Lower Klamath National Wildlife Refuge (LKNWR)
    - Flows at Shasta and Scott Rivers throughout the year
5. Water Quality (expressed in the Basin Study as water temperature)
    - Average Annual maximum weekly average temperature (MWAT) in the Klamath River at Klamath, CA
6. Flood Control
    - Number of days per year that flood control releases are made from Upper Klamath Lake
    - Mean annual volume of flood control releases from Upper Klamath Lake
    - Date of seasonal peak flow at JC Boyle, Copco 1, and Iron Gate

The summary presented here focuses on three representative performance measures, while the Basin Study Technical Report summarizes results of the system reliability analysis for all identified performance measures. The three selected measures discussed in the Summary Report were selected by the TWG and include:

1. Average Klamath Project Supply (April-September)
2. Average Annual Water Deliveries to LKNWR
3. Average Annual MWAT in the Klamath River at Klamath, CA

In addition to these measures, the system reliability analysis evaluated several basin-wide response variables: average monthly streamflow, storage, and water temperature, at select locations throughout the basin.

System Reliability without Adaptation

Results of the system reliability analysis support the common understanding that the Klamath River Basin has historically experienced difficulties in meeting the range of water needs. Table 1 summarizes the historical baseline, the CMIP5 2070s CT scenario, and the corresponding range of equally likely projections for the three selected performance measures. Although several climate change scenarios (including the CT) suggest wetter future conditions and higher annual flow volumes at many locations in the basin (which may reduce water supply and demand imbalances), greater challenges are anticipated for ecological resources such as fish and wildlife.

Seasonal irrigation supplies to the Klamath Project stay about the same by the 2070s, according to the CMIP5 CT scenario, but the range of possible changes show decreases to modest increases under all equally likely scenarios. It is important to reiterate that historical baseline and future simulations in the system reliability analysis were based on the same operating rules under the 2012 Biological Assessment and associated 2013 joint BiOp.

Substantial changes are projected for ecological resources such as average annual deliveries to LKNWR and the MWAT in the Klamath River at Klamath, CA. Projected average annual deliveries to LKNWR range from roughly one- to two-thirds of the model-simulated historical baseline conditions.

Table 1.—Summary of System Reliability without Adaptation for Three Selected Performance Measures

Performance Measure	Historical Simulation	2070s CMIP5 CT Scenario	Range Across All Equally Likely Scenarios
Average Klamath Project Supply Full delivery is assumed 390,000 AFY	361,000 AFY	362,000 AFY	318,000 AFY to 374,000 AFY
Average Annual LKNWR Deliveries AFY	25,000 AFY	14,000 AFY	8,000 AFY to 16,000 AFY
Average Annual MWAT “Poor” classification is >63.7 degrees F	76 degrees F	81 degrees F	79 degrees F to 84 degrees F

As previously mentioned, model-simulated historical MWAT in the Klamath River at Klamath, CA has been classified as “poor” according to the 2012 Southern Oregon/Northern California Coast (SONCC) Evolutionary Significant Unit (ESU) salmon recovery plan. As the climate warms, coho salmon and other salmonids and fish species that rely on cool water temperatures could be increasingly stressed. This highlights the importance of cool water refugia for the survival of these fish in the Klamath River.

Additional analysis of basin-wide response variables shows that shifts in the timing of seasonal streamflow and the timing of reservoir fill and drawdown are likely. Timing of seasonal streamflow is defined as the time at which half of the annual flow has occurred. It should be noted that current operating rules under the 2012 Biological Assessment and associated 2013 joint BiOp rely on historical hydrologic patterns. Projected shifts in the timing of streamflow and storage in the basin, as a result of climate change, may require greater flexibility in operating rules to allow for changing hydrologic patterns.

Results from model simulations show that a shift toward higher rainfall runoff and reduced snowmelt runoff causes increased mean annual flood volumes, a change in the timing of flood releases to earlier in the year, and small changes in hydropower production. For Upper Klamath Lake, the timing of highest seasonal reservoir levels and subsequent releases for irrigation is projected to occur up to one month earlier under the 2070s CT scenario, with a range of 13 days to 31 days across all equally likely scenarios. However, unlike Upper Klamath Lake, the timing of storage at Iron Gate is expected to remain about the same, even though storage volume may increase slightly. Review of the historical baseline simulation for Iron Gate storage indicates that reservoir levels did not fluctuate substantially through the year.

