

**Planning Alternatives for Lake Mendocino (Coyote Valley Dam) in the Upper  
Russian River System  
Storage and Water Supply Reliability Study**

By

PABLO TOMAS SILVA JORDAN  
B.S. (Pontificia Universidad Católica de Chile) 2010

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Hydrologic Sciences

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

---

(Samuel Sandoval-Solis, Chair)

---

(Carlos E. Puente)

---

(Jay R. Lund)

Committee in Charge  
2016

To Vero, Tomas, Joaquin and the ones to come...

“A model is a platform for a disciplined discourse”

Professor Uri Shamir

# Table of Contents

List of Tables .....	6
List of Figures .....	7
Abstract .....	9
Acknowledgements .....	10
1. Introduction .....	1
1.1. Research objectives .....	2
2. Literature Review .....	4
2.1. Reservoir operation and performance.....	4
2.2. Planning alternatives to improve water supply reliability .....	7
2.2.1. Expand surface water storage capacity .....	8
2.2.2. Groundwater storage .....	10
2.2.3. Updating operating plans .....	11
2.2.4. Forecast operation .....	13
2.3. Water transfers.....	15
3. Case of Study: Upper Russian River Basin.....	18
3.1. The Russian River Basin .....	18
3.2. Water availability .....	20
3.3. Anthropogenic alterations.....	22
3.3.1. Coyote Valley Dam.....	22
3.3.2. Potter Valley Project .....	25
4. Method.....	27
4.1. Lake Mendocino Allocation Model.....	29
4.1.1. Water Demands .....	31
4.1.2. Water Supply.....	35
4.1.3. Operation.....	36
4.1.4. Mass Balance.....	38
4.2. Current and Alternative Water Management Strategies.....	38
4.3. Reliability Analysis: Performance Criteria.....	41

5. Results: Model performance under alternative policies .....	43
5.1. Storage Reliability Analysis .....	43
5.1.1. Reservoir Storage Reliability .....	43
5.1.2. Rule Curve analysis during Refill Season.....	44
5.1.3. Monthly Storage Distribution .....	46
5.2. Tradeoff analysis .....	49
6. Discussion.....	54
7. Conclusions .....	58
7.1. Limitations.....	58
References .....	60

## List of Tables

Table 1 Planning alternatives to address water supply reliability (Adapted from Hanak et al., 2011).....	8
Table 2 Average water availability for the Upper Russian River system (thousand acre-feet) .....	35
Table 2 Reliability results for both Storage conditions and PVP scenarios.....	43

# List of Figures

Figure 1 Location of potential surface storage projects (DWR, 2010). ..... 9

Figure 2 Groundwater recharge projects throughout California, relative to priority groundwater basins (Rohde, 2014) ..... 11

Figure 3 Folsom Reservoir Rule Curve (USACE, 2004)..... 12

Figure 4 Forecast Reservoir Operation Systems Components based on the California-Nevada River Forecast Center of the National Weather Service (NWS-CNRFC). Retrieved from the California Energy Commission (Georgakakos et al., 2012)..... 14

Figure 5 Main conveyance and storage projects throughout California (Hanak et al., 2011)..... 16

Figure 6 (a) Russian River watershed; (b) Schematic of the Upper Russian River system, its main reaches and control points..... 18

Figure 7 Cumulative mean annual diversions from the Eel River and Unimpaired flows (in thousand acre-feet / year) for the Upper Russian River system (Flint et. al., 2015) ..... 21

Figure 8 Coyote Valley Dam Rule Curve with respect to the reservoir storage in acre-feet and elevation in feet (USACE & SCWA, 2000) ..... 23

Figure 9 Minimum instream flows based on Decision 1610 and summer time modified Biological Opinion. At the end of May, the combined storage of Lake Pillsbury (LP, Eel River) and Lake Mendocino (LM) is evaluated (LP & LM > 130,000 acre-feet). In October, only Lake Mendocino (LM) storage is evaluated (LM > 30,000 acre-feet). Adapted from SCWA, Term 17 report, 2015..... 24

Figure 10 Schematic of the Potter Valley Project including its main components: Cape Horn Dam, Lake Pillsbury (Scott Dam), and the Diversion Tunnel into the Russian River(Friends of the Eel River, 2016). Pictures taken by the author. .... 26

Figure 11 Representation of the methodology along with the three specific objectives of this study ..... 28

Figure 12 WEAP interface of the UCD Water Allocation Model of the Upper Russian River..... 29

Figure 13 Schematic of the UCD Water Allocation Model for the Upper Russian River Basin..... 30

Figure 14 (a) Distribution of annual average water demands. (b) Annual variation of average water demands per type. (Adapted from SCWA, Term 17 report, 2015). ..... 32

Figure 15 (a) Average surface water demands (thousand acre-feet / year) for the Upper Russian River system. West Fork and PVP are not included. (b) Average total agricultural water demands (thousand acre-feet / year) including surface and groundwater sources for the Upper Russian River system and their

surface-groundwater share (percentage) per reach. West Fork and PVP are not included (Adapted from SCWA, Term 17 report, 2015).....	34
Figure 16 Biological Opinion flows and Hydrologic Index for the upper Russian River system (USACE & SCWA, 2000).....	37
Figure 17 Water management strategies implemented in the model .....	39
Figure 18 Non-exceedance probability for PVP On comparing the current storage capacity and the augmented storage capacity .....	45
Figure 19 Non-exceedance probability for PVP Off comparing the current storage capacity with the augmented storage capacity .....	46
Figure 20 Monthly distribution of reservoir storage for both the current storage capacity and the augmented storage capacity under the Baseline Scenario with PVP On .....	47
Figure 21 Monthly distribution of reservoir storage for both the current storage capacity and the augmented storage capacity under the Baseline Scenario with PVP Off.....	48
Figure 22 Tradeoff analysis given storage capacity and PVP diversions combinations. Performance measured using the occurrence based annual storage reliability.....	49
Figure 23 Reservoir storage occurrence annual-based reliability for (a) augmented capacity on 10 TAF increments; (b) for reductions in current PVP diversions in 10 percent intervals .....	50
Figure 24 Contour lines of the annual storage reliability on Lake Mendocino for both additional storage capacity (y-axis) and share of current PVP diversions (x-axis).....	51
Figure 25 Shortages upstream and downstream of Lake Mendocino for variations in storage and PVP diversions. (a) Upstream of CVD with respect to storage; (b) Downstream of CVD with respect to storage; (c) Upstream of CVD with respect to PVP diversions; (d) Downstream of CVD with respect to PVP diversions.....	52
Figure 26 Tradeoff between additional storage in Lake Mendocino and share of current PVP inflow.....	57



## **Abstract**

A water availability model (UCD -Model) was developed to assess water supply reliability for Lake Mendocino (Coyote Valley Dam, CVD) on a monthly time step at a reach scale on the upper section of the Russian River (above the confluence with Dry Creek). Two water management alternatives were evaluated to determine their impact on reservoir storage reliability. Historically, CVD was built for flood management but incorporated water supply as an additional objective. It was originally planned to be raised from the current storage capacity (phase 1 completed in 1959), augmenting storage capacity by 75,000 AF. This second phase was never executed. Additionally, diversions from the Eel River into the Russian River basin through the Potter Valley Project (PVP) have been consistently reduced over the past 20 years. Therefore, these diversions were assessed to determine the impact on the system's reliability. Preliminary results suggest that the reliability of the system could be seriously reduced with the current and augmented storage capacity conditions if Potter Valley Project (PVP) diversions are reduced over time.

This study was developed as part of the study for the Russian River Flood Control and Water Conservation Improvement District (RRFC) to address the “long-term water supply reliability of the Lake Mendocino and the Upper Russian River system”, referred as Term 17 project. This analysis illustrates the significance of developing an integrated water resources model that allows a better understanding of the relative importance that the different components have, integrating conflicting objectives to address the systems' reliability. The system is more sensitive to changes in water transfers, but there is a potential additional volume that could be stored that is not capture with current storage capacity.

## Acknowledgements

I would like to thank the University of California, Davis Hydrologic Science Graduate Group, their professors and students, for their support and shared knowledge. Their passion and outstanding research work encouraged me to go beyond. Particularly, I would like to express my sincere gratitude to Dr. Samuel Sandoval-Solis, my research advisor and whom after all these years, I can call my friend. His relentless “thirst” of knowledge and restless guidance drove my work and inspired me to become a better scientist, a future water manager, and above all, a better person. Thanks also to Dr. Carlos Puente, whose hydrologic understanding sat the foundation of my research, but most importantly, his inspiring presence shed a light of truth that shines far beyond the hydrologic field. Finally, thanks to Dr. Jay Lund for his wisdom and shared experience that gave me a valuable understanding of water management and policy within California.

I would like to acknowledge the generosity and confidence that the Russian River Flood Control and Improvement Water Conservation District gave us to develop this study. Special thanks to Sean White, former General Manager for his guidance and for trusting on a non-Californian, non-US student a delicate matter that is so relevant for their agency. Thanks also to Tamara Alaniz, current General Manager of the RRFC, and to Chris Delaney from Sonoma County Water Agency for their assistance throughout this whole project.

Finally, I would like to thank my wife and family, to whom I dedicate this thesis. Thanks for your patience, generosity, and constant support, for getting on board in this dream and sometimes crazy adventure. It may be the most repeated cliché, but it would not have been possible without you. Gracias Vero, Tomas, Joaquin!

# 1. Introduction

Managing sustainable water resources systems has been defined as a multidisciplinary and interdependent problem, which requires meeting objectives for both society and the environment now and in the future (Loucks, 2005). Changes over time in water supply, environmental streamflow requirements, and recreational objectives combined with significant reductions in new infrastructure and aging current infrastructure, poses concerns over the reliability of water resources systems (Hanak et al., 2011; Labadie, 2004). Existing operating plans are usually based on historical climate information. In multipurpose reservoirs for flood management and water supply, rules curves are usually developed based on a statistical analysis of past runoff and flood events (Brekke et al., 2009).

Similarly, water managers have different alternatives to cope with climate variability that range from structural change (increase water supply and/or storage) to management alternatives with potential benefits for society and the environment (Watts, 2007). Presently, reservoirs should have been optimized to operate under different levels of water availability (Park & Kim, 2014). However, their effective operation may not be attainable under anticipated climate-changes (Kim, 2009). Therefore, different initiatives have been analyzed to address water supply shortages and improve the long-term reliability of the system. Additional storage enables to manage and capture a variable hydrology while attaining a more reliable water supply system (ACWA, 2015). On the other hand, reoperation alternatives allow water managers to address hydrologic variability “through more flexible infrastructure and management systems” (Watts, 2007).

The overall goal of this study is to evaluate the impact on reservoir storage reliability under current and alternative water management strategies in the Upper Russian River basin

(from the Russian River headwaters to Dry Creek). This analysis illustrates the significance of developing an integrated water resources model which allows sustainable management of the system and to evaluate different alternatives for improving supply reliability. Extended flow and climate change data will support comprehensive analysis for the upper Russian River. Therefore, understanding the relative significance of different system components requires a transparent and scientifically based analysis that integrates conflicting objectives to address and improve the system's water supply reliability.

### **1.1. Research objectives**

This study was developed to address critical water management strategies and introduces an approach to aid decision-making. A case study is used to apply this method, based on reservoir storage and inter-basin water transfers. Key components of the system are examined to understand the performance of these management strategies. Results from this research will provide supportive information for water managers and stakeholders that can assist upcoming decisions related to minimum in-stream flows, development of new hydrologic index, reoperation of the reservoir, inter-basin water diversions, and water use and allocation throughout the system.

The specific objectives of the study are to: (1) develop a tool that simulates the hydrology, infrastructure and water demands in the Upper Russian River; (2) define and evaluate the current and alternative water management strategies, comparing the baseline conditions with changes in storage capacity and changes in water transfers (PVP); and (3) perform a storage reliability and tradeoff analysis given a series of combinations of storage capacity and water transfer.

This assessment was developed as part of a study for the Russian River Flood Control and Water Conservation Improvement District (RRFC) to address the “long-term water supply reliability of the Lake Mendocino and the Upper Russian River system” (SCWA, 2015), referred as Term 17 project. Further details of the State Water Resources Control Board (SWRCB) order or the Term 17 project can be found on the Sonoma County Water Agency (SCWA) report, published on April 30, 2015.

## **2. Literature Review**

### **2.1. Reservoir operation and performance**

Much water resources infrastructure in the United States and especially in western states was designed and built more than fifty years ago (USACE, 2005). Climate change, population growth, and hardening agricultural demands have increased pressure on scarce water resources (DWR, 2013). Although there is little agreement over precipitation trends in climate change, several studies agree that temperature rise will reduce snowpack storage, and alter seasonal runoff both in magnitude and timing (Cayan, 2008). Competition over water supplies will increase with time (IPCC, 2007), as few water sources are available when compared to past development (DWR, 2013). Given this range of changes, scientifically based models are required to further understand the problem, to evaluate potential strategies, and to address conflict resolution among stakeholders with respect to water scarcity (Lund, 1997; Loucks, 1990; Sandoval-Solis, 2013)

Construction of large-scale water storage projects in the western U.S. has almost halted for the past 40 years (Hanak et al., 2011). Moreover, the yield of these projects may have changed over time due to new water uses from the original design, such as water supply, streamflow requirements for ecosystems, and recreational objectives (Labadie, 2004). Additionally, operational restrictions are often imposed on reservoirs due to federal regulations, legal agreements or adjudications, or specific interest (Labadie, 2004).

Similarly, many existing operating plans are based on historical climate information. Flood operations are an example where rules curves were developed based on risk and statistical analysis of previous runoff and flood events (Brekke et al., 2009). Changes in climate, watershed

land use, environmental needs and social values of water over time may require more frequent review of operating rules. These changes may broaden and constrain the operational alternatives and be further complicated by stakeholder's disagreements on objectives and future uncertainties, such as those related to climate change (Labadie, 2004; Georgakakos et al., 2012). Some regions in California already have shown a shifted early runoff peak of 15 to 30 days (Mote, 2006). For reservoirs with operational procedures established for the historical climate, these changes in runoff patterns and precipitation will undermine their original design performance. Early runoff will occur during the flood protection season, at the same time when reservoirs are at their lowest storage to create flood capacity. Additionally, that early volume will not be available to fill reservoirs as intended during the spring, affecting water supply reliability (DWR, 2013). Even though a reservoir's operational rules were designed using the best available information to meet the original objective, nowadays they may not be effectively operated under the anticipated changes (Kim, 2009).

Within the State of California are more than 1,400 dams owned and operated by Federal, State, local and private agencies (DWR, 2015). Several dams that were built by the USACE serve for flood attenuation and they are usually sponsored by a local agency. Thus, water supply is within their main purposes. Similarly, hydropower is often the main objective for several dams within California and is also frequently included in water supply projects to provide economic benefits. Those competing objectives are generally difficult to balance and are even more challenging to implement operation policies that would optimize two or more objectives to their full individual extent. Therefore, to address this new scenario without compromising the benefits of the water resources system, different planning alternatives should be developed by water managers.

System reoperations will require changing existing operation and management to increase the benefits of the water resources system (DWR, 2013). The combination of aging infrastructure and operation plans that were design based on historical records and purposes provides the adequate time frame to address operational changes in water systems (Georgakakos et al., 2012). Evaluation of different alternatives will require collaboration between federal, state and local agencies. Operational changes may seem easier to be implemented than new infrastructure. Nonetheless, the multipurpose operation of some reservoirs includes water supply, ecosystem benefits, and flood management, and Congressional approval is required in some cases.

Construction of large-scale infrastructure is has become increasingly exceptional, so greater emphasis has been made on managing current infrastructure and evaluating its performance under potentially unplanned conditions (McMahon et. al., 2006). According to the list of performance metrics developed by McMahon (2006), this study focuses on the reliability of the system. The reliability of a reservoir can be defined in several ways, but it generally refers to the probability that the reservoir will be able to meet a certain target evaluated over a given period of simulation. Time-based reliability is usually calculated for either annual or monthly time steps and is obtained by dividing the number of periods that the reservoir did meet a given target over the total number of periods for the simulation. A variation of this concept is the occurrence-based reliability which refers to the probability of meeting the target for at least some time in a particular year (Klemes, Srikanthan, & McMahon, 1981). The monthly time-based reliability and the annual occurrence-based reliability were used in this study to assess reservoir performance. Another metric that is used to assess systems performance particularly when two alternatives are compared is the Pareto optimal curve. It is usually associated with multiobjective



optimization, where decision makers are interested in the trade-off between two or more strategies (Kapelan, Savic, & Walters, 2005).

To provide an overall framework of different strategies that have identified as applicable for water supply systems, the following section describes the main alternatives related with reservoir storage reliability within California. This study focuses only on reservoir storage capacity as a way to improve the systems reliability in the context of Term 17 project. In a highly managed system like California, inter-basin water transfer played a major role in supporting agricultural and urban development as well as improving the systems reliability when this transfer provides an alternative source for water supply. Assessing impact on water supply reliability is also part of the study.

## **2.2. Planning alternatives to improve water supply reliability**

The California Water Plan update 2013 defines a comprehensive set of resource management strategies (RMSs) to provide solutions for the range of challenges. With respect to water supply, two planning categories can be defined based on the time needed to implement: (1) those implementable in the short term, related to operation, and (2) those that require long-term adaptations, related with new infrastructure (Brekke et al., 2009). A summary of these strategies appears in Table 1.

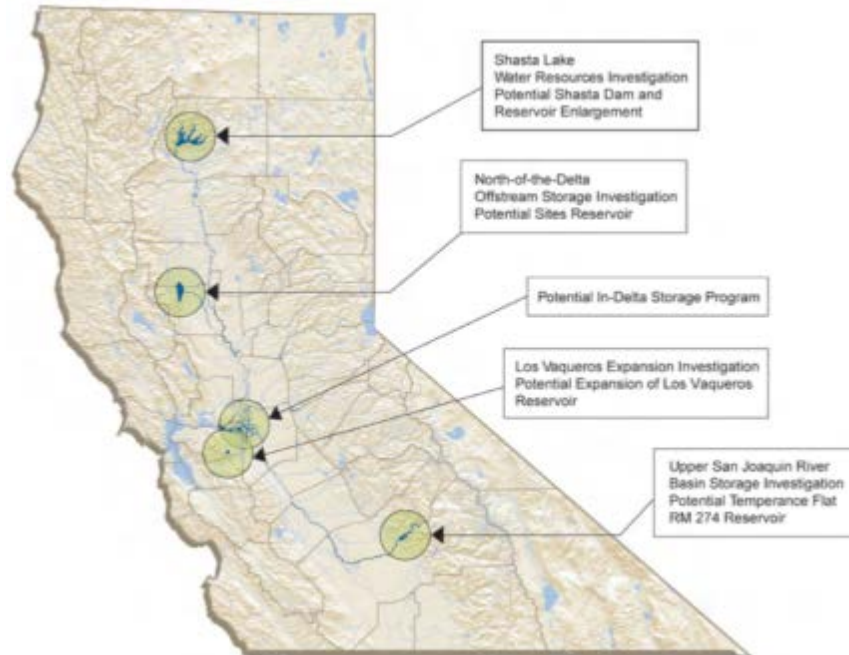
**Table 1 Planning alternatives to address water supply reliability (Adapted from Hanak et al., 2011)**

<b>Category</b>	<b>Planning Strategy</b>
<b>Facilities</b>	Surface water storage*
	Groundwater storage
	Water treatment and desalination
<b>Systems Operations</b>	Recycling urban wastewater
	Reservoir operating plans*
	Forecast operation
	Groundwater integration
<b>Demand Reduction and Policy</b>	Demand reduction-efficiency
	Water transfers*
	Public Outreach
	Land Use Planning

\* Strategies addressed on this study

### 2.2.1. Expand surface water storage capacity

Surface water supply is a major objective of California’s water system. Even though the era of infrastructure development ended about 30 years ago (Hanak et al., 2011) and most of the best sites have been taken, California remains dependent on surface water (DWR, 2013). Despite the growing controversy about dams, they are a critical element for providing reliable water supplies. The CALFED Program has identified five potential projects that could be developed in order to expand surface water storage (see Figure 1): Shasta Lake Reservoir Enlargement, North-of-the-Delta new Reservoir site, In-Delta Storage, Los Vaqueros Reservoir Expansion, and Upper San Joaquin River Basin Storage (DWR, 2013). The main objectives of these projects are to enhance water supply, water quality, and ecosystem restoration.



**Figure 1 Location of potential surface storage projects (DWR, 2010).**

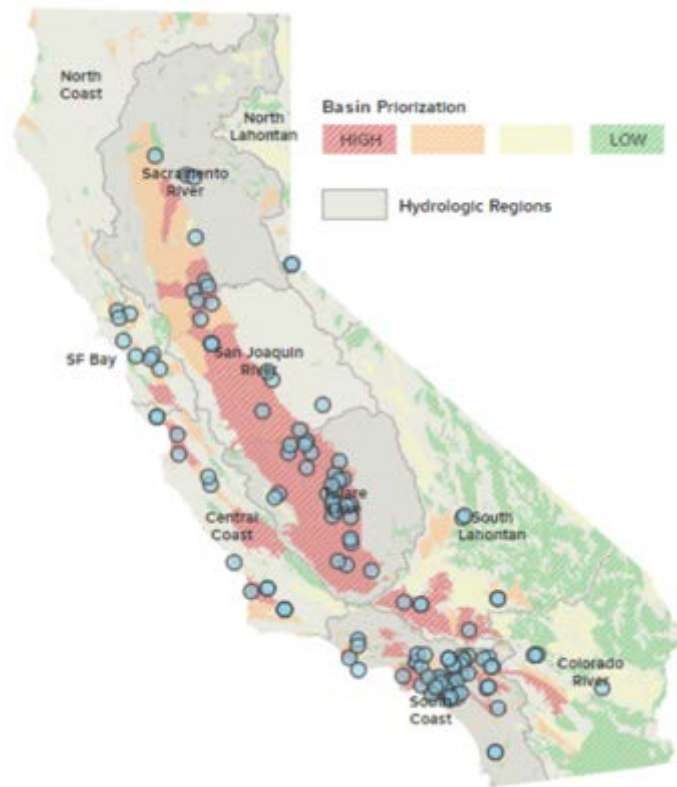
Many local agencies also rely on surface water projects. Local and regional surface storage facilities provide a wide range of water uses, from water supply, flood control, hydropower, recreation, and ecosystem among others (DWR, 2013, p. Vol. 3 Ch. 14). Few new reservoirs have been built since the 1960s, and the main storage development has been done through reservoir enlargement and groundwater. Therefore, rehabilitation or expansion of existing reservoir capacity should be considered as a main alternative for local agencies to develop additional surface water storage.

### **2.2.2. Groundwater storage**

Managing surface water and groundwater together allows water managers to take advantage of their shared benefits. The combination of both storage capacities provides additional flexibility, but requires adequate infrastructure and coordinated management (DWR, 2013). Groundwater recharge occurs naturally when surface water infiltrates into the soil and moves down into the aquifer. Several recharge alternatives can enhance this process: recharge basins, injection wells, in-lieu groundwater storage, and floodplain restoration among others allow surface water diversion and replenishment of depleted aquifers (Weeks, 2015). To engineer this process available storage capacity, hydrogeologic feasibility, conveyance infrastructure, and water quality are among the main feasibility considerations (DWR, 2013, p. Vol. 3 Ch. 9).

Recent legislation regarding groundwater management in California (Sustainable Groundwater Management Act, SGMA) requires the formation of local groundwater sustainability agencies (GSAs) to manage groundwater resources in a sustainable way for the long term. Local organizations will be required to undertake this process, which will involve cooperation and stakeholder participation, understanding the groundwater context, and defining and implementing a groundwater management portfolio. This offers an opportunity to develop infrastructure to capture and store groundwater, and improve monitoring of groundwater supplies, allowing local agencies to increase water supply reliability (Union of Concerned Scientist, 2015). Additionally, the objective of Senate Bill X2 1 (SB X2 1) is to incorporate climate change adaptation strategies, such as the “reoperation of existing reservoirs, flood facilities, and other water facilities in conjunction with groundwater storage to improve water supply reliability, flood hazard reduction, and ecosystem protection and to reduce groundwater

overdraft” (DWR, 2013). More diverse portfolios of water supply need to account for groundwater in a sustainable way. A proper operational procedure would need to be developed to determine the timing for storing runoff in surface reservoirs or divert (or release) this runoff and store it in downstream aquifers. Moreover, SGMA implementation offers opportunities to implement conjunctive management plans integrated with reservoir operation.



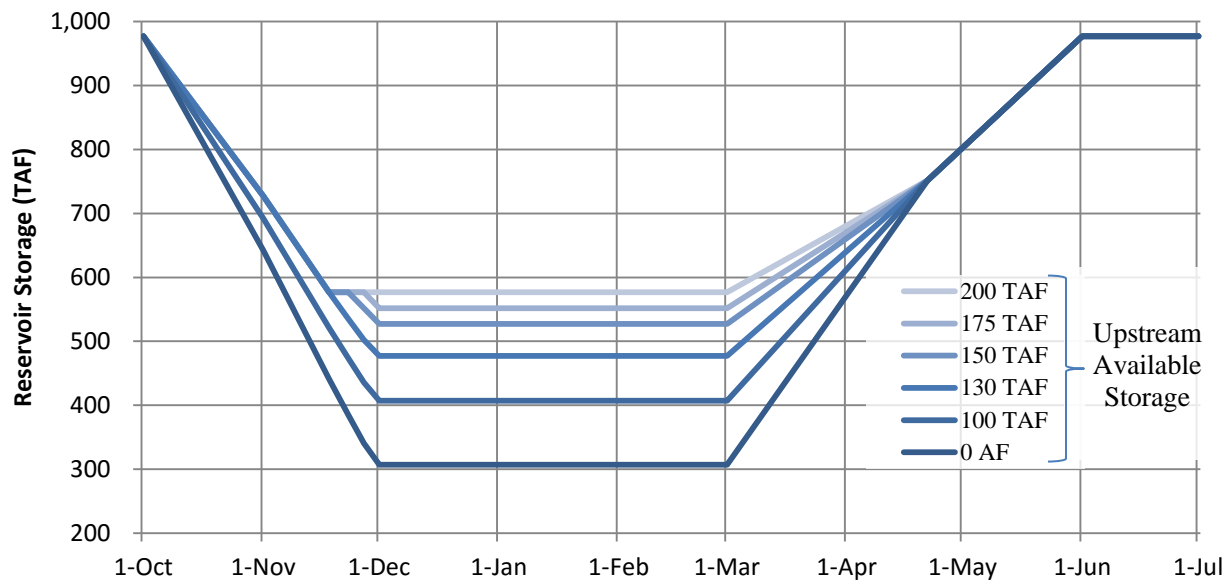
**Figure 2 Groundwater recharge projects throughout California, relative to priority groundwater basins (Rohde, 2014)**

### **2.2.3. Updating operating plans**

Reservoirs throughout California are operated based on seasonal storage targets that provide flood space during the wet season and conservation storage during the filling (spring and

snowmelt) and dry season. Rule curves create a flood management pool by drawing down storage during the wet season when most high runoff events occur (refer to Figure 3).

Correspondingly, they allow the reservoir to refill during the snowmelt season, while the flood hazard is reduced as the dry season gets closer. The storage thresholds are obtained based on historical observation and risk analysis (Brekke et al., 2009).



**Figure 3 Folsom Reservoir Rule Curve (USACE, 2004)**

Although the main advantage of rule curves is their operational simplicity, they do not account for present watershed and weather conditions (Howard, 1999). Today, reservoir operations based on rule curves are mainly driven by reservoir storage capacity during a given event, runoff potential from the upstream basin, and channel capacity downstream (Brekke et al., 2009). Based on these inputs, climate change may affect rule curve operation based on suggested changes in magnitude, frequency, and duration of storm events that should be controlled by the

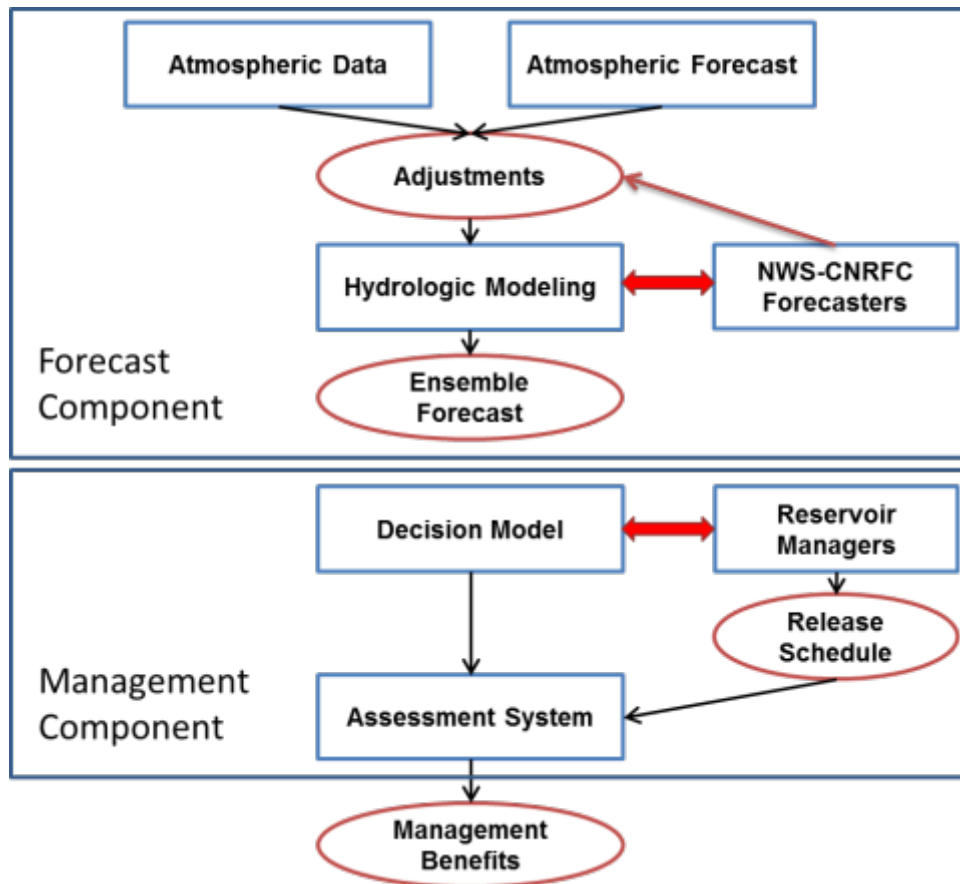
reservoir. Similarly, potential changes in snowmelt timing, summer soil moisture, vegetation, and wildfire risk also could trigger the need to modify existing operation (Dettinger et. al., 2004).

Periodic evaluations and operational changes occur, but often they require Congressional authorization along with time and resources. Nonetheless, changing operational procedures based on historic data may be necessary as expected (i.e., demand growth) and unexpected (i.e., climate change) challenges may arise that deviate from the original project. As presented by Brekke et al. (2009) on their assessment of reservoir operations risk under climate change, additional rainfall-runoff during the wet season and early snowmelt recession due to temperature rise could lead to additional flood space and changes on reservoir refill timing. Moreover, recent studies suggest that reservoir operation requires a more formal and direct optimization as well as a more defined objective function (Howard, 1999; HRC-GWRI, 2013). Therefore, analyzing reservoir performance under current and alternative operational procedures is required to better understand potential water management strategies.

#### **2.2.4. Forecast operation**

Technical developments during the satellite era have improved weather forecast skills. At the same time, climate change has been the main driver of natural resources debate. Both have created the opportunity to improve reservoir operations with additional information not available when reservoirs were designed and built. Two forecast approaches have been defined: long-term or interannual, and short-term or intra-seasonal (Brekke et al., 2009). Most seasonal forecasting is done by predictions of El Niño or La Niña. Knowing in advance if it is going to be a wet or dry year could influence and determine a set of operational rules to store more water, activate

conservation measures (related with demand reduction), or modify the flood pool to hedge seasonal storage.



**Figure 4 Forecast Reservoir Operation Systems Components based on the California-Nevada River Forecast Center of the National Weather Service (NWS-CNRFC). Retrieved from the California Energy Commission (Georgakakos et al., 2012)**

On the other hand, short-term weather forecast models have improved their skills over the last few years, which allow them to predict rain events with higher accuracy, although extreme event predictions are still highly uncertain (Ralph et al., 2010). This short-term or seasonal forecast has a great influence on reservoir operation, which allows releases before a flood event. Initiatives concerning Forecast Informed Reservoir Operation (FIRO) have been developed over



time, which provides water managers with additional strategies to operate reservoirs in a flexible manner (see Figure 4). Watershed monitoring programs, weather and runoff forecasting are tools that have enabled FIRO's research results to adjust current flood control guidelines while optimizing limited resources and storage capacity without affecting flood hazard and dam safety (Report, Unpublished). Nonetheless, further research is needed to develop better forecast models, to incorporate them into reservoir operations, and to assess potential storage reliability improvements (Brekke et al., 2009).

### **2.3. Water transfers**

California's water system has an elaborate network of conveyance and storage infrastructure built over time and is controlled by different Federal, State, and local agencies (see Figure 5). Two main projects, the Federal Central Valley Project (CVP) and the State Water Project (SWP) convey water from the wet north into the thirsty southern California, which are considered the two main distribution systems in California. Besides these two major infrastructure networks, several local inter-basin water transfer projects have been implemented for water supply and hydropower. Thus, the State's economic growth has greatly depended on water-transfer infrastructure networks and water redistribution in location and time.

Several benefits from water transfers have been identified: to meet water demands either permanently or during a limited period of time; to improve systems reliability by avoiding depletion or maintaining storage levels; to meet water quality and environmental objectives; hydropower generation, among others (Lund & Israel, 1995). However, despite the beneficial primary objective, a number of ecological impacts have also been identified with respect to inter-

basin water transfers. Alteration of the natural flow regime, changes in aquatic habitat, water quality and the introduction of invasive species are one of the main impacts (Meador, 1992).