Adaptation Strategy Concepts for Reducing Imbalances in Water Supply and Demand

Numerous studies have affirmed that climate change has already impacted water resources, and this trend is projected to continue for decades despite possible mitigation efforts. Adaptation planning is a required step in the development of a basin study with an overarching objective of identifying measures to reduce projected water supply and demand imbalances.

Identification, screening, and evaluation of adaptation strategy concepts for the Basin Study is based on results from the system reliability analysis without adaptation, as well as review of existing studies that have identified possible adaptation strategies for meeting the needs of various basin water users.

Adaptation Strategy Concept Identification and Screening

Adaptation strategy concepts were identified through a combination of stakeholder input and a comprehensive review of studies on climate change and water supply issues, both for the Klamath River Basin, as well as the broader Pacific Northwest. A total of 185 adaptation strategies were identified and evaluated in a screening process. With input from the TWG, adaptation strategies were divided into five major categories, in part to facilitate the screening process.

The five major categories are:

- decrease demand
- governance and implementation
- increase supply
- miscellaneous (consisting of those strategies not fitting into the other categories)
- modify operations

An initial screening effort evaluated strategies in each of these five categories to determine if they could be represented by the Basin Study models. Strategies that could be modeled were evaluated quantitatively, and strategies that could not be modeled in the current Basin Study modeling framework were documented for potential future qualitative evaluation. Following the initial screening process, the strategies were further evaluated and ranked according to their implementation risk and uncertainty, reliability, and environmental effect. This evaluation and ranking process was similar to the approach taken for evaluating actions proposed in the On Project Plan for the Klamath Project (Klamath Water and Power Agency, 2014), which was developed to align water supply and demand within the Klamath Project.

Based on the evaluation of all 185 identified adaptation strategies, the TWG arrived at five adaptation strategy concepts that encompass a wide range of individual adaptation strategies. The five adaptation strategy concepts were intended to be broad and to allow for greater understanding of the sensitivities of the basin to changes in water supply and demand, as well as operational changes.

Figure 9 illustrates the process for identifying, screening, and evaluating adaptation strategies to result in the five adaptation strategy concepts explored through the Basin Study. 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 potential future evaluation, but were not considered further as part of the Basin Study.