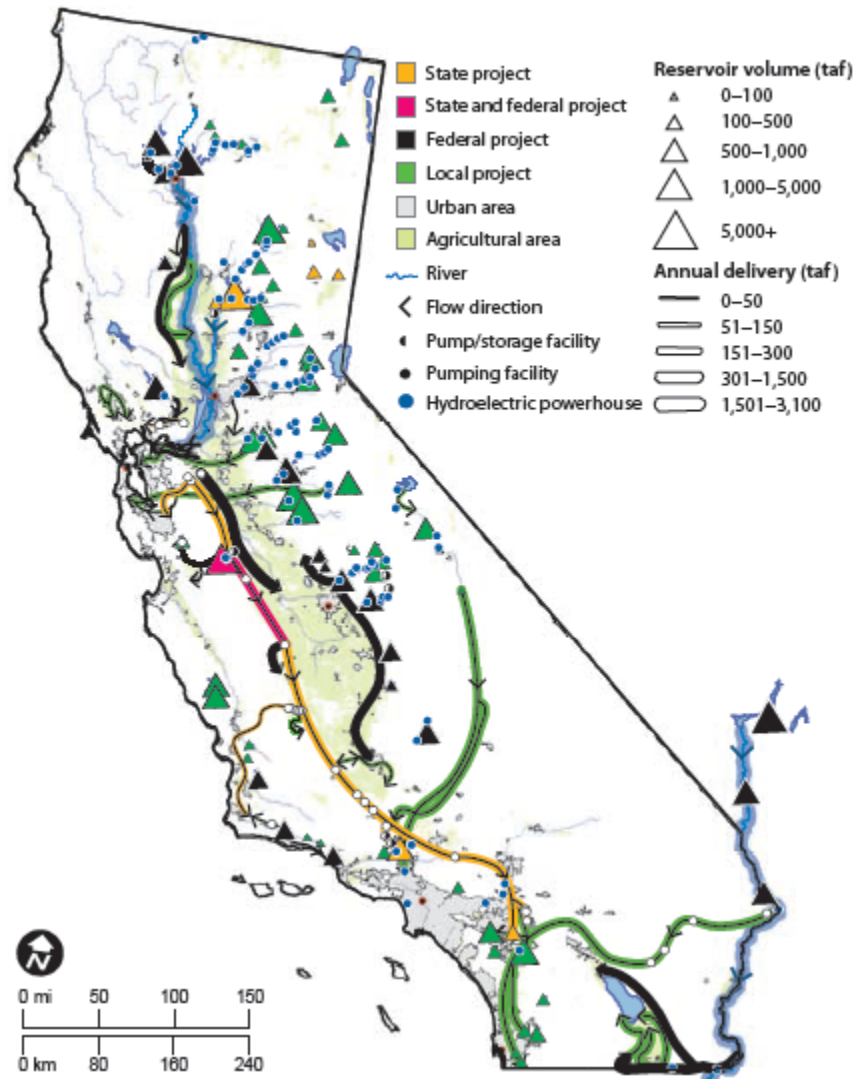


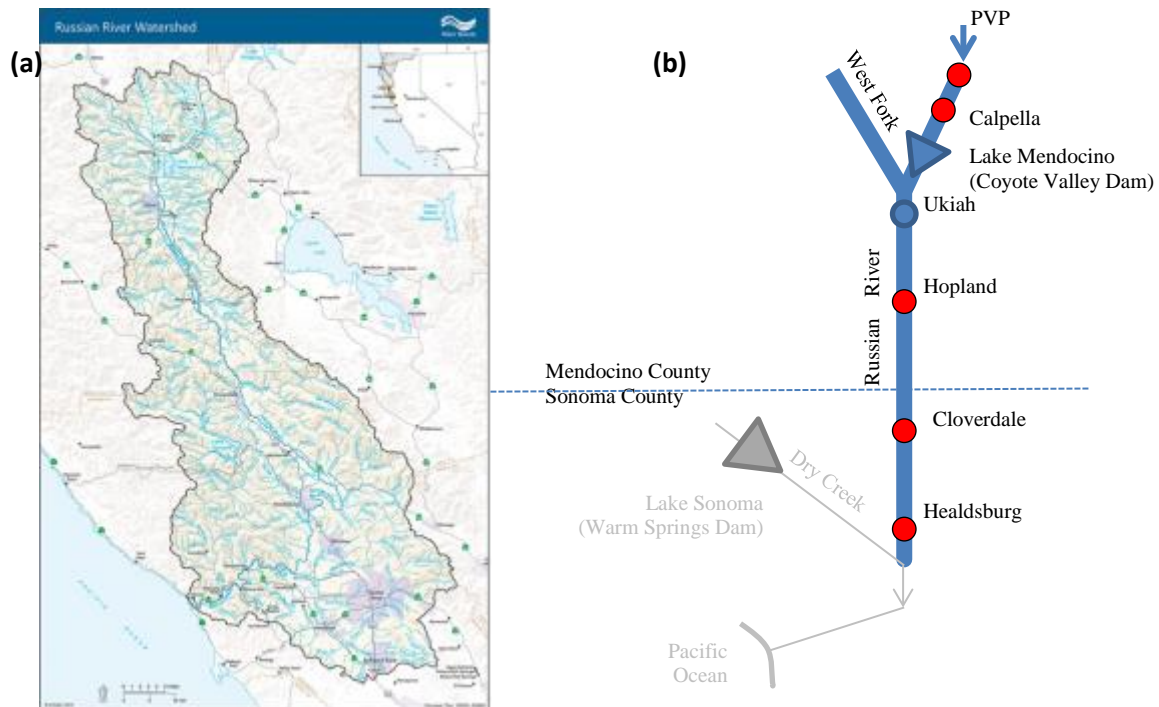
Figure 5 Main conveyance and storage projects throughout California (Hanak et al., 2011)

One significant impact of the implementation of water transfer infrastructure in California's history is the dependence of the basin's development on the transferred water and the alteration of the natural flow regime resulting in the steady degradation of the aquatic and riparian ecosystems. Water rights have been granted for urban water supply and agricultural

settings based on the transferred volumes. Over time, the system tends to rely on the transferred water, despite the fact that the original agreements may be modified or new regulations may be implemented. Significant efforts have been made to minimize the impacts over time, but water managers have also acknowledged that is not always feasible to restore the original flow regime without compromising other beneficial uses of the transferred water.

### 3. Case of Study: Upper Russian River Basin

#### 3.1. The Russian River Basin



**Figure 6 (a) Russian River watershed; (b) Schematic of the Upper Russian River system, its main reaches and control points**

The Russian River basin is in the southeast part of Mendocino County and the northern part of Sonoma County (Figure 6a). The basin drains approximately 1,485 square miles, including most of Sonoma and Mendocino Counties (USACE & SCWA, 2000). The Russian River headwaters are about 16 miles north of the city of Ukiah, and extend 110 miles before entering the Pacific Ocean at Jenner. The main stem of the river begins about 3 miles north of Ukiah, where the East and West Fork converge at a location known as the Forks, draining Potter and Redwood Valleys, respectively. Downstream, it flows south through Ukiah, Hopland, Alexander and Healdsburg Valleys, and 22 miles before its mouth, it bends westwards and flows

through the northwestern region of the Santa Rosa plain, crossing the Coast Ranges (USGS, 1965). The Russian River basin is a highly productive agricultural area, where more than 80,000 acres of vineyard (74%), pasture (19%), and orchards (7%) are grown (SCWA, 2013). Agricultural industry revenues are half billion dollars per year (Sonoma County, 2014; Mendocino County, 2014). Also, the Russian River provides water to more than 600,000 people in Mendocino, Sonoma, and Marin Counties.

The geology of the Russian River watershed has northwest trending mountains ranges, which parallel the main structural formations of the region (USGS, 1965). Altitudes in the basin vary from sea level up to 4,344 feet on Mount St. Helena. Hills and mountains are about 85 percent of the basin, and alluvial valleys are the remainder area (USGS, 1965). The main tributaries on the river's upper section (i.e., above the confluence with Dry Creek) include the East Fork, Big Sulphur Creek, and Maacama Creek. On the lower section of the river, the main tributaries are Dry Creek and Mark West Creek (USACE & SCWA, 2000).

The basin has a Mediterranean climate with warm dry summers and wet winters, and a highly fog-influenced coastal region and hot interior valleys. Precipitation is mainly as rainfall, with snow falling only on the higher ridges and occasionally on the upper valleys. Nearly 90 percent of runoff is between November and April (USACE, 1986) due to Pacific winter storms. Winter precipitation usually results in flash floods due to low evapotranspiration conditions and the reduced permeability of the rocks in the mountainous areas of the basin (USGS, 1965).

This study is focused only on the Lake Mendocino water supply reliability. Therefore, the following sections will describe the Upper Russian River system that goes from the headwaters down to the junction of Dry Creek with the main stem of the Russian River, south of the city of

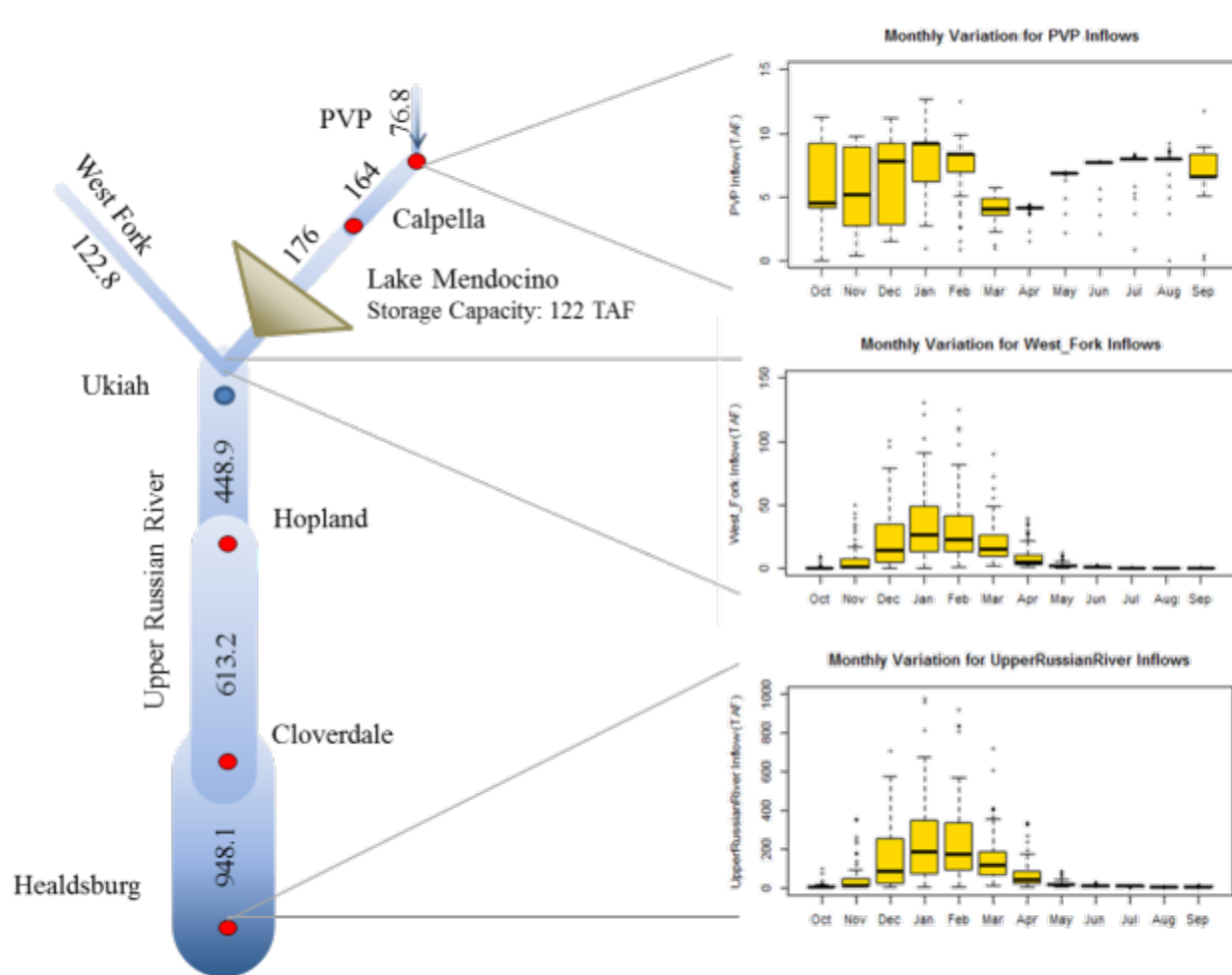
Healdsburg (schematic presented in Figure 6b). Dry Creek and Warm Spring Dam are not included in the system.

### **3.2. Water availability**

Water availability in the Upper Russian River, has two patterns. First, unimpaired flows (presented in Figure 7 for the average annual flow) were used to account for the natural input of the system, “unaffected by man-made influences such as water diversions or reservoir operation” (SCWA, 2015). These datasets were developed for historical climate (1910 to 2013) and potential climate change impact (2000 to 2099) by the USGS (Flint et al., 2015) and account for the cumulative flows downstream of the Potter Valley Project (PVP) discharge point.

Additionally, PVP diversions from the Eel River (described in the next section) were estimated using the Eel River model version 2.5 developed by the Natural Resources Consulting Engineers (Oakland, CA) and the SCWA, representing the post-2006 operations.

As seen in Figure 7, PVP diversions have a nearly steady average flow throughout the year that varies from 5 to 9 thousand acre-feet per month. More importantly, in summer (between May and August) there is almost no interannual variation, providing a highly reliable flow during the agricultural growing season. It is also important to compare the average annual flow of 76 thousand acre-feet with the total demands and environmental allocation (explained in section 4.1), where the annual average coincide, but the standard deviation for PVP is significantly greater.



**Figure 7 Cumulative mean annual diversions from the Eel River and Unimpaired flows (in thousand acre-feet / year) for the Upper Russian River system (Flint et. al., 2015)**

With respect to the unimpaired flows downstream of the PVP discharge point, at the Forks (junction of the East and West fork), the characteristic seasonality of the basin’s Mediterranean climate can be observed. Although it considers PVP flows, winter precipitation is significantly higher. Nonetheless, Figure 7 shows that PVP is approximately 25 percent of the cumulative annual flow of the forks, where the average annual flow contribution for the East and West fork is 100 and 122 thousand acre-feet, respectively. Nearly 30 percent of total average annual flow for the Upper Russian River systems is generated at this point (the Forks), and the

additional 70 percent or approximately 600 thousand acre-feet come from the contribution of the valleys located downstream.

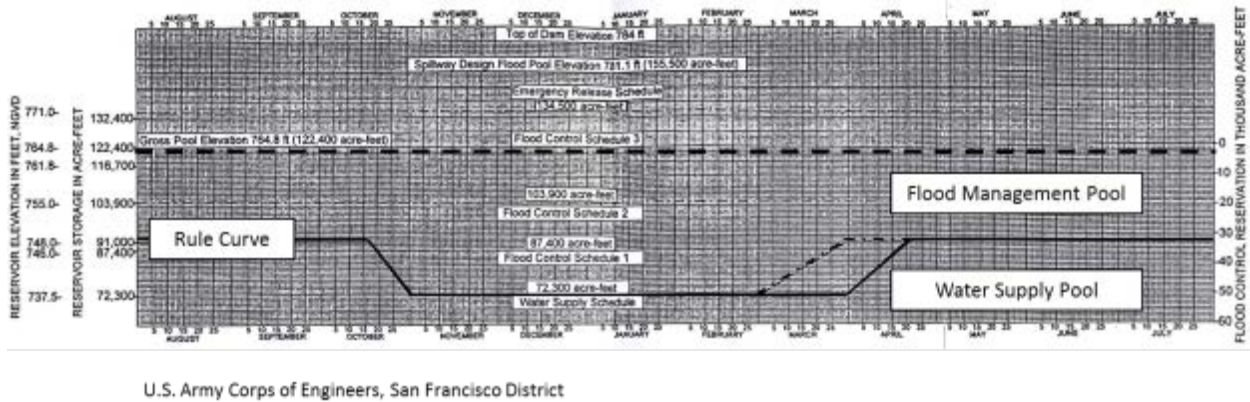
Finally, at the discharge point of the basin (where the main stem meets with Dry Creek), the average annual flow is nearly one million acre-feet, an order of magnitude greater with respect to the East or West forks but maintaining the same seasonality. Additionally, when water availability is compared with total demands and environmental allocation, it becomes evident that not even the whole Upper Russian River system has enough water to meet total demands during the driest years. Therefore, both PVP and Lake Mendocino storage are considered the main components to maintain the system's reliability.

### **3.3. Anthropogenic alterations**

#### **3.3.1. Coyote Valley Dam**

There are two main reservoirs in the Russian River basin. Coyote Valley Dam (CVD) was constructed in 1959 by the USACE on the East Fork, approximately 1 mile upstream of the Forks, and controls a drainage area of 105 square miles (USACE & SCWA, 2000). Warm Spring Dam (WSD) is located on Dry Creek and controls a drainage area of about 130 square miles and it was completed in 1983 by the USACE. Lake Mendocino is administered by the USACE and the SCWA and RRFC as the local sponsors. Lake Mendocino was originally designed in two construction phases. The first phase, constructed in 1959, had an original storage capacity of 122,400 acre-feet that based on the sedimentation rate measured in 2001, currently can store 116,500 acre-feet (SCWA, 2015). The second phase was never completed, but current efforts are further explained in section 4.2.





**Figure 8 Coyote Valley Dam Rule Curve with respect to the reservoir storage in acre-feet and elevation in feet (USACE & SCWA, 2000)**

The operation of Coyote Valley Dam considers both the Rule Curve developed by the USACE and the environmental constraints defined by Decision 1610 and the Russian River Biological Opinion. The USACE maintain and coordinate releases from CVD during flood management operations according to the Water Control Manual that was published after the construction and revised in 1986 (see Figure 8). Thus, the Rule Curve has a seasonal storage threshold to meet both flood management operations (storage above the Rule Curve) during the rainy season and water conservation during the dry season (storage below the Rule Curve). On the other hand, SCWA controls and coordinates releases to meet water rights permits associated with agricultural, commercial and residential users, SCWA and several public water systems, and minimum instream flow requirements under Decision 1610.

Finally, a Hydrologic Index is used to define the year type (see Figure 9). Cumulative inflows to Lake Pillsbury (Scott Dam) are measured between January and June to define the Water Supply Conditions as Normal, Dry, or Critical. This index will determine the environmental allocation or minimum instream flows. After June, both the storage of Lake

Pillsbury (LP) and Lake Mendocino (LM) are used to obtain the summer and fall flows associated with each index (from June to December)

### Hydrologic Index

Cumulative inflow to Lake Pillsbury (Thousand Acre Feet) as of						
Date	1/1	2/1	3/1	4/1	5/1	6/1
Normal	≥8	≥39.2	≥65.7	≥114.5	≥145.6	≥160
Dry	<8	<39.2	<65.7	<114.5	<145.6	<160
Critical	<4	<20	<45	<50	<70	<75

Water Supply Conditions Prevailing on 6/1 Apply Through 12/31

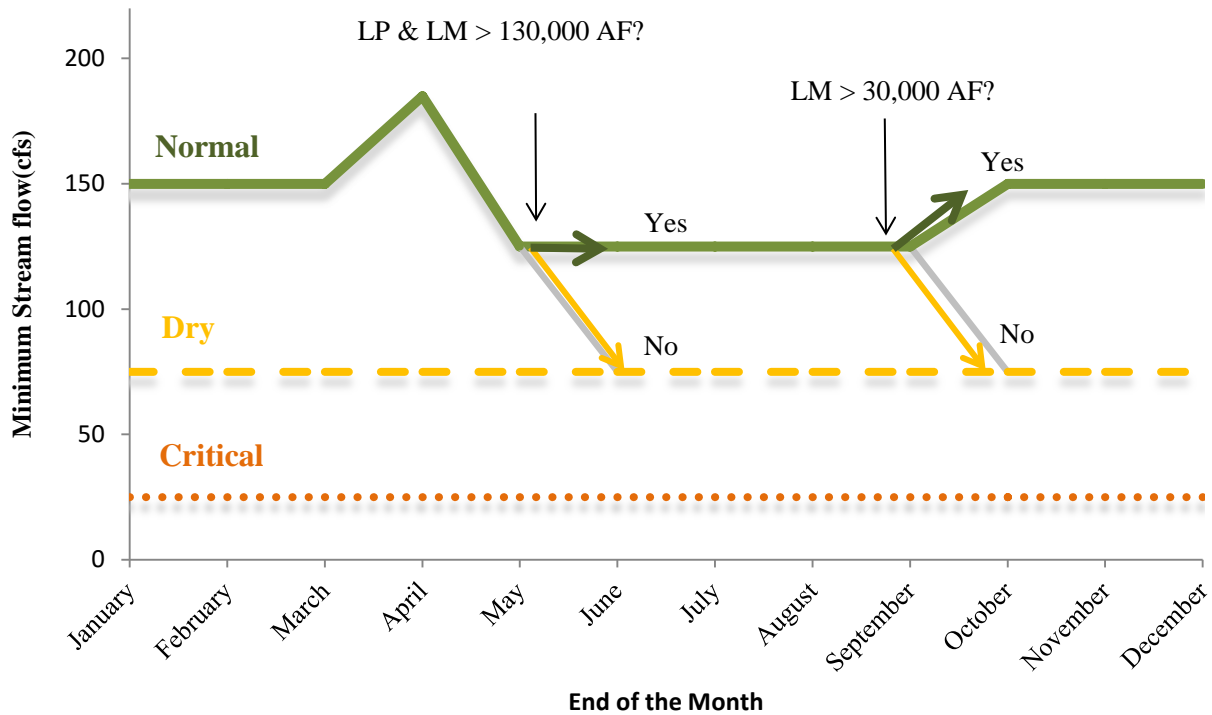
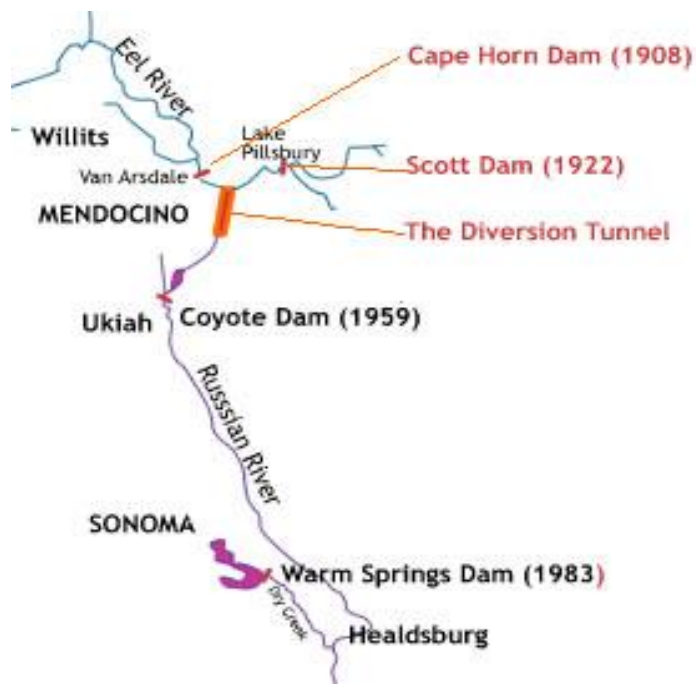


Figure 9 Minimum instream flows based on Decision 1610 and summer time modified Biological Opinion. At the end of May, the combined storage of Lake Pillsbury (LP, Eel River) and Lake Mendocino (LM) is evaluated (LP & LM > 130,000 acre-feet). In October, only Lake Mendocino (LM) storage is evaluated (LM > 30,000 acre-feet). Adapted from SCWA, Term 17 report, 2015.

### **3.3.2. Potter Valley Project**

From 1908, diversions from the Eel River through a tunnel to the East Fork began as part of the Potter Valley Project, owned and operated by PG&E since 1930 (see Figure 10). These diversions subsequently increased after Scott Dam and Lake Pillsbury were constructed on the Eel River (1922), allowing reliable agricultural production and urban development in Mendocino and Sonoma Counties (MCWA, 2010). PVP diversions from the Eel River changed streamflow at the East Fork and the upper sections of the Russian River into a perennial water course (MCWA, 2010). The combined effect of the reservoirs operation and the Eel River imported waters reduced winter flow peaks and substantially increased summer flows (MCWA, 2010). The significant reductions in PVP diversions since 2006 due to the FERC license amendment were accounted for in this study by an approximation of the post-2006 operations as the current PVP operation.

PVP diversions are the only inter-basin water transfer into the Russian River system. Even though it was planned as a hydropower project, their implications have gone far beyond this project. As described by Lund and Israel (1995), this water transfer has increased the system's flexibility, with special implication during drought periods. In terms of water supply, it has allowed the system to directly meet water demands, avoiding the higher cost of new supply developments, using storage to reduce the seasonal peak demand, and overall, improving the system reliability. Additionally, PVP diversions were the main source of water supply before the construction of Coyote Valley Dam, and afterward, they became an essential water source to fill the reservoir with snowmelt runoff from the Eel River during the spring and summer.



Lake Pillsbury (Scott Dam)



Cape Horn Dam



Figure 10 Schematic of the Potter Valley Project including its main components: Cape Horn Dam, Lake Pillsbury (Scott Dam), and the Diversion Tunnel into the Russian River (Friends of the Eel River, 2016). Pictures taken by the author.

## 4. Method

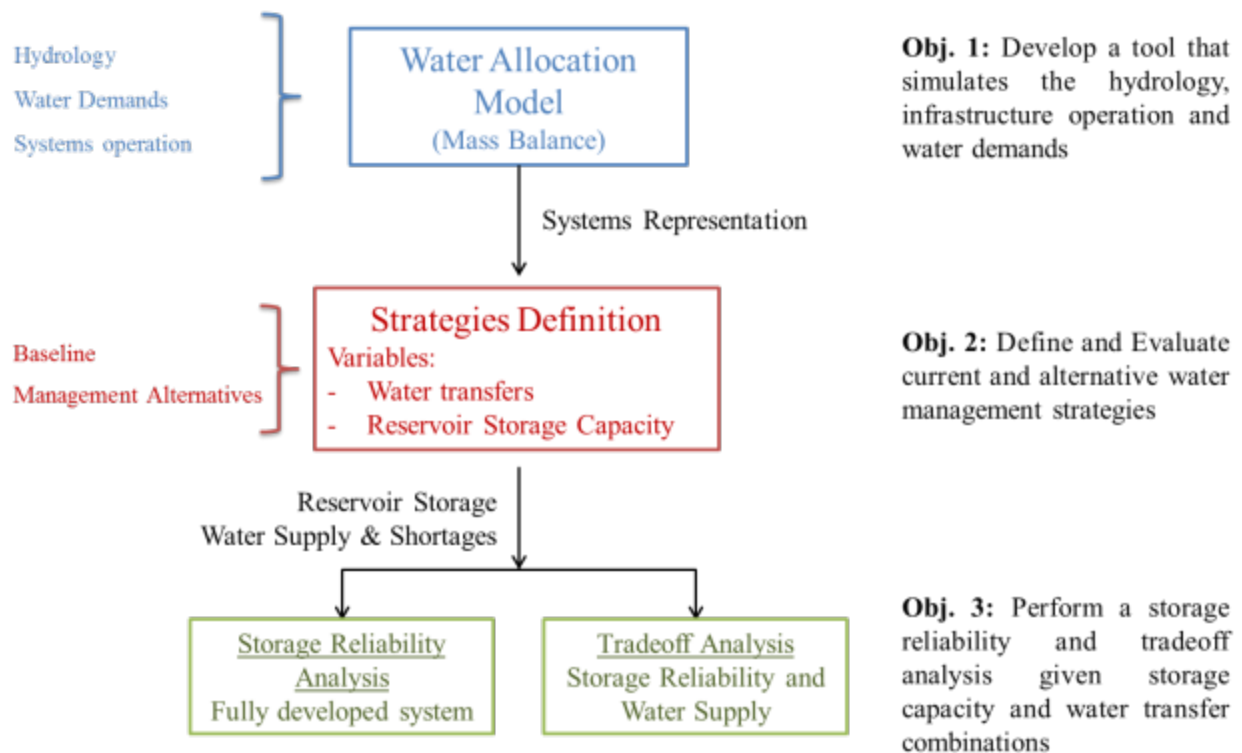
This section describes the methods used to evaluate the reservoir reliability using an integrated water resources approach. The method was implemented to meet each one defined objective (see Figure 11): first, a water allocation model was developed as a tool to simulate the hydrology, infrastructure and water demands along the Upper Russian River system. The three main inputs of this model were the hydrology of the basin, the water demands, and the systems operation, mainly related to the reservoir operation and environmental allocation. Hydrologic inflow data used for this model spans from 1911 to 2013. The model characterization and structure is explained in section 4.1.

Second, current and alternative water management strategies were defined along with the RRFC. The approach was to compare baseline conditions and management alternatives with respect to two main variables: water transfer into the Russian River basin, and the reservoir storage capacity. These two strategies represent the major concerns in terms of water supply and storage reliability in the long term. Although the model had implemented additional variables such as future water demands and climate conditions, the main drivers are related to the defined strategies. Additional information regarding both management strategies is explained in section 4.2.

Finally, based on the system representation and the defined strategies, the reservoir storage, and the water supplied results were analyzed using two different approaches: a storage reliability analysis was done for the fully developed system, and a tradeoff analysis was done for permutations of reservoir storage capacity and water transfer share. The former analysis considered the baseline conditions versus fully augmented storage capacity, and completely turned off water transfer. The latter analysis compared both strategies with a combination of

different storage capacities from baseline to fully augmented, and from current diversions to no transfer. Both the reservoir storage reliability and the water supply reliability were analyzed in this third phase. The performance criteria used to perform this analysis is presented in section 4.3 and the results are presented in section 5.

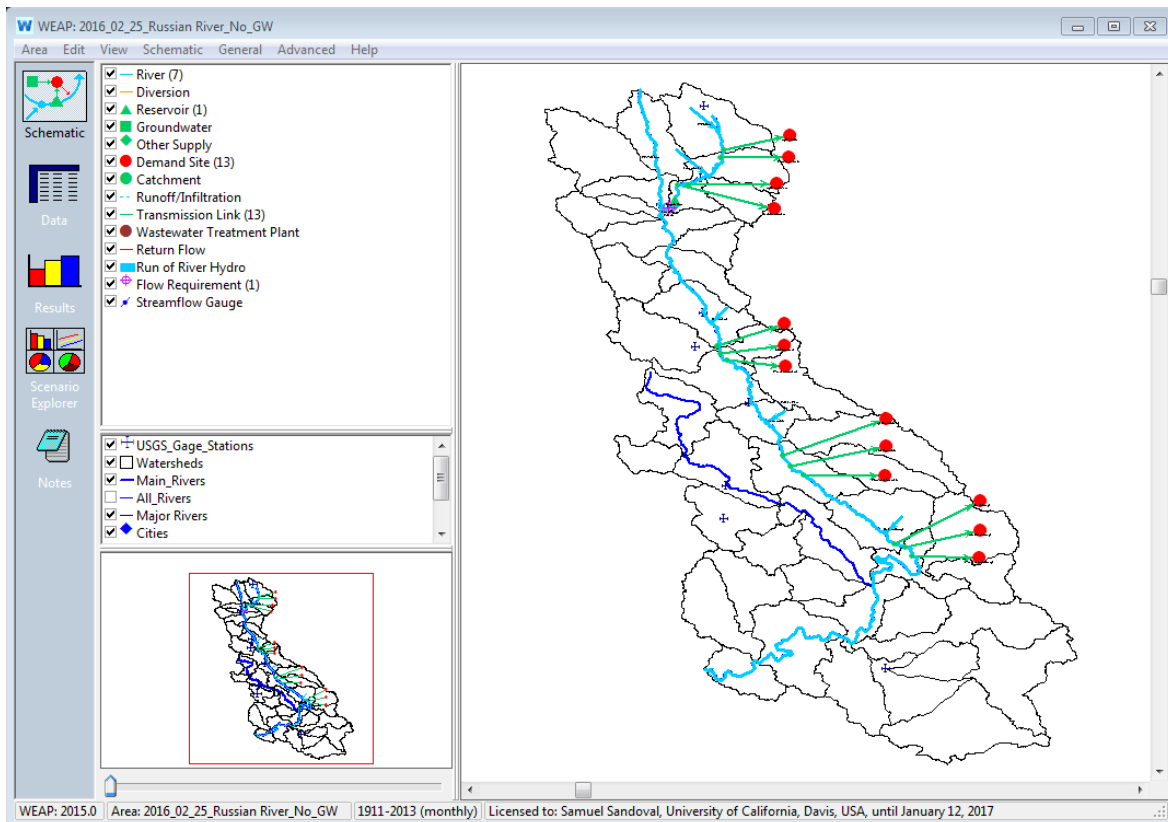
The following sections describe the model, the defined strategies and the performance criteria that was used to obtain the study results.



**Figure 11 Representation of the methodology along with the three specific objectives of this study**

## 4.1. Lake Mendocino Allocation Model

The water planning model used in this study (UCD-Model) was based on the SCWA Water Supply Model (SCWA-Model) that was developed to meet the SWRCB requirement of Term 17 and its mandate to evaluate the long-term reliability of the Upper Russian River system and Lake Mendocino to meet environmental and water supply demands. The UCD Water Allocation Model was implemented using the Water Evaluation and Planning (WEAP) platform, which allows integrating water availability with water management for a better understanding of the interactions and dependence between them.



**Figure 12 WEAP interface of the UCD Water Allocation Model of the Upper Russian River**

As presented in Figure 6, the Upper Russian River extends from the headwaters in Redwood Valley and Potter Valley to the junction of Dry Creek with the main stem, south of Healdsburg. Thus, as originally defined on the SCWA-Model, the model has seven control points: PVP, Calpella, Lake Mendocino, West Fork, Hopland, Cloverdale, and Healdsburg, five of which are named after the correspondent USGS streamflow-gaging stations. Incremental Flows were added at each reach and Water Demands were computed at five of them, the remaining two, PVP and the West Fork, were considered as headflows. The model estimates on a monthly time step the volume of water required to meet the environmental and minimum stream flows at each of the control points downstream of Lake Mendocino.

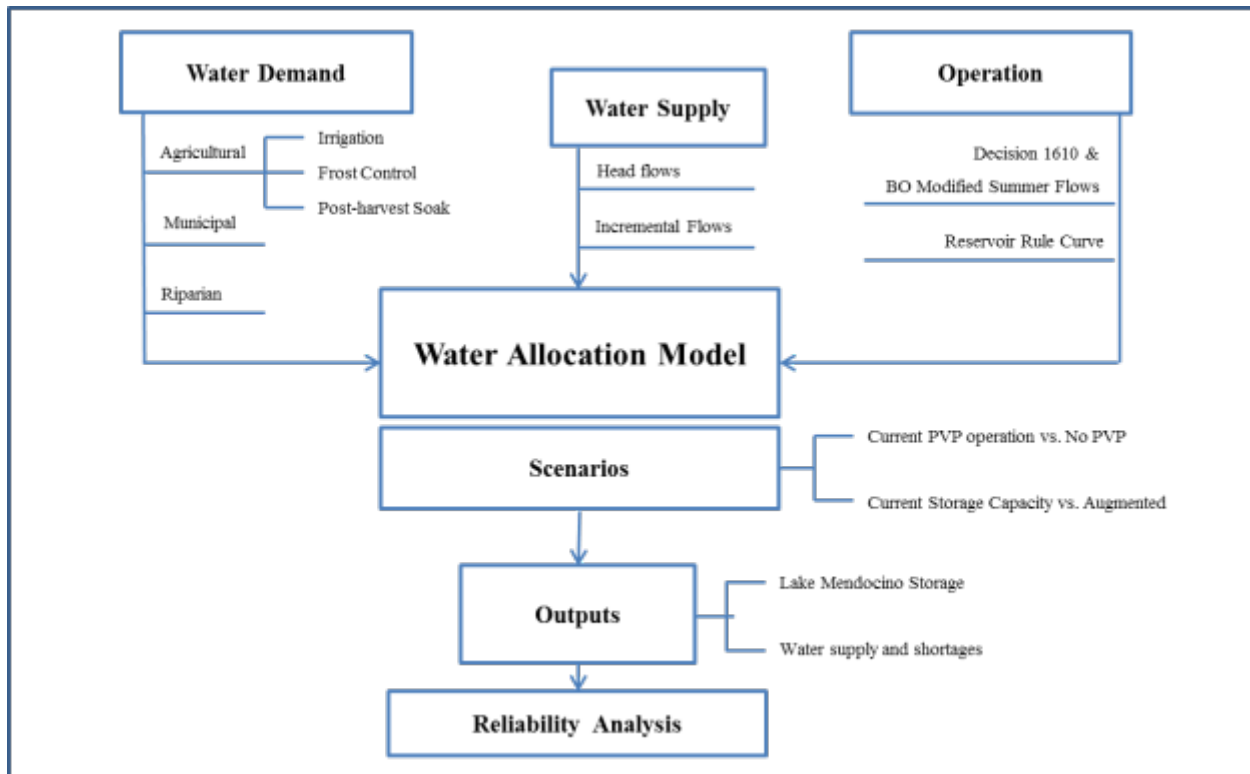


Figure 13 Schematic of the UCD Water Allocation Model for the Upper Russian River Basin



A schematic representation of the model appears in Figure 13. The three main inputs of the model are the water demands, water availability or water supply, and the operation of the system. Based on this information and the defined scenarios (explained in the following section), the outputs associated with Lake Mendocino storage and water supplied were analyzed in terms of the system's reliability.

#### **4.1.1. Water Demands**

The water demands considered in this model are: municipal and industrial, riparian, and agricultural water uses for every reach (see Figure 14). Municipal water use was estimated based on the current population and the water use of the existing nine public water systems. Surface water and groundwater pumping from the Russian River aquifer is the primary source of water supply for this system. The current conditions were established based on the 2009-2013 period and the water production records submitted to DWR in the annual Public Water system Statistics (PWSS). Annual water demands were estimated using the average over this five-year period, which was considered the current demand and water use projections were estimated based on either future water demands or population growth, depending on the size of the supply system.

On the other hand, riparian water losses were considered as a monthly scaling factor of the total agricultural water demands between May and October for every reach. Riparian water losses were based on a riparian vegetation delineation done using May 2013 USGS Landsat 8 imagery data (USGS, 2013) and ETa based on the SEBAL (Surface Energy Balance Algorithm

for Land)1 results from the Davids Engineering report. Monthly patterns were obtained for wet and dry years and replicated for the whole evaluation period.