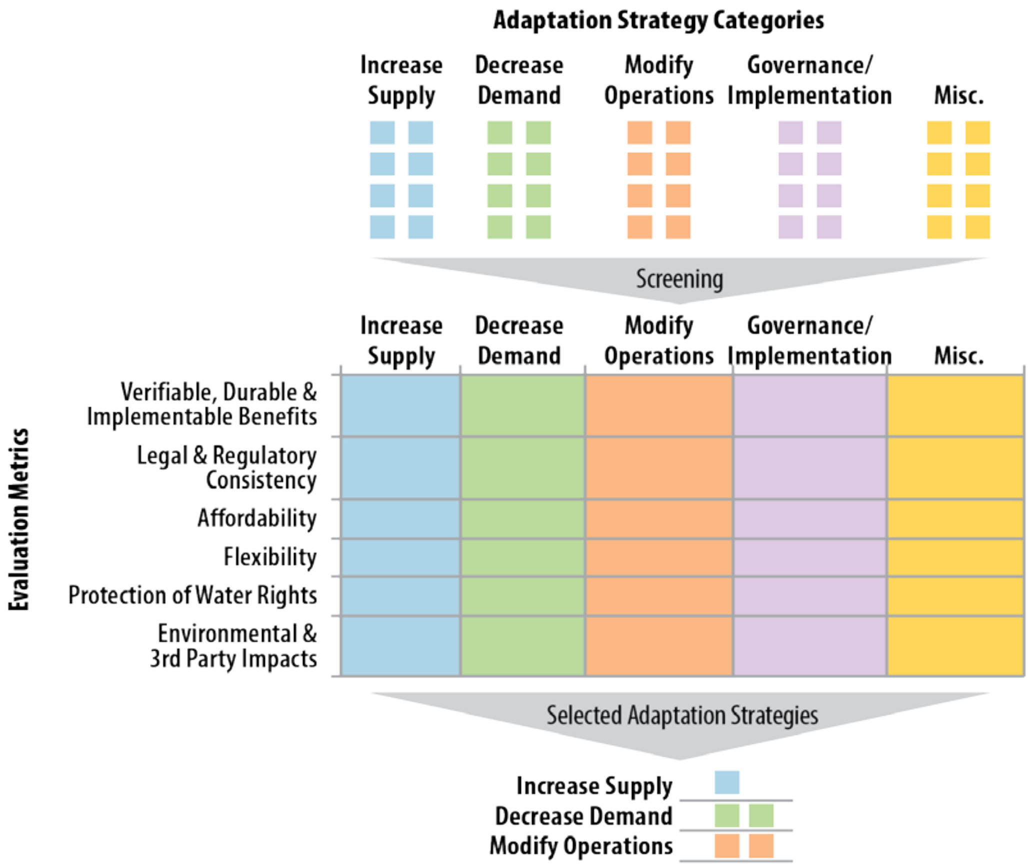


Figure 9.—Adaptation strategy concept evaluation and screening.

The five adaptation strategy concepts explored through the Basin Study do not represent individual, or groupings of, proposed projects. The intent is to use information from evaluating broad adaptation strategy concepts to focus attention on those types of strategies, which the basin appears to be most sensitive to, and then work with stakeholders and other interested groups to determine where strategy concepts could best be applied. Figure 10 summarizes the adaptation strategy concepts.

System Reliability with Adaptation Strategy Concepts

The Basin Study evaluates system reliability with each of the five adaptation strategy concepts to explore their ability to reduce climate change impacts. The Klamath Basin RiverWare model operating rules, as well as inputs to the RiverWare model and corresponding USGS river temperature model, were modified as needed to represent each adaptation strategy concept. Model simulations using projected future scenarios provided results that could be evaluated according to system reliability metrics and basin-wide response variables, as in the system reliability analysis. In general, the results of the model analysis using the adaptation strategy concepts show that the selected strategy concepts do have the ability to modestly reduce the impacts of climate change.

Decrease Demand	
	**Agricultural Water Conservation.—**This adaptation strategy concept is defined as a reduction in agricultural demand in all irrigated agricultural regions in the basin. Two strategies are explored as part of this adaptation strategy concept, namely demand reductions of 30 and 50 percent. Reductions in agricultural water demand might be obtained through actions such as canal lining and pump operation optimization; crop idling, irrigated land retirement and rain-fed agriculture; shifting agricultural production to more drought tolerant crops; or converting irrigation systems to more efficient technologies.
	**Additional Supply to Upper Klamath Lake.—**This adaptation strategy concept captures the additional 30,000 acre-feet of water provided for Upper Klamath Lake in the Upper Klamath Basin Comprehensive Agreement (2014) as generated by land retirement actions in the upper Klamath River Basin. The assumption is that operating rules are not modified to compensate for the additional Upper Klamath Lake inflow. This adaptation strategy concept may be considered a demand reduction, but stakeholders generally discuss this quantity as additional supply to Upper Klamath Lake.
Increase Supply	
	**Additional Surface Water Storage Capacity.—**This adaptation strategy concept is defined as the volume of water released from Link River Dam beyond what is delivered to the Klamath Project and released for downstream environmental needs under the 2012 Biological Assessment and 2013 BiOp. Currently, under the 2012 Biological Assessment and 2013 BiOp, this quantity is categorized as environmental water; however, this adaptation strategy concept assumes this quantity could be stored for future use.
Modify Operations	
	**Sensitivity of Model-Simulated Water Temperature to Changes in Flow and Climate.—**This adaptation strategy concept includes exploring relationships between water temperature change and streamflow change to estimate the needed change in flow to obtain a desired change in Klamath River temperature. Such information may help determine what changes in water management could counter the impacts of climate change.
	**Tributary Water Temperature Reduction.—**This adaptation strategy concept addresses the need for cold water refugia in summer months to support fish and wildlife, particularly salmonids in the Klamath River Basin tributaries. This concept is based on existing emergency water management planning in the Shasta River Basin, where groundwater may be pumped and supplied to the river in place of warmer surface water releases from reservoirs.

Figure 10.—Adaptation strategy concepts explored in the Basin Study.