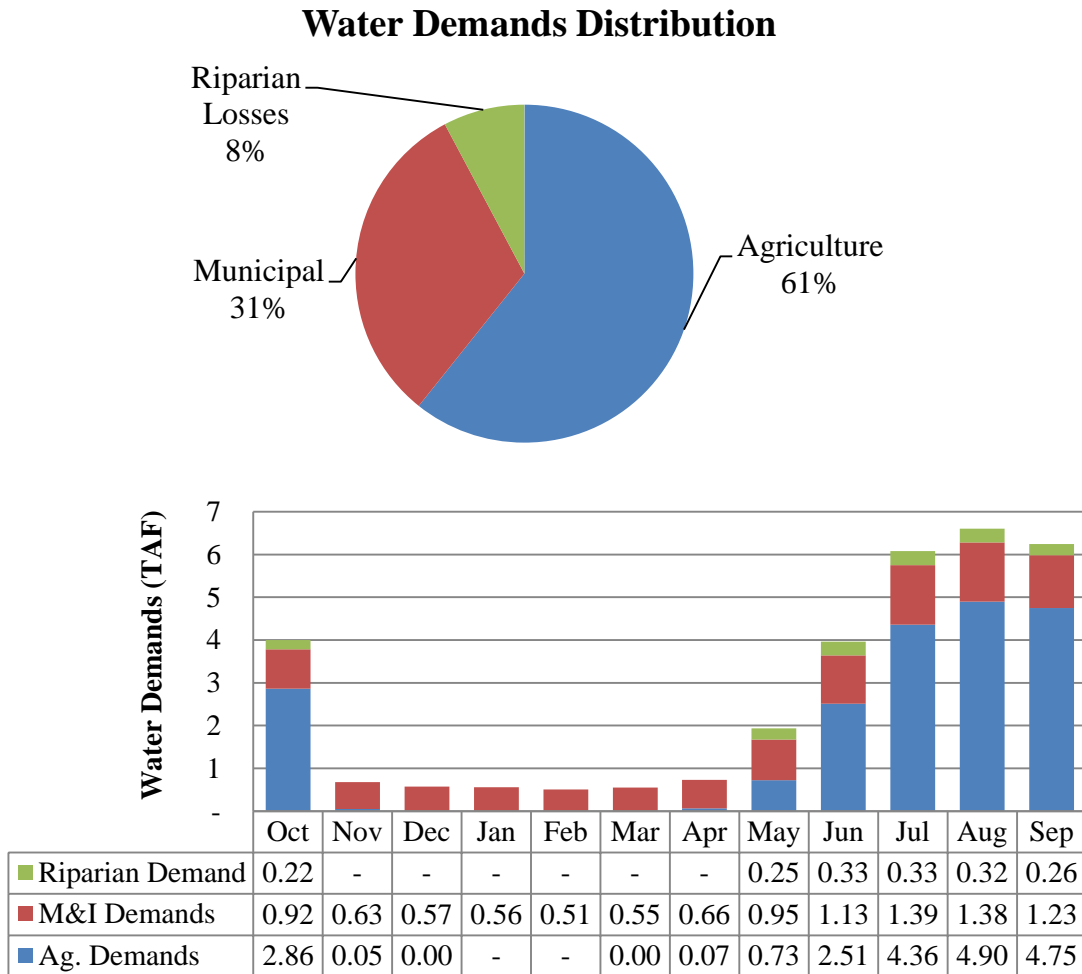


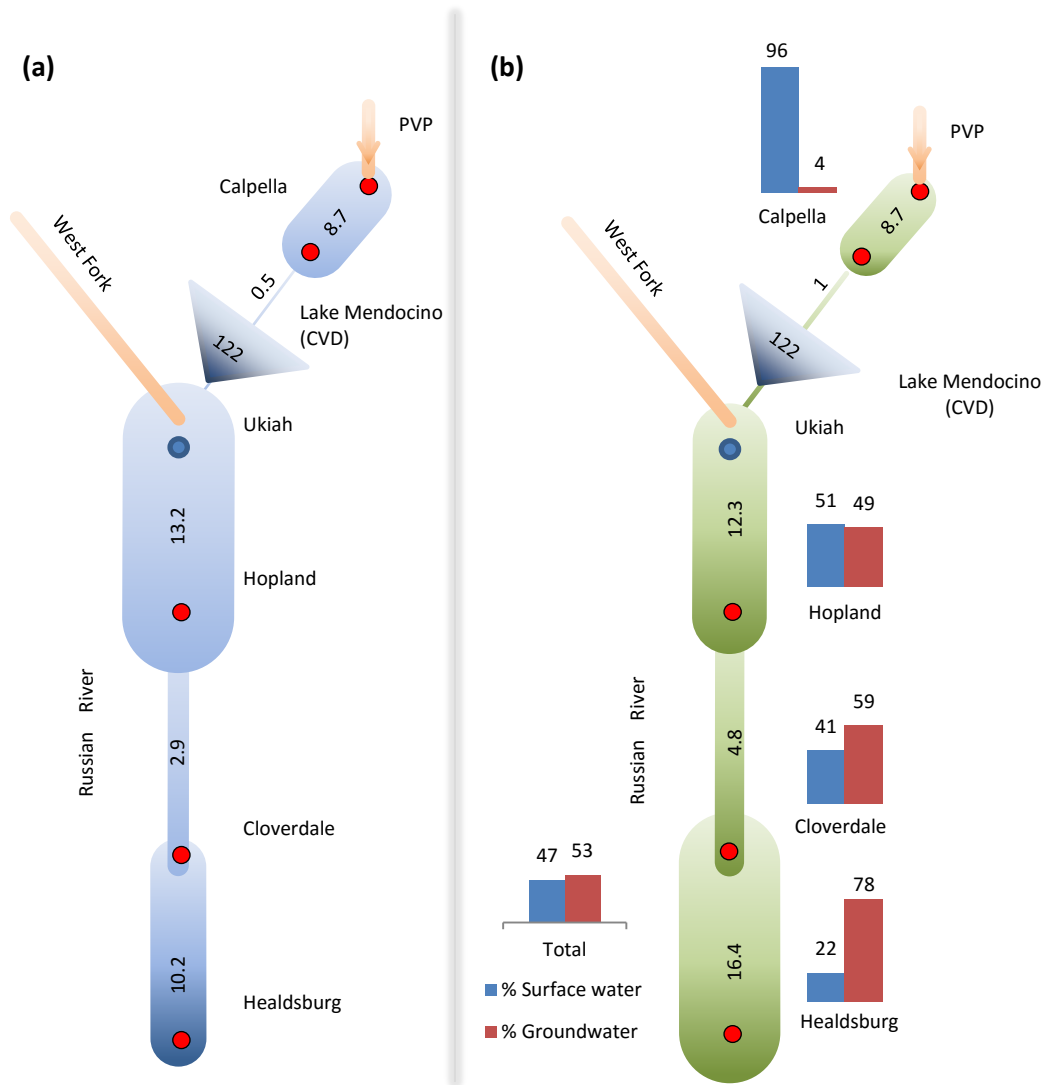
Figure 14 (a) Distribution of annual average water demands. (b) Annual variation of average water demands per type. (Adapted from SCWA, Term 17 report, 2015).

Agricultural water uses presented in Figure 14 and Figure 15 were developed based on land use and water use category: irrigation, frost protection, and post-harvest application. Water that was used for irrigation was estimated based on seasonal crop water duties, for each of the

<sup>1</sup> <http://davidsengineering.com/projects/remote-sensing/kaweah-delta-water-conservation-district-remote-sensin/>

main crops grown in this region. These crop water duties were based on an agricultural water model developed by Davids Engineering for the SCWA (SCWA, 2013). Monthly irrigation requirements based on evapotranspiration (ET) were aggregated on an annual basis to obtain the annual water demand. Due to frost control protection during the spring after bud break, water is often used in the Upper Russia River to protect vineyards and orchards. Although storage ponds have reduced the instantaneous flow diverted from the river or pumped from groundwater, the use of overhead sprinklers requires high applications over extended periods of time (hours) which reduces the monthly streamflow. The overall volume of water diverted monthly for this purpose was estimated based on the number of frost events and the net water use, also considering an estimation of the acreage that is frost protected. Post-harvest applications were based on the UC Cooperative Extension – Ukiah (UCCE –Ukiah) report for the Mendocino county, and an estimation of 50 percent over vineyards on Sonoma County (SCWA, 2015). Projections of agricultural water use were based on land use changes, where all new developed fields were assumed to be vineyards, which is the dominant crop in the watershed. In Mendocino County, the growth approach was site specific due to their confined area. The Sonoma County historical trends were used for growth projections, where the average rate was assumed to be the increase in vineyard acreage to 2045. The differences between Low and High water demand relied on the vineyard acreage since water use in vineyards is lower than in other crops. Figure 15a shows the average surface water demands (on the left) for every reach considering only diversions from the Russian River. Figure 15b shows average agricultural demands as an example to represent the variations between reaches, including both surface and groundwater sources. Therefore, as an example, total surface demands in Ukiah-Hopland reach are 13.2 thousand acre-feet, but agricultural demands are 12.3 thousand acre-feet from which only 51

percent correspond to river diversions. The remaining 6.9 thousand acre-feet (13.2 minus 51 percent of 12.3) corresponds to urban and riparian demands.



**Figure 15 (a) Average surface water demands (thousand acre-feet / year) for the Upper Russian River system. West Fork and PVP are not included. (b) Average total agricultural water demands (thousand acre-feet / year) including surface and groundwater sources for the Upper Russian River system and their surface-groundwater share (percentage) per reach. West Fork and PVP are not included (Adapted from SCWA, Term 17 report, 2015).**

#### 4.1.2. Water Supply

**Table 2 Average water availability for the Upper Russian River system (thousand acre-feet)**

<b>River Reach</b>	<b>Oct</b>	<b>Nov</b>	<b>Dec</b>	<b>Jan</b>	<b>Feb</b>	<b>Mar</b>	<b>Apr</b>	<b>May</b>	<b>Jun</b>	<b>Jul</b>	<b>Aug</b>	<b>Sep</b>	<b>Total</b>
Diversion from PVP	6.25	5.49	6.45	7.51	7.21	4.04	4.01	6.59	7.23	7.47	7.61	6.98	<b>76.83</b>
Calpella	0.45	4.26	15.85	22.90	21.13	13.93	5.94	1.78	0.52	0.14	0.04	0.06	<b>87.00</b>
Lake Mendocino	0.26	0.41	1.52	2.78	2.71	1.98	0.98	0.50	0.39	0.34	0.30	0.25	<b>12.41</b>
<b>Total East Fork</b>	<b>6.95</b>	<b>10.16</b>	<b>23.81</b>	<b>33.19</b>	<b>31.05</b>	<b>19.95</b>	<b>10.93</b>	<b>8.87</b>	<b>8.14</b>	<b>7.95</b>	<b>7.95</b>	<b>7.28</b>	<b>176.24</b>
West Fork	0.48	5.84	22.61	32.85	29.91	19.45	8.29	2.37	0.69	0.18	0.06	0.06	<b>122.77</b>
<b>Total at The Forks</b>	<b>7.43</b>	<b>15.99</b>	<b>46.42</b>	<b>66.04</b>	<b>60.95</b>	<b>39.41</b>	<b>19.22</b>	<b>11.24</b>	<b>8.82</b>	<b>8.13</b>	<b>8.01</b>	<b>7.34</b>	<b>299.01</b>
Hopland	0.61	6.17	25.73	39.63	37.58	24.98	11.17	2.90	0.81	0.21	0.07	0.08	<b>149.94</b>
Cloverdale	0.76	7.62	29.14	42.51	40.74	27.40	11.85	2.99	0.81	0.21	0.07	0.10	<b>164.21</b>
Healdsburg	1.38	14.74	55.18	89.95	86.25	54.48	24.70	5.94	1.59	0.41	0.13	0.19	<b>334.93</b>
<b>Total Upper Russian River</b>	<b>10.18</b>	<b>44.52</b>	<b>156.47</b>	<b>238.13</b>	<b>225.52</b>	<b>146.27</b>	<b>66.95</b>	<b>23.07</b>	<b>12.03</b>	<b>8.97</b>	<b>8.28</b>	<b>7.70</b>	<b>948.08</b>

Presented on Table 2 are the unimpaired flows that were used to account of the natural input of the system, “unaffected by man-made influences such as water diversions or reservoir operation” (SCWA, 2015). These datasets were developed for historical climate (1910 to 2013) and potential climate change impact (2000 to 2099) by the USGS (Flint et al., 2015). PVP diversions from the Eel River were estimated using the Eel River model version 2.5 developed by the Natural Resources Consulting Engineers (Oakland, CA) and SCWA. The significant reductions in PVP diversions since 2006 due to FERC license amendment were accounted in the model by an approximation of the post-2006 operations as the current PVP operation.

### **4.1.3. Operation**

The operation of Coyote Valley Dam was modeled based on the Rule Curve developed by the USACE. It also considers environmental constraints defined by Decision 1610 and the Russian River Biological Opinion (Figure 9). The model assumes that storage may not be higher than the Rule Curve, and so sufficient water will be released from storage above it to maintain storage at the top of conservation pool. Additionally, to maintain minimum instream flow requirements, releases were made to either meet this constraint (compliance release) or the downstream demands. Minimum instream flow requirements were based on the hydrologic Water Supply Condition index defined under Decision 1610 which sets the monthly minimum instream flow for the Russian River between January and May, and the Dry Spring condition index based on Lake Mendocino and Lake Pillsbury storage combined, which applies from June to December. Flows defined by Decision 1610 constraint minimum flow between November and April and the interim flow requirements of the Biological Opinion constrain flows between May and October. Therefore, based on the Water Supply Conditions (WSC) and the Dry Spring condition index combined along the year, the criteria described on Figure 16 must always be met to comply with the Biological Opinion flows for the upper Russian River system.

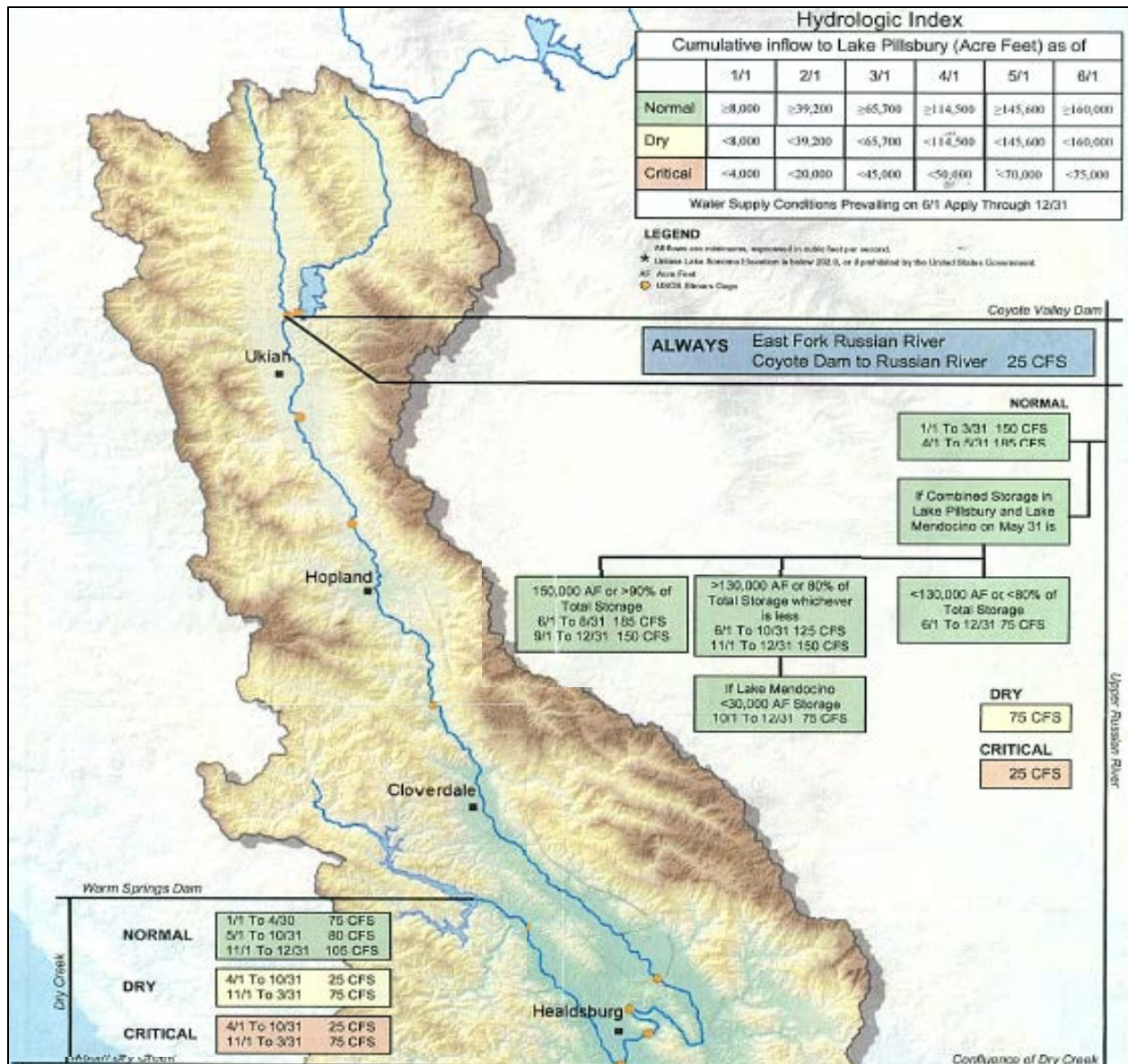


Figure 16 Biological Opinion flows and Hydrologic Index for the upper Russian River system (USACE & SCWA, 2000)

#### **4.1.4. Mass Balance**

After all this information is organized in the model, a mass balance is performed for each reach and at each time step based on the available water and the corresponding demand, which will result in a net gain or loss for each reach. Additionally, the model will compare the net reach gain with the minimum flow requirement. If it is greater, it will assign a compliance release as zero. Otherwise, the required release from the reservoir is obtained to meet the environmental allocation. After all compliance releases are calculated and compared with the available water in the reservoir, a release decision is made based on the critical reach. As mentioned before, if the difference between the available water (previous time step storage plus inflows into the reservoir) exceeds the Rule Curve threshold for that given month, the reservoir first release will be that difference. If it is less than the calculated compliance release, it will add the additional requirement. Otherwise, the storage will be kept at the Rule Curve volume.

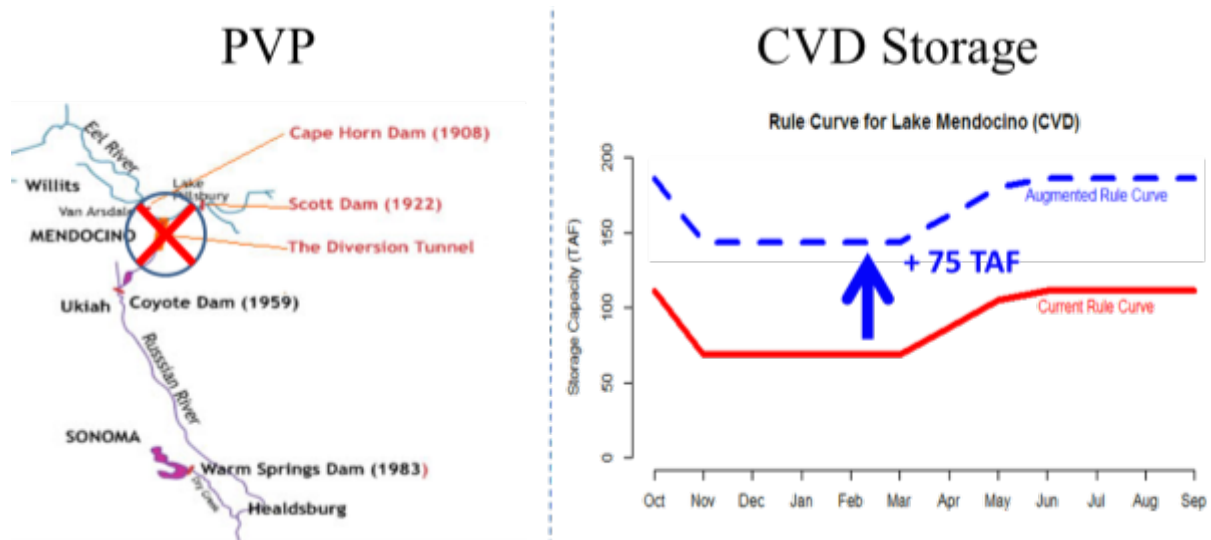
## **4.2. Current and Alternative Water Management Strategies**

The water management strategies were defined in agreement with the RRFC. The objective was to represent their main concerns regarding the reliability of the reservoir storage and the diversions from the Eel River. Therefore, the analysis focused on raising Coyote Valley Dam which will increase Lake Mendocino storage, and on PVP operations and potential future reductions in the diverted flows (see Figure 17).

First, storage in Lake Mendocino was addressed based on the original project whose second phase was never completed. The reservoir was designed to be raised 36 additional feet from the current 160 feet earth embankment dam height, which would have increased the storage



capacity by approximately 75,000 acre-feet. Today, there is an ongoing evaluation led by the USACE concerning Coyote Valley Dam storage augmentation. It is part of the Corps SMART<sup>2</sup> Planning 3x3x3 policy that assesses the raising feasibility under the current dam safety standards (began in December 2014). This scenario was implemented in the model using the Current Rule Curve and the potential additional storage. To maintain current environmental allocation thresholds and flood management pool, it was assumed that the augmented storage conditions will have an Augmented Rule Curve that would be 75 thousand acre-feet above the current thresholds. Dry Spring condition index which considers Lake Mendocino storage as an input was also shifted by the same amount.



**Figure 17 Water management strategies implemented in the model**

On the other hand, PVP diversions have been reduced significantly since the implementation (2006) of a Biological Opinion issued by the National Marine Fisheries Service

<sup>2</sup> SMART: Specific, Measurable, Attainable, Risk-informed and Timely.

(NMFS) in 2002(National Marine Fisheries Service, 2002)<sup>3</sup>. As a response, SCWA has filed five Temporary Urgency Change Petition (TUCP) (SWRCB, 2013) with the SWRCB requesting temporary reductions on the minimum instream flows of the Russian River to “preserve adequate water supply storage in Lake Mendocino” (SCWA, 2015). The May 1, 2013’s order issued by the SWRCB after the third TUCP requested a water supply reliability study for Lake Mendocino and was included as Term 17 in the Order. As it was mentioned before, under Term 17 it was required to evaluate the long-term reliability of the system to meet environmental and water demands, considering potential impacts of climate change, land use and water demands projections (SWRCB, 2013). PVP diversions were also included in the Term 17 study, to evaluate the impact that no-flow from PVP would have on the Upper Russian River system. Therefore, a fully turned-off diversion was implemented in the model.

Finally, the strategies that were implemented in the model and analyzed in detail are:

- (1) Baseline Conditions: Current PVP operations and current reservoir storage capacity.
- (2) PVP On – Augmented Capacity: Current PVP operations and fully augmented reservoir storage capacity.
- (3) PVP Off – Current Capacity: No inflow from PVP and current reservoir storage capacity.
- (4) PVP Off – Augmented Capacity: No inflow from PVP and fully augmented storage capacity.

---

<sup>3</sup> After the Biological opinion was issued in 2002, in 2004 the federal Energy Regulatory Commission (FERC) amended the PVP license No.77, which was finally implemented in 2006 ("FERC Order Amending License, 106 FERC ¶ 61,065," 2004)

### 4.3. Reliability Analysis: Performance Criteria

Two approaches were used to perform the reliability analysis. First, the storage reliability of the reservoir was addressed from three different perspectives, which considered the baseline conditions versus fully augmented storage capacity and completely turned off water transfer (PVP).

- Reservoir Storage Reliability: comparison of the reservoir storage reliability for the different scenarios, both annually and monthly. The annual storage reliability is defined as the annually occurrence-based reliability or the number of years over the whole model-time domain that the reservoir went dry at least one month in a determined year. The monthly storage reliability represents the time-based reliability or number of months that the reservoir went dry over the total number of months. As it is shown in section 5, the results are presented for the Current Storage versus the Augmented Storage Capacity and for both Current and No PVP operations.
- Rule Curve analysis during the refill season:
  - Comparison of the reservoir storage under the different scenarios with the respective Current and Augmented Rule Curve during the reservoir refill season that goes between January and June. This comparison was done to assess the percentage of time that the reservoir storage would be at the top of conservation during the late wet season and beginning of the spring, where the Rule Curve is at the lowest for the Conservation Pool or at the rising limb.
  - Comparison of the augmented reservoir storage with the current Rule Curve during the refill season (between January and June). This comparison was done to assess the percentage of time when the storage under the augmented capacity

scenario was at the current Rule Curve or above it. It represents the number of times that under the same hydrologic conditions, the augmented reservoir scenario would store additional water instead of releasing it when reaching the Rule Curve.

- Monthly Storage Distribution: comparison of the monthly storage distribution of the reservoir under current and the augmented capacity conditions including the average monthly values and the respective Rule Curve for both PVP scenarios.

Additionally, a tradeoff analysis was done to compare the reservoir storage reliability and water supply reliability for combinations of reservoir storage capacity and water transfer share. Under this analysis, the annual storage occurrence-based reliability was used as the performance criteria to compare both strategies. Similarly, with respect to water supply, annual average shortages upstream and downstream of the reservoir were used to compare the defined strategies. The deficit or water supply shortage is defined as the difference between the demand requirements and the supplied water averaged only over the shortage periods. It is only calculated for the defined demands, not for the reservoir compliance releases.

## 5. Results: Model performance under alternative policies

### 5.1. Storage Reliability Analysis

#### 5.1.1. Reservoir Storage Reliability

The occurrence based annual and the time based monthly reliability is presented in Table 3 (A) for current and augmented capacity conditions, PVP On and PVP Off water transfers. If PVP is maintained as current conditions, the system is fully reliable for both the current and the augmented storage capacity. On the other hand, under PVP Off, the reservoir would go dry 48 percent of the time at least one month during the year in contrast to 17 percent under the augmented capacity conditions.

**Table 3 Reliability results for both Storage conditions and PVP scenarios**

		(A) Reservoir Storage Reliability (Empty Reservoir)				(B) At the Top of Conservation during Refill Season		(C) Above Current Rule Curve during Refill Season
		Occurrence based Annual Reliability		Time based Monthly Reliability				
Storage Conditions		Current	Augmented	Current	Augmented	Current	Augmented	Augmented
Water transfers	PVP On	0%	0%	0%	0%	47%	45%	100%
	PVP Off	48%	17%	11%	4%	20%	13%	65%

Similarly, the time based monthly reliability is 100 percent for both current and augmented capacity conditions if PVP diversions are maintained, whereas under PVP Off the reservoir would go dry 11 percent and 4 percent of the months for current and augmented capacity conditions, respectively. The difference between the annual and monthly reliability is explained by lack of PVP flows, the reservoir goes dry almost the same month every year

(September) and it usually gets refilled the following month, with the beginning of the wet season. A deficit in a single month can be catastrophic for the agriculture of this region because the crop that is grown (wine grapes) are very sensitive to irrigation.

### **5.1.2. Rule Curve analysis during Refill Season**

#### **Observed storage compared with the respective Rule Curve between January and June**

Shown in Table 3 (B) are the results for the percentage of time that the storage level was at the Rule Curve (according to USACE rules, it cannot go above). For PVP On, reservoir storage was at the Top of Conservation almost the same number of months for both current and the augmented capacity. As can be observed for both cases, between 45 and 47 percent of the time the storage was at the maximum possible level for the given month (Rule Curve). The difference between these scenarios is only explained by a bigger reservoir area which increases evaporation.

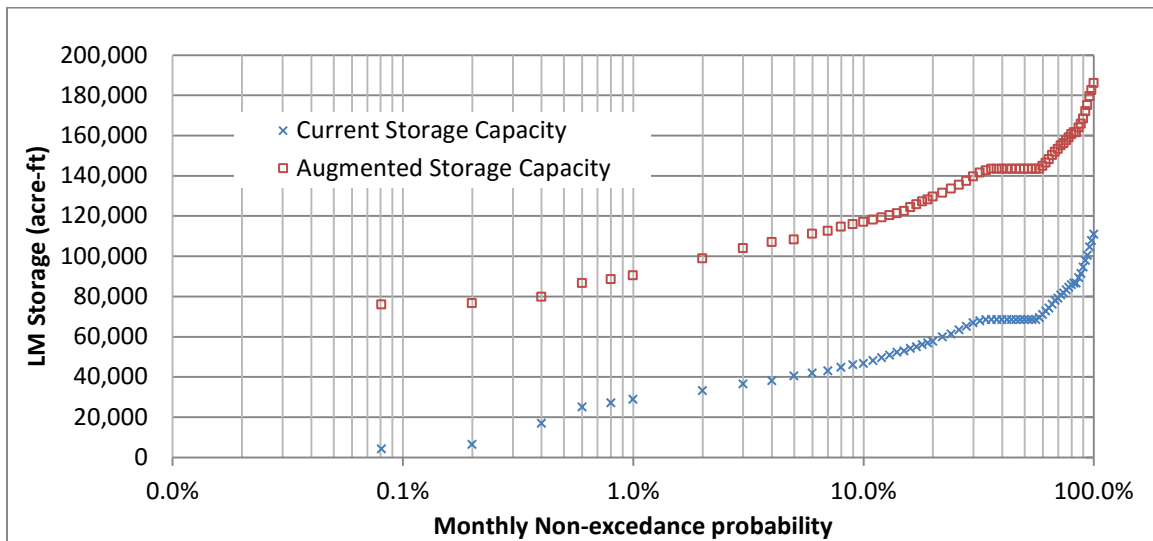
On the other hand, the results for PVP Off showed that 20 percent of the time under the current storage capacity the reservoir was at the top of conservation pool. At the same time, under the augmented storage capacity conditions only 13 percent of the time the storage capacity was at the top of conservation pool. Thus, without PVP inflows the reservoir will not fill as often as it did in the previous case.

#### **Observed storage compared with the current Rule Curve between January and June**

Shown in Table 3 (C) are the results for the observed storage compared with the current Rule Curve for the period between January and June. For the current storage capacity conditions, the results under the scenario with PVP On are the same to the ones presented in Table 3 (B). However, when the storage of the augmented capacity scenario is compared with the current Rule Curve, 100 percent of the time the reservoir storage was above this level. Likewise, for the

case without PVP flows the results had a similar outcome. The observed storage under the augmented capacity was 65 percent of the time above the current top of conservation level.

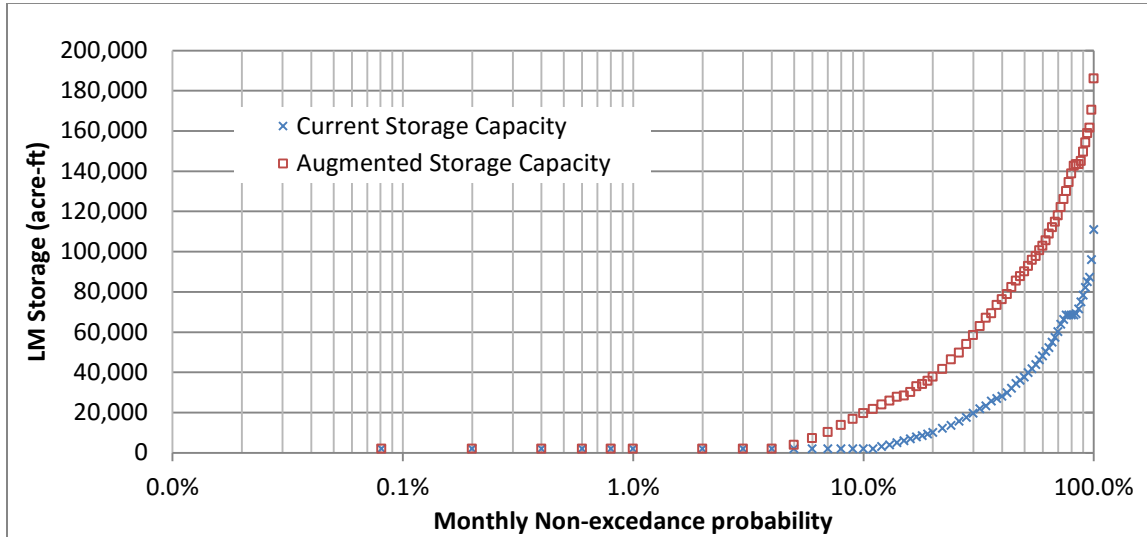
These results are supported by a non-exceedance probability analysis for each scenario, which shows a similar trend between the current and the augmented storage capacity conditions for current PVP diversions. Figure 18 shows that the lower end of both curves followed the same trend, but with a slight difference on the lowest value. The current storage capacity curve almost reached the minimum storage capacity of 2,000 acre-ft, whereas the augmented storage condition had still more than 70,000 acre-ft stored. The greatest difference between these two conditions was observed during the end of the 1976-1977 water year drought were under the current storage capacity the reservoir went almost dry whereas under the augmented capacity scenario, the reservoir had enough water to meet the downstream demands.



**Figure 18 Non-exceedance probability for PVP On comparing the current storage capacity and the augmented storage capacity**

Without PVP flows, the results in Figure 19 showed a greater probability that reservoir storage will be empty or below the top of conservation. Correspondingly, the current storage

capacity scenario results in a less reliable system (11 percent of the months is empty) and an overall lower stored volume, where approximately 50 percent of the time the volume is below 34,000 acre-ft which is near the lower storage historically measured in Lake Mendocino. In comparison, for the same non-exceedance probability under the augmented capacity conditions, the volume stored is 94,000 acre-ft.



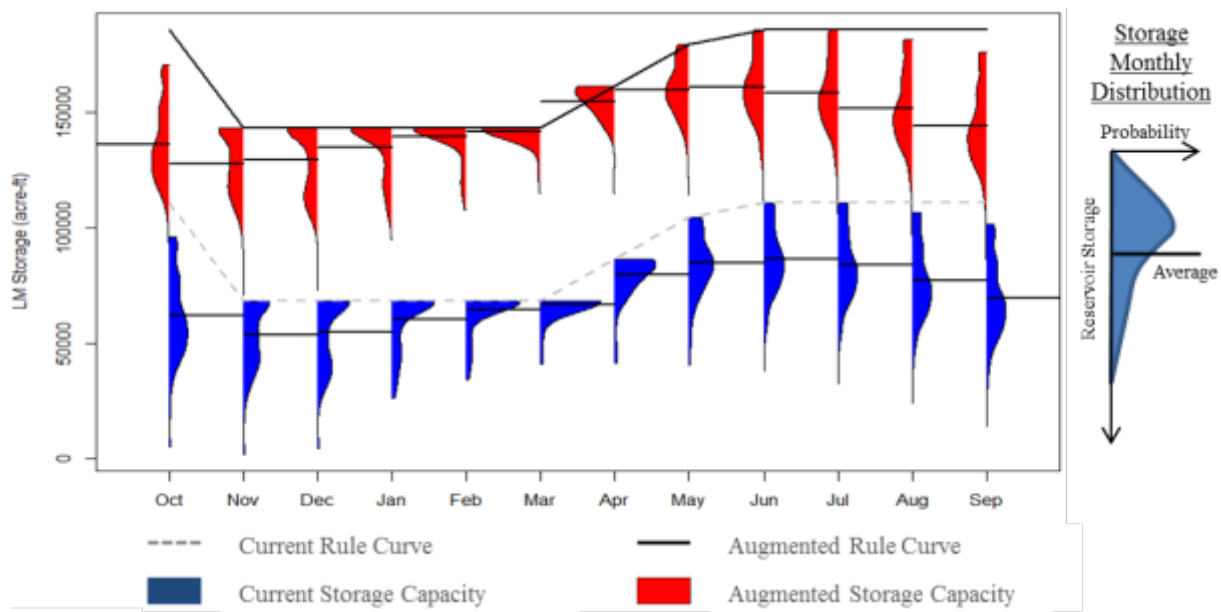
**Figure 19 Non-exceedance probability for PVP Off comparing the current storage capacity with the augmented storage capacity**

### 5.1.3. Monthly Storage Distribution

Finally, Figure 20 and Figure 21 compare the monthly distribution for each storage capacity scenario under both diversion conditions, complementing the previous analysis. These bean plots show the probability mass function (PMF), displayed vertically, of CVD reservoir storage for the current and augmented storage capacity in blue and red respectively. The horizontal line on each vertical distribution represents the average for the given month and the given storage conditions, and the thicker the mass (plot), the higher probability to observe that



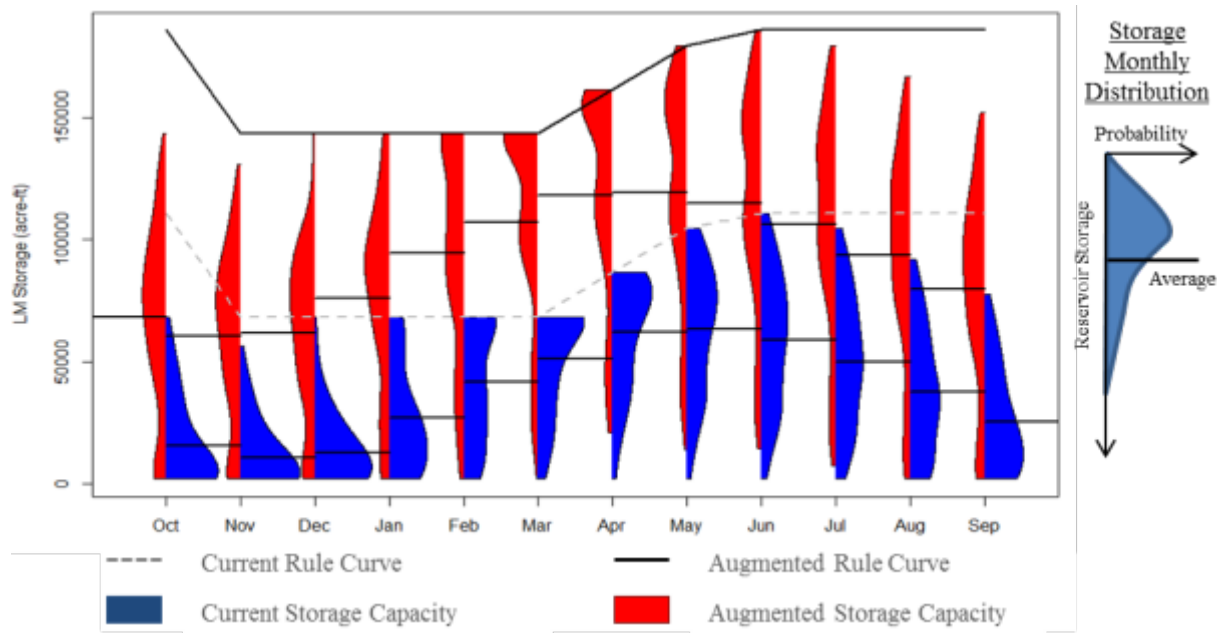
storage that given month. Figure 20 shows a similar trend between both storage conditions, where the monthly distributions, monthly average, and seasonal shape is almost the same but shifted upward by nearly 75 thousand acre-feet. It can also be noticed the dryer months (October, November, and December) where the reservoir is at risk of going dry for the current storage capacity conditions whereas, for the augmented storage conditions, the reservoir storage does not reach the 70 thousand acre-feet threshold. Similarly, the average storage for the end of the winter and beginning of spring season was close to the top of conservation threshold, which explains the results presented in Table 3 for the percentage of time that the reservoir was at the rule curve during the refill season.