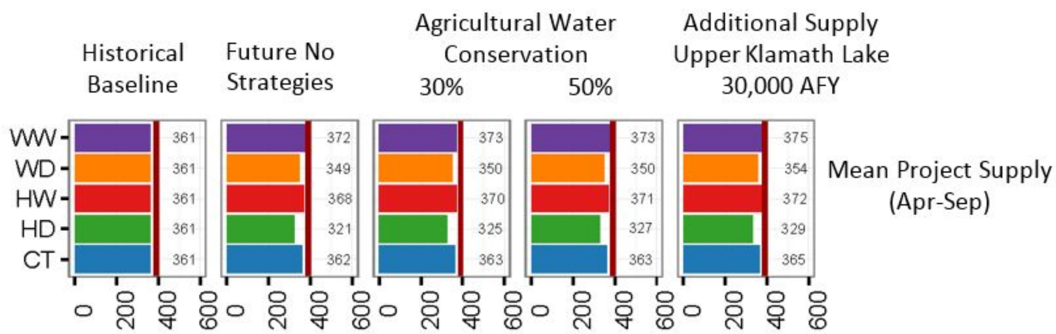
Key findings from evaluation of each adaptation strategy concept are summarized in figure 11.

	**Additional Surface 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. Because of limited Upper Klamath Lake storage and current operational constraints, alternative storage opportunities could be explored.
	**Agricultural Water Conservation.—** In parts of the basin where water deliveries are driven by agricultural demand, model results show that reducing agricultural demands results in noticeable increases in streamflow downstream. However, within Reclamation's Klamath Project, deliveries are based on available water in Upper Klamath Lake and forecasted seasonal inflow due to the guidelines in the 2012 BA and 2013 BO. Therefore, a reduction in agricultural demands within the Klamath Project does not lead to substantial changes in seasonal Klamath Project water supply. If deliveries within the Klamath Project were based solely on agricultural demand, then it is likely that a reduction in these demands would have a greater impact on streamflow and hydropower in the Klamath River.
	**Additional Supply to Upper Klamath Lake.—**Additional inflow to Upper Klamath Lake of 30,000 AFY shows potential for reducing water supply and demand imbalances in the Klamath River Basin. Still, this additional inflow does not have a substantial impact on seasonal Klamath Project supply, primarily because of current operating criteria under the 2012 Biological Assessment and 2013 BiOp that require water to meet certain instream flows. Any increase to Upper Klamath Lake requires that a portion of the water be added to instream flow.
	**Tributary Water Temperature Reduction and Sensitivity of Model-Simulated Water Temperature to Changes in Flow and Climate.—**These two adaptation strategy concepts illustrate that Klamath River temperature at Klamath, CA 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, results indicated that the effort spent to reduce mainstem Klamath River temperatures should focus on reducing tributary water temperature rather than modifying river operations.

Figure 11.—Adaptation strategy concept evaluation key findings.

The Basin Study analysis of adaptation strategy concepts summarizes results for the three representative performance measures described in the system reliability analysis. These performance measures include average Klamath Project supply (April-September), average annual water deliveries to LKNWR, and average annual MWAT. In addition, the analysis includes evaluation of several basin-wide response variables, which consist of average monthly streamflow, storage, and water temperatures at select locations throughout the basin. Future climate scenarios are represented in figures 12 through 14 as: warm-wet (WW), warm-dry (WD), hot-wet (HW), hot-dry (HD), and central tendency (CT).

Figure 12 illustrates results for average seasonal Klamath Project supply. In each figure panel, the red line marks the assumed full seasonal supply of 390,000 AFY. The figure shows that under both model-simulated historical and future scenarios full seasonal supply is not met during all years. Results are shown only for those adaptation strategy concepts that potentially impact Klamath Project supply, namely agricultural conservation and a 30,000 acre-feet increase of inflow to Upper Klamath Lake. Changes in water temperature do not affect seasonal Klamath Project supply.



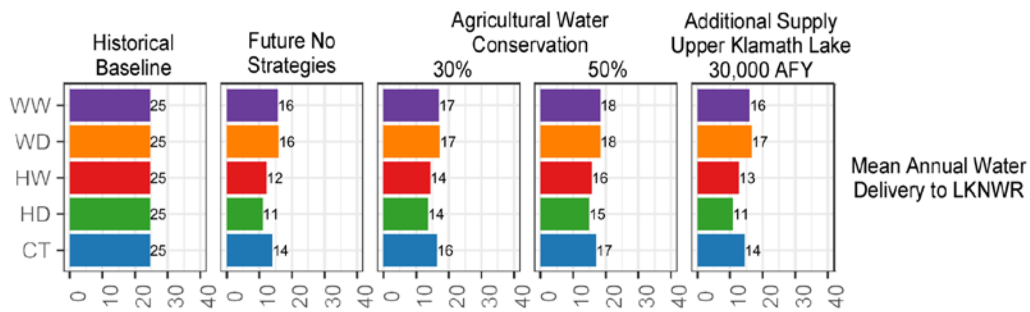
Notes: Historical Baseline and Future No Strategies scenarios do not incorporate any adaptation strategy concepts. The red line marks the assumed full seasonal supply of 390,000 AFY.

Figure 12.—Summary of historical and future system reliability for the 2070s with adaptation strategy concepts for average seasonal Klamath Project supply.

Overall, these adaptation strategy concepts do not substantially reduce the water supply and demand imbalance for the Klamath Project. Though it may seem inconsistent that Klamath Project demand is not fully met even with 30 percent or 50 percent reductions in demand, this is likely a result of current model operating constraints.

Under the 2013 joint BiOp, water allocations and deliveries to the Klamath Project are based on available supply and within the context of historical data. Further investigation of model constraints and their impact on results will occur through follow-on studies like the Klamath Basin Reservoir Operations Pilot Study, in which the Klamath Basin RiverWare Model will be refined.

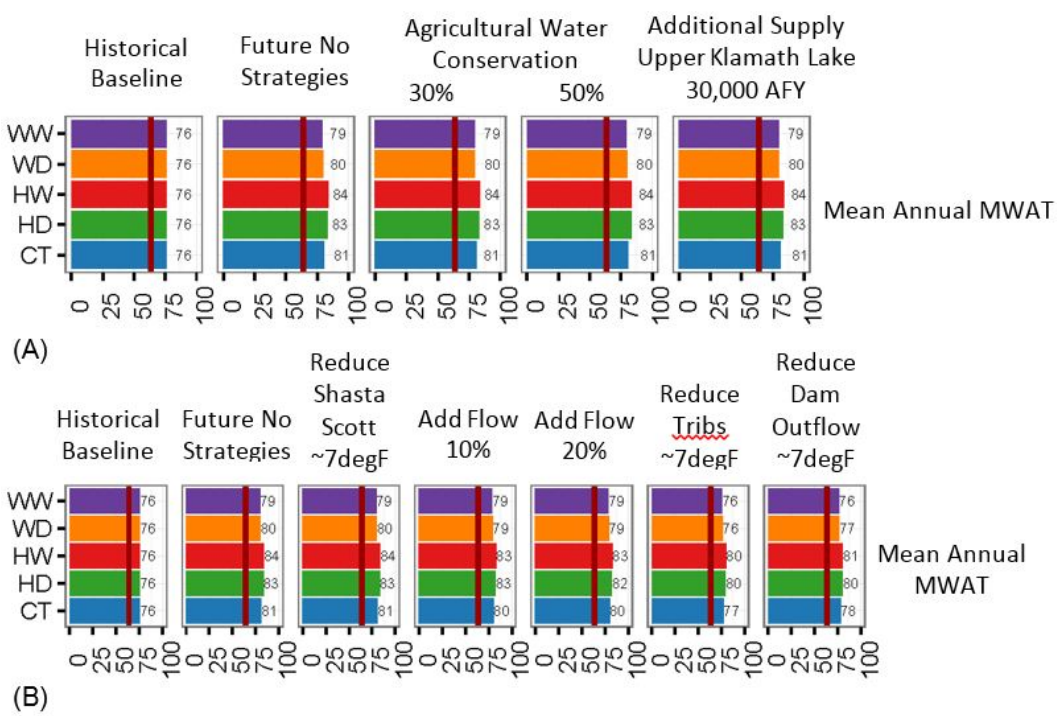
Figure 13 illustrates results for average annual deliveries to the LKNWR with the model analysis representing how two adaptation strategies may impact system reliability. Results are shown only for those adaptation strategy concepts that potentially impact Klamath Project Supply, namely agricultural conservation and increased inflow to Upper Klamath Lake. Changes in water temperature do not affect deliveries to the LKNWR. Overall, climate change negatively impacts deliveries to the refuge. The adaptation strategy concepts analyzed in the Basin Study did little to reduce the water supply and demand imbalances for the refuge, although reduction in agricultural demand by 50 percent has the most substantial impact on deliveries.