**Figure 20 Monthly distribution of reservoir storage for both the current storage capacity and the augmented storage capacity under the Baseline Scenario with PVP On**

On the other hand, for the PVP Off case the results vary depending on months (see Figure 21). For the period February to June, the monthly distribution is similar for both the current and the augmented capacity scenarios, although the latter has a greater dispersion due to the higher

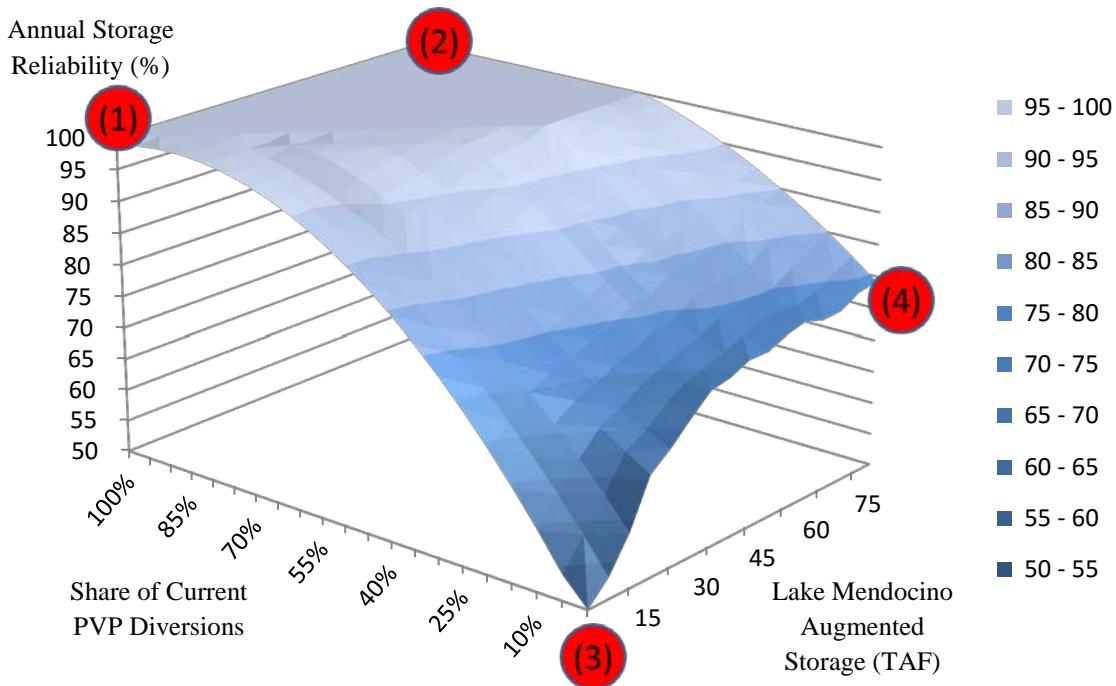
capacity of the reservoir. On the contrary, the monthly distribution between July and January for the current capacity case is substantially skewed to the minimum capacity of the reservoir and is intensified between October and December. The period between September and January accounts for almost 90 percent of the months that the reservoir was empty. During the same period (September to January), the monthly distribution for the augmented capacity scenario has a more disperse range with an average that is high above the minimum level. Finally, it can be observed the influence of PVP over the monthly average storage (horizontal black lines) that was kept closer to the top of conservation during winter and spring, and always above the current Rule Curve. However, with PVP Off the average storage decreases considerably, although a substantial amount of time the storage is above the current top of conservation (65 percent of the months, see Table 3).



**Figure 21 Monthly distribution of reservoir storage for both the current storage capacity and the augmented storage capacity under the Baseline Scenario with PVP Off**

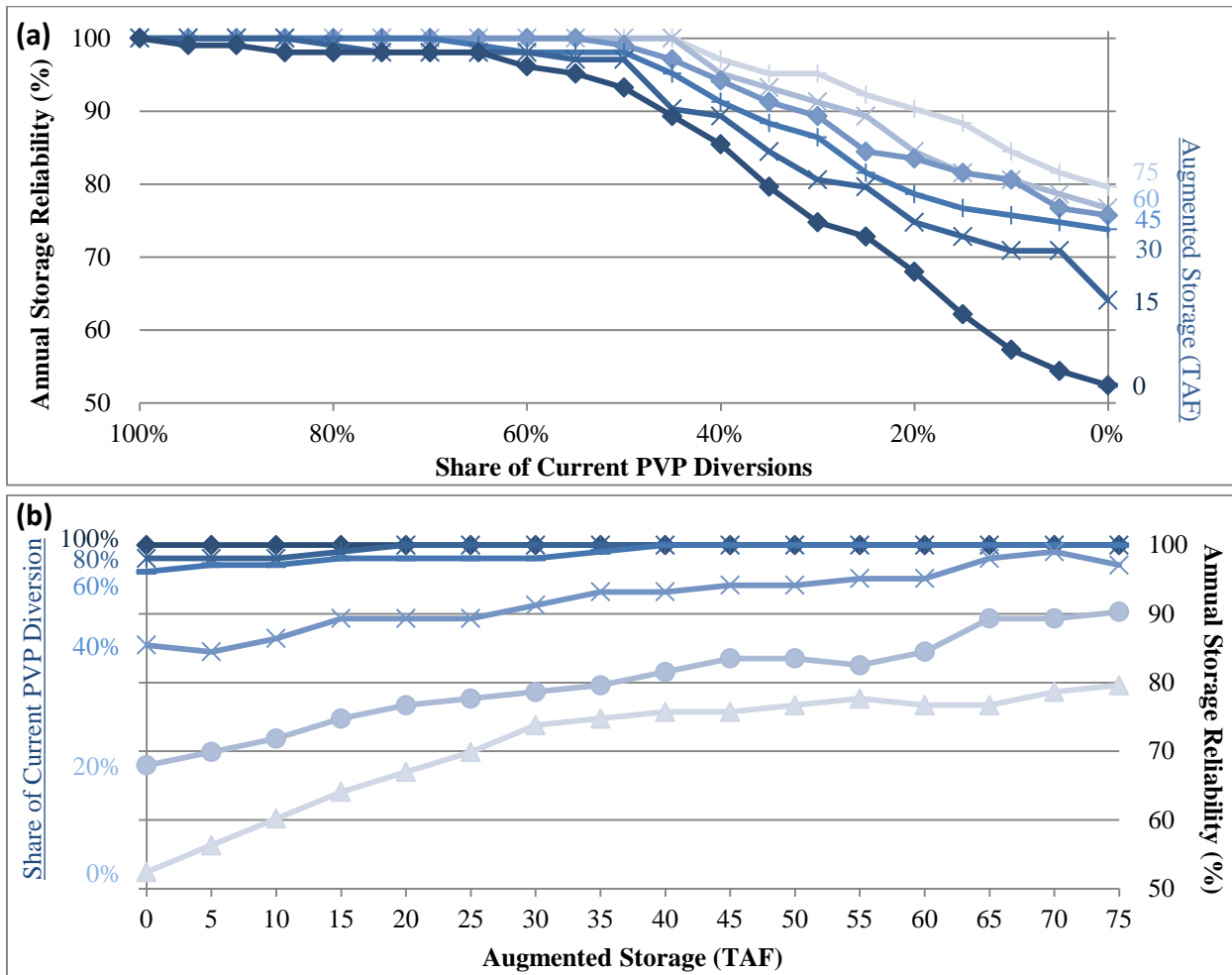
## 5.2. Tradeoff analysis

The reservoir storage reliability and water supply reliability were analyzed for the two alternatives: raising Coyote Valley Dam and changing PVP inflows. The annual storage occurrence-based reliability was used as the performance criteria to compare both strategies. Results for this analysis are presented in Figure 22 as a reliability surface for combinations of augmented storage capacity and share of current PVP diversions. A plateau can be observed on the upper center portion of the surface for several permutations of storage and PVP diversions that will result in a fully reliable system (from (1) to (2)). On the other hand, when current PVP diversions are at zero percent and augmented storage is also zero (3), the lowest values for the occurrence based annual reliability are observed reaching 50 percent (center bottom portion of the surface).



**Figure 22 Tradeoff analysis given storage capacity and PVP diversions combinations. Performance measured using the occurrence based annual storage reliability.**

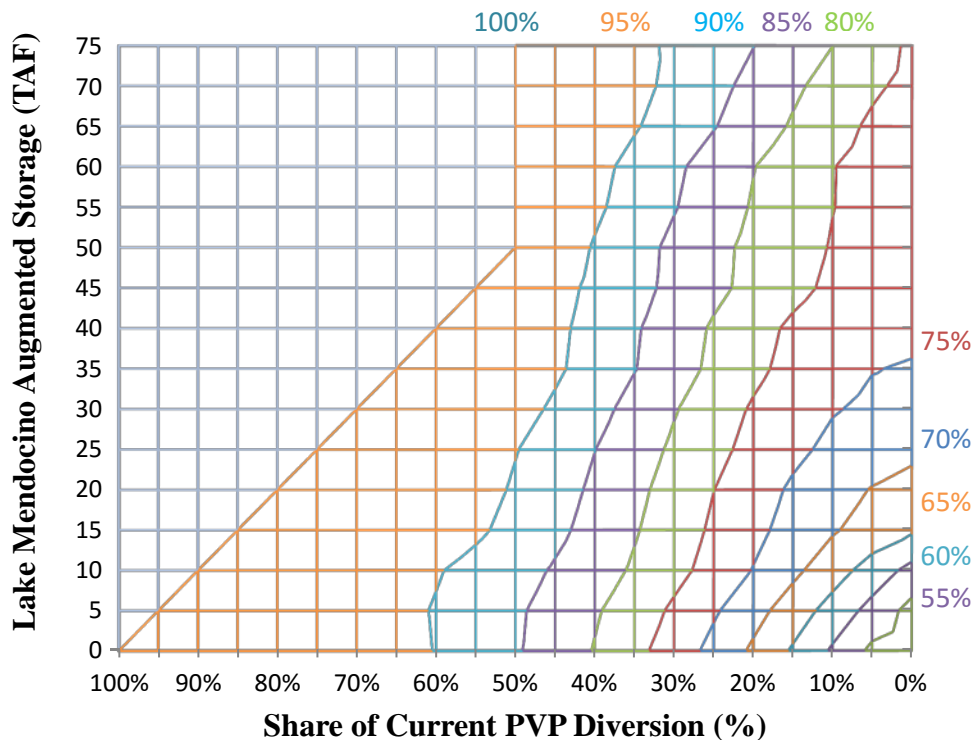
The same results are presented in Figure 23a for increments in 15 thousand acre-feet of additional storage, and Figure 23b for reductions in PVP diversions in 20 percent intervals. The reliability of the system varies from 52 percent without PVP flows and current reservoir capacity, up to 83 percent when the reservoir is raised the maximum height.



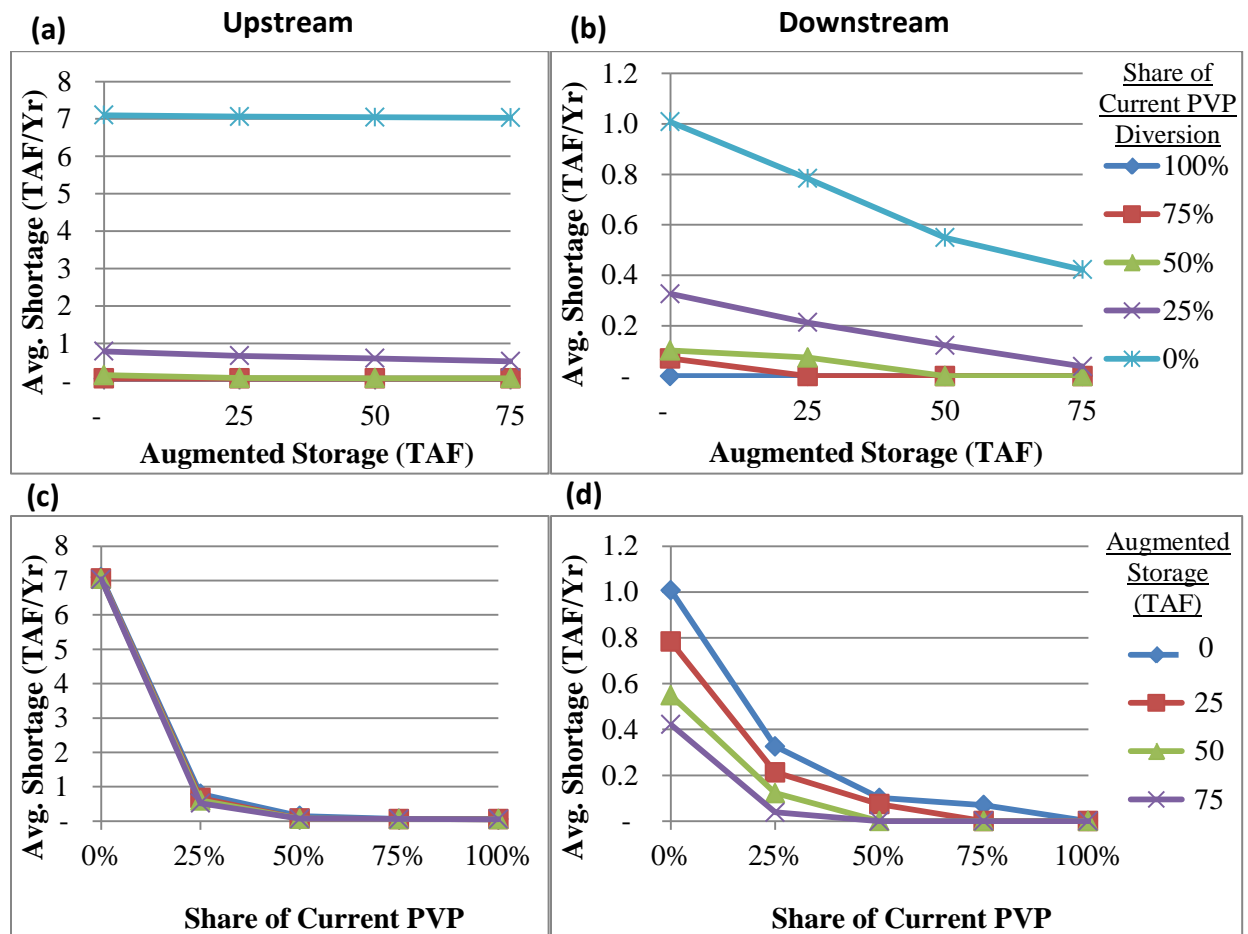
**Figure 23 Reservoir storage occurrence annual-based reliability for (a) augmented capacity on 10 TAF increments; (b) for reductions in current PVP diversions in 10 percent intervals**

On the other hand, with PVP flows or 100 percent of current diversions, reservoir reliability is 100 percent regardless of storage capacity. Additionally, two thresholds can be derived from these results: first, if PVP diversions are kept above 50 percent of current volumes, the storage reliability will be kept above 95 percent. Second, if the storage is augmented above 35 thousand acre-feet, the storage reliability does not change significantly.

A reliability map based for both decision variables is presented in Figure 24 for the annual storage reliability in CVD, obtained from the surface presented in Figure 22. To create this plot, the heights were obtained based on storage increments of 5 TAF and PVP diversion share intervals of 5 percent. Contour lines for reliability increments of 5 percent were drawn on this map to represent the relation between augmented storage and PVP diversions.