Notes: Historical Baseline and Future No Strategies scenarios do not incorporate any adaptation strategy concepts.

Figure 13.— Summary of historical and future system reliability for the 2070s with adaptation strategy concepts for average annual deliveries to the LKNWR.

Figure 14 illustrates results for mean annual MWAT of the Klamath River at Klamath, CA. In each figure panel, the red line marks the threshold of 63.7 degrees F, which indicates poor habitat suitability. The figure shows that the poor habitat suitability threshold is exceeded under both model-simulated historical and future scenarios.



Notes: Historical Baseline and Future No Strategies scenarios do not incorporate any adaptation strategy concepts. The red line marks the threshold of 63.7 degrees F, which indicates poor habitat suitability.

Figure 14.—Summary of projected historical and future mean annual MWAT of the Klamath River at Klamath, CA, in the 2070s with adaptation strategy concepts.

Overall, climate change negatively impacts Klamath River temperatures. Adaptation strategy concepts involving changes in flow volume and timing (refer to figure 14, panel A) do not have a noticeable impact on river temperature (i.e. agricultural demand reduction and additional inflow to Upper Klamath Lake). Exploration of the sensitivity of river temperature to changes in flow and tributary water temperature shows that flow changes do not have a noticeable impact on Klamath River temperature (refer to figure 14, panel B). However, reducing tributary water temperature in all tributaries, or even just at the dams, does have a noticeable impact.

Key Findings and Next Steps

Klamath River water users and stakeholders have long called for a comprehensive and integrated approach to water management to balance the needs of all water users. The Basin Study evaluates how current and future water supply and demand affect these various needs. Identified adaptation strategy concepts provide water users, stakeholders and Reclamation with an understanding of the degree to which increasing supply, decreasing demand, and modifying operations could reduce supply and demand imbalances.

The Basin Study builds on earlier work and provides a comprehensive knowledge base and suite of tools that can address long term planning needs. The Basin Study process provided an opportunity for valuable collaborations and incorporation of a state of the art groundwater model and river temperature model into the system reliability analysis.

The results of the Basin Study show that the Klamath River has historically faced water supply and demand imbalances. Climate change, particularly warming, could put greater stress on the river and the needs it supports. Small improvements may be possible to reduce these imbalances. **The adaptation strategy concepts with the greatest potential for reducing imbalances are summarized in figure 15.**

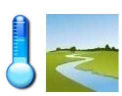
	Reducing tributary water temperatures through conjunctive surface and groundwater management
	Increasing inflows into Upper Klamath Lake
	Increasing surface and groundwater storage opportunities in the basin

Figure 15.—Adaptation strategy concepts with the greatest potential for reducing imbalances.

The adaptation strategy concepts evaluated in this Basin Study may be further studied to refine understanding of potential benefits. The agencies and stakeholders involved in that refinement process should include those potentially affected by their possible implementation.

Refinement of Adaptation Strategy Concepts and Supporting Information

The Basin Study relied upon projected future conditions that were developed using existing model frameworks and inputs. Identified adaptation strategy concepts evaluated by the Basin Study are broad (i.e. not specific proposed projects) by design and were intended to identify the sensitivity of the Klamath River Basin to various types of management changes. A number of possible efforts that could further enhance our understanding of climate change impacts on the Klamath River Basin have been identified.

- **Refinement of River Temperature Analysis**.**—**Expansion of the river temperature analysis to include the Trinity River (model under development by USGS) would enhance the understanding of operational changes in the Trinity River on water temperature in the Lower Klamath Basin.

- **Refinement of Ecosystem Demands and Vulnerabilities**.**—**Additional analysis of the relationships between climate change and ecosystems would further support and refine the findings in this study. In addition, incorporation of temperature modeling for the Trinity River, in development by the USGS, could enhance our understanding of climate change impacts 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 provide more comprehensive groundwater data which would improve the analysis completed in this Basin Study.

- **Reservoir Operations Refinement**.**—** The Klamath River Basin reservoir operations pilot study on Upper Klamath Lake, currently being funded by Reclamation, will enhance the ability to quantify Upper Klamath Lake inflows and provide for an improved understanding of Upper Klamath Lake operations.

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