**Figure 24** Contour lines of the annual storage reliability on Lake Mendocino for both additional storage capacity (y-axis) and share of current PVP diversions (x-axis)



**Figure 25 Shortages upstream and downstream of Lake Mendocino for variations in storage and PVP diversions. (a) Upstream of CVD with respect to storage; (b) Downstream of CVD with respect to storage; (c) Upstream of CVD with respect to PVP diversions; (d) Downstream of CVD with respect to PVP diversions**

Similarly, with respect to water supply, annual average shortages upstream and downstream of CVD reservoir were used to compare the defined strategies. The deficit or water supply shortage is presented in Figure 25 for an augmented storage perspective and variations of PVP diversions for demands upstream and downstream of Lake Mendocino. Figure 25a and c show the average annual shortages upstream of Lake Mendocino do not depend on storage

(Figure 25a), but strongly depend on PVP Diversions (Figure 25c) where shortages are reduced from 7 thousand acre-feet to less than 1 thousand acre-feet if PVP diversions go from 0 to 25 percent. These shortages represent a reduction from nearly 80 percent of upstream demands down to less than 10 percent. Downstream of Lake Mendocino, shortages are reduced for both additional storage and higher PVP diversions, with significant improvements for storage capacity augmented from 0 to 50 thousand acre-feet and from 0 to 25 percent of current PVP diversions. Although there is an improvement downstream of Lake Mendocino, these shortages represent less than 5 percent of downstream demands and they are reduced to less than 1 percent if PVP diversions go from 0 to 25 percent.

## 6. Discussion

### Current vs Augmented Storage

The reliability of the system to meet environmental and water supply requirements is directly related to the reservoir storage capacity. Coyote Valley Dam was originally constructed for flood control purposes, but over time, the development of the Russian River watershed has relied on the water stored at this dam. During this period, changes in water demands, water inputs, and diversions from the Eel River through PVP had influenced the management of the system. Results presented in this report demonstrate the strong dependence of the Russian River basin on PVP diversions. Moreover, the reliability of the reservoir could be seriously reduced without it. However, changes in reservoir storage capacity suggest opportunities to improve system water supply reliability.

PVP diversions from the Eel River had sustained reservoir storage since its construction. Nonetheless, recent reductions in diverted flows have reduced the stored volume. Simulation results comparing the reliability of the reservoir with PVP diversions and without them showed strong dependence of the current system where 11 percent of the time the reservoir will go dry, but more than 48 percent of the years will have a dry month. The effect is concentrated between September and January, a time when the reservoir starts to fill again only if there is enough early winter precipitation. On the other hand, the flood risk will be reduced without PVP diversions and if the reservoir is managed with the current Rule Curve because has a lower average storage during the flood season.

The current storage capacity reservoir with PVP flows showed to be a more reliable system than without PVP. During periods of sufficient inflows and high storage, both human and environmental objectives were supplied. However, when the system faced droughts of



consecutive dry years objectives were at risk to be not fully supplied. Recent changes in PVP diversions, persistent population growth, and land use changes may drive the system more often to water supply shortage. Although raising the dam is under current feasibility evaluation due to dam safety standards, it was originally designed to be raised approximately 36 feet, with 75,000 acre-ft volume. Results indicate that if PVP diversions were kept as they are currently, the system will have an almost equal response regardless of the storage capacity, but the reservoir storage will be augmented approximately the same volume that the reservoir would be raised.

There are substantial differences for the case without PVP diversions, where the system relies entirely on water inflows within the watershed. The study results indicate that water supply reliability will be reduced with the current storage capacity, and less reduced with a bigger reservoir. Specifically, under severe conditions, the larger capacity reservoir can store enough water to meet environmental and water supply demands longer (about an extra year), but if the dry period extends long enough, the reservoir will go dry regardless of the reservoir storage capacity. Additionally, whenever the reservoir goes dry, the larger capacity reservoir recovers faster than under the current conditions because the latter usually reaches the top of conservation threshold whereas the greater capacity of the larger reservoir allows storing more water.

Although a higher capacity will not prevent it to go dry, 65 percent of the months the storage will be above the current capacity threshold. Finally, the hydrology and water inflows to the system suggest that the reservoir gets filled during the late winter and early spring when the top of conservation is at the lowest level or gradually increasing. Therefore, the main water inputs of the systems are not fully stored due to flood control operations. During this period, the reservoir storage would be usually above the current rule curve if no flood control releases occur, or, as the augmented capacity simulation indicates, allow the system to keep a higher storage.

Ultimately, a bigger reservoir allows not only to store water from the wet season to be used during the dry and high demand season but also to transfer the remaining storage annually, improving the water supply reliability.

### **Tradeoff analysis**

The reliability of the system is more exposed to variations in PVP diversions than storage augmentation. As seen in Figure 24, if PVP inflow is reduced 50 percent from current volume, additional capacity has to be augmented in the same proportion to keep the system as reliable as it is today. However, if PVP is further reduced, additional storage capacity improves the reliability of the system but it does not reach full supply. This can be noticed in Figure 23a, where for no current PVP diversions, the highest reliability for 75 thousand acre-feet of additional storage is 83 percent, which means that the reservoir will go dry at least once every 5 years. Similarly, the results presented Figure 25a and b showed that additional storage will reduce shortages both upstream and downstream of the reservoir. Nonetheless, reductions upstream are marginal compared with the deficit (Figure 25a), whereas downstream reductions are moderate but highly dependent on PVP (Figure 25b). This can be described by the slope of the curves that showed a much steeper transition when PVP is augmented as compared with storage augmentation.

When shortages are analyzed for upstream and downstream users, the value of PVP and augmented storage varies considerably. For upstream users, the value of PVP slightly changes with respect to additional storage. This is supported by the results presented Figure 25 where little reductions in upstream shortages were observed for additional storage. On the other hand, downstream users perceive the benefits of both PVP diversions and augmented storage. Results

presented in Figure 25 showed that under current storage conditions PVP inflows may completely reduce shortage whereas additional storage does not improve the water supply reliability under current PVP diversions and for no PVP, raising the dam may reduce shortages by 50 percent.

The thresholds to maintain current reliability for each alternative are presented in Figure 26, derived from the contour plot showed in Figure 24. If PVP is maintained under current conditions, additional storage does not improve the reliability of the system (already 100 percent). However, without additional storage capacity, there is a significant reduction in the reliability of the system if PVP inflow is reduced. This effect is attenuated with greater storage capacity, with a 1:1 relation between additional storage and PVP reductions to maintain 100 percent reliability. However, if PVP is reduced below 50 percent, it is not possible to substitute the reduction in PVP inflow with additional storage capacity and maintain current performance.

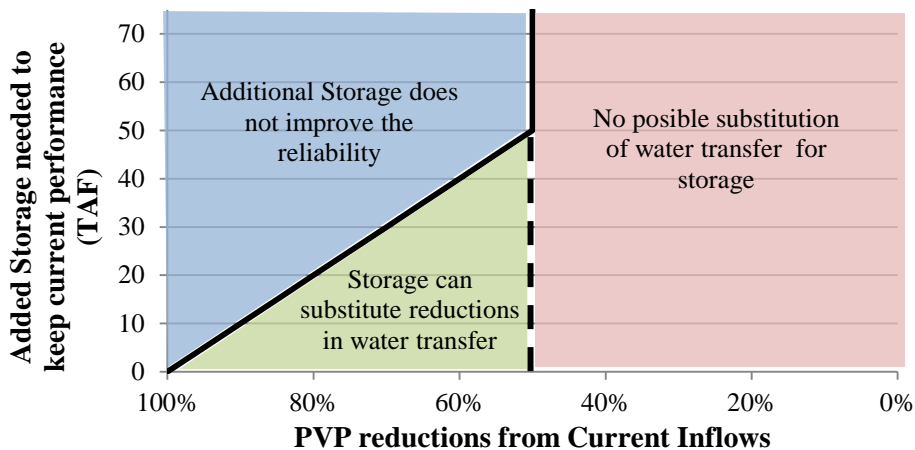


Figure 26 Tradeoff between additional storage in Lake Mendocino and share of current PVP inflow

## **7. Conclusions**

Water management strategies were analyzed for the Upper Russian River system. A water allocation model was developed to simulate the hydrology and operation of the system. Additionally, along with the RRFC, reservoir storage and inter-basin water transfers were analyzed. Finally, a relation between the share of current PVP diversion and the volume of additional storage was derived to represent the shortage threshold between storage and inflow resources.

Insights for decision makers were derived from this study. First, the system relies on PVP inflows. The reliability of the Upper Russian River is more sensitive to changes in PVP than changes in storage capacity, for both storage reliability and water supply reliability. Second, raising Coyote Valley Dam improves the storage reliability but a bigger reservoir will not prevent shortage if PVP inflow is removed. There is a potential additional volume to be stored during the refill season that is not captured with current storage capacity. Additionally, current performance levels can be maintained raising the dam if PVP inflows are above 50 percent of current volumes. Otherwise, additional storage improves the systems operation but does not achieve current performance. The tradeoff analysis shed light on the relative importance of storage capacity and inflows for this system.

### **7.1. Limitations**

This study had several limitations. First, it does not account for surface-groundwater interactions. Water demands were obtained from an end-use analysis and an average annual share of groundwater use was incorporated into the model. Therefore, the model only assesses

the surface water usage which is directly related to the reservoir operation and the inter-basin transfer of PVP. Additional management strategies could be implemented if groundwater storage and conjunctive use are included in the systems operation.

Second, although operation of the reservoir and minimum instream flow requirements are components of the system operation, it is not an operation model. The monthly time-step does not allow modeling of flood management releases and downstream thresholds of flood channel capacity or flow forecasts. Therefore, forecast informed strategies cannot be implemented, which might provide alternatives to the current rule curve, particularly during the flood management and refill season. Additionally, water allocation occurs at the reach level, not at the user level. Therefore, it provides an overall understanding of the system but it does not represent real-time operation, particularly under high demand peaks such as frost control.

Finally, the model was developed for the Upper Russian River system. It considers the area directly influenced by Lake Mendocino. However, it does not allocate water downstream of Dry Creek, and it does not incorporate the operation of Lake Sonoma. Additional water supply benefits might be derived if both reservoirs are managed together and if both water demands and water availability on the lower basin are integrated into the model.

## References

- American Society of Civil Engineers. (2005). *Report card for America's infrastructure*. Retrieved from <http://www.asce.org/reportcard/2005/index.cfm>.
- Association of California Water Agencies. (2015). *21st Century Water Storage: Recommendations for California's Future*. Sacramento: ACWA.
- Brekke, L., Kiang, J., Olsen, J., Pulwarty, R., Raff, D., Turnipseed, D., . . . White, K. (2009). *Climate change and water resources management—A federal perspective: U.S. Geological Survey Circular 1331, 65 p* <http://pubs.usgs.gov/>.
- Brekke, L., Maurer, E., Anderson, J., Dettinger, M., Townsley, E., Harrison, A., & Pruitt, T. (2009). *Assessing reservoir operations risk under climate change*. *Water Resour Res* 45.
- Cayan, D., Maurer, E., Dettinger, M., Tyree, M., & Hayhoe, K. (2008). Climate change scenarios for the California Region. *Climate Change* 87, S21–S42.
- Dettinger, M. D., Cayan, D. R., Meyer, M. K., & Jeton, A. E. (2004). Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. *Clim. Change*, 62, 283 – 317, doi:10.1023/B:CLIM. 0000013683.13346.4f.
- DWR. (2010). *CALFED Surface Storage Investigations - Progress Report*. Department of Water Resources.
- DWR. (2013). *California Water Plan, Update 2013*. California, Department of Water Resources.
- DWR. (2015, Dec). *Dam Safety*. Retrieved from DWR: <http://www.water.ca.gov/damsafety/damlisting/>
- FERC Order Amending License, 106 FERC ¶ 61,065, 77-110 (Federal Energy Regulatory Commission January 28, 2004).
- FIRO Report. (Unpublished). *A comprehensive Plan to Evaluate the Viability of Forecast Informed Reservoir Operation (FIRO) for Lake Mendocino*. USGS, USACE, SCWA, NOAA, CRIPPS, USBR, IWRSS, MCRRFC&WCID.
- Flint, L., Flint, A., Curtis, J., Delaney, C., & Mendoza, J. (2015). *Unimpaired Mean Daily Streamflow in the Russian River and Upper Eel River Basins, California under Historical and Projected Future Climates: U.S. Geological Survey Data Release*. doi:10.5066/F71C1TX4.
- Friends of the Eel River*. (2016, 5 31). Retrieved from PG&E's Potter Valley Hydroelectric Project: [eelriver.org/about/potter-valley-project-dams/](http://eelriver.org/about/potter-valley-project-dams/)
- Georgakakos, A. P., Yao, H., Kistenmacher, M., Georgakakos, K. P., Graham, N. E., Cheng, F. Y., . . . Shamir, E. (2012). Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir Management. *Journal of Hydrology*, 412, 34-46.

- Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, j., . . . Thompson, B. (2011). Managing California's Water: From conflict to reconciliation. In PPIC. ppic.org.
- Howard, C. D. (1999). Death to rule curves. *WRPMD'99, Preparing for the 21st Century* , (pp. 1-5). ASCE.
- Hydrologic research Center and Georgia Water Resources Institute (HRC-GWRI). (2013). *Integrated Forecast and Reservoir Management (INFORM): Enhancements and Demonstration Results for Northern California (2008-2012)*. California Energy Commission. Publication number: CEC-500-2014-019.
- Kapelan, Z. S., Savic, D. A., & Walters, G. A. (2005). Multiobjective design of water distribution systems under uncertainty. *Water Resources Research* 41, W11407.
- Kim, S., Tachikawa, Y., Nakakita, E., & Takara, K. (2009). Reconsideration of Reservoir Operations under Climate Change: Case Study with Yagisawa Dam, Japan. *Annual Journal of Hydraulic Engineering, JSCE* 53, 597-611.
- Klemes, v., Srikanthan, R., & McMahon, T. (1981). Long-memory flow models in reservoir analysis: what is their practical value? *Water Resources Research* 17 (3), 737 - 751.
- Labadie, J. W. (2004). Optimal operation of multireservoir systems: State-of-the-art review. *Journal of water resources planning and management*, 130(2), 93-111.
- Loucks, D. P. (1990). "Analytical Aids to Conflict Management" in W. Viessman and E.T. Smerdon (eds.). *Managing Water-Related Conflicts: The Engineers Role, ASCE, N.Y.*, 23-37.
- Loucks, D. P. (2005). *Water Resources Systems Planning and Management; An Introduction to Methods, Models and Applications*. United Nations Educational, Scientific and Cultural Organization.
- Lund, J. R., & Israel, M. (1995). Water Transfers in Water Resource Systems. *Journal of Water Resources Planning and Management* 121(2), 193 - 204.
- Lund, J. R., & Palmer, a. R. (1997). Water resource system modeling for conflict resolution. *Water Resources Update* 3.108, 70-82.
- McMahon, T. A., Adebayo J, A., & Zhou, S.-L. (2006). Understanding performance measures of reservoirs. *Journal of Hydrology* 324, 359 - 382.
- MCWA. (2010). *Water Supply Assessment for the Ukiah Valley Area Plan*. Ukiah: Mendocino County Water Agency.
- Meador, M. R. (1992). Inter-basin Water Transfer: Ecological Concerns. *Fisheries* 17:2, 17-22.
- Mendocino County. (2014). *Annual Crop Report*. Retrieved from California Department of Food and Agriculture
- Milly, P., Dunne, K., & and Vecchia, A. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, v. 438, 347–350.

- Mote, P. (2006). Climate driven variability and trends in mountain snowpack in western North America. *Climate*, 19, 6209 - 6220.
- National Marine Fisheries Service. (2002). *Biological opinion for The Proposed License Amendment for the Potter Valley Project*. Federal Energy Regulatory Commission.
- Order Approving Temporary Urgency Change, Permits 12947A, 12949, 12950, and 16596 (SWRCB, Division of Water Rights May 1, 2013).
- Park, J. Y., & Kim, S. J. (2014). Potential Impacts of Climate Change on the Reliability of Water and Hydropower Supply from a Multipurpose Dam in South Korea. *Journal of the American Water Resources Association (JAWRA)* 50(5), 1273-1288.
- Ralph, F. M., Sukovich, E., Reynolds, D., Dettinger, M., Weagle, S., Clark, W., & Neiman, A. P. (2010). "Assessment of Extreme Probabilistic Quantitative Precipitation Forecasts and Development of Regional Extreme Event Thresholds Using Data from HMT-2006 and COOP Observers. *Journal of Hydrometeorology*, 1286-1304.
- Rohde, M. (2014, July 31). *Understanding California's Groundwater*. Retrieved April 26, 2016, from Water in the West: <http://waterinthewest.stanford.edu/groundwater/recharge/>
- Sandoval-Solis, S., Teasley, R. L., McKinney, D. C., Thomas, G. A., & Patino-Gomez, C. (2013). Collaborative Modeling to Evaluate Water Management Scenarios in the Rio Grande Basin. *JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION (JAWRA)* 49(3), 639-653.
- Sonoma County Water Agency. (2013). *Russian River Applied Water Estimates, Development Report by Davids Engineering, INC.*
- Sonoma County. (2014). *Annual Crop Report*. Retrieved from California Department of Food and Agriculture
- Sonoma County Water Agency. (2015). *Lake Mendocino Water Supply Reliability Evaluation Report - Term 17*. Santa Rosa, CA: Sonoma County Water Agency.
- U.S. Army Corps of Engineers. (1986). *Coyote Valley Dam and Lake Mendocino, Russian River, California, water control manual. Appendix I to master water control manual, Russian River basin, California.*
- U.S. Army Corps of Engineers. (2004). *Folsom Dam and Lake, American River, California, Water Control Manual update*. U.S. Army Corps of Engineers.
- U.S. Army Corps of Engineers; Sonoma County Water Agency. (August 18, 2000). *Russian River Biological Assessment Interim Report 1 - Flood Control operations at Coyote Valley and Warm Springs Dams.*



U.S. Geological Survey; CA Department of Water Resources. (1965). *Geology and Ground Water in Russian River Valley Areas and in Round, Laytonville and Little Lake Valleys - Sonoma and Mendocino Counties, California*. Washington: United States Government Printing Office.

U.S. Geological Survey. (December 2013). *May 2013 Landsat 8 Imagery*.

Union of Concerned Scientist. (2015). *The Big Water Supply Shift*. Retrieved November 17, 2015, from <http://www.ucsusa.org/global-warming/global-warming-impacts/california-water-supply-shift#.VkvlpH6rRhE>

Watts, R., Richter, B., Opperman, J., & Bowmer, K. (2007). Dam Reoperation in an Era of Climate Change. *Marine and Freshwater Research* 62(3), 321-327.

Weeks, E. (2015, November 5). *A Historical Overview of Hydrologic Studies of Artificial Recharge in the U.S. Geological Survey*. Retrieved from USGS: [http://water.usgs.gov/ogw/pubs/ofr0289/epw\\_historical.html](http://water.usgs.gov/ogw/pubs/ofr0289/epw_historical.html)