Central Valley Refuge Management under Non-stationary Climatic and Management Conditions

By

KARANDEV SINGH
B.S. (University of California, Davis) 2013

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE
in
Civil and Environmental Engineering
in the
OFFICE OF GRADUATE STUDIES
of the
UNIVERSITY OF CALIFORNIA
DAVIS

Approved:

____________________**[SIGNED]**____________________

Jay R. Lund, Chair

____________________**[SIGNED]**____________________

Samuel Sandoval Solis

____________________**[SIGNED]**____________________

Jonathan Herman

Committee in Charge
2015

This page is left blank intentionally.

Acknowledgements

It takes a dream to begin, motivation to keep going, and determination to finish.

– Unknown

This has been my mantra all along. Of course, none of this would be possible without the support and encouragement of my family, friends, colleagues and the committee members. Thank you Dr. Jay Lund, Dr. Josh Viers and Rachael Esralew for providing me with the opportunity to work on this project. It's your trust, encouragement and patience throughout the process that kept me going. Thank you Dr. Josue Medellin-Azuara for always finding time to answer my endless questions. Thanks to the CWS staff – Catheryn Lawrence, Barbara Bellieu and Chris Bowman – and the research group for your help and guidance. A very special thanks to Mustafa Dogan for being there all along be it day, night, workday or weekend. Your friendship undoubtedly made this a very enjoyable experience.

I would also like to express my sincere appreciation to the members of my thesis committee, Dr. Jay Lund, Dr. Samuel Sandoval and Dr. Jon Herman. Thank you for taking time to review the thesis and providing invaluable feedback. Last but not least, I am indebted to my parents, fiancé and my brother; without your unconditional love and support I simply wouldn't be where I am today.

This page is left blank intentionally.

Abstract

Agricultural water users represent nearly 65% (23.1 MAF/yr) of the total statewide demand. More than 90% of the demand is concentrated in the Central Valley with 40% in Tulare Basin, 20% in Lower Sacramento and San Joaquin Valley, and 10% in Upper Sacramento Valley. CVPIA refuge deliveries, on the other hand, constitute less than 2% (0.5 MAF/yr) of the total demand. Even then, only 89% of the Level 2 deliveries and 47 % of incremental Level 4 have been met between 2001 and 2014. Refuge managers cite budgetary constraints and rising cost of water as the major impediment in realizing Full Level 4 deliveries. Some estimates indicate that, on average, the cost of acquiring water has increased 400% since 1990s. Global warming and regional hydro-climatic alterations are likely to further limit state's ability to manage water, reduce total volume of available water and intensify competition for surface water. Historically, reduction in surface water supplies is substituted with groundwater pumping. Long-term overdraft and Sustainable Groundwater Management Act (SGMA) provisions will, however, limit future pumping opportunities. This research examines impacts from a warm-dry climate, peripheral tunnels, groundwater overdraft regulations, and competing environmental flow demands on water deliveries to CVPIA refuges. The study is conducted within a statewide framework using CALVIN – a hydro-economic optimization model of State of California – to capture the physical, environmental and policy constraints in the existing water management system. Sixteen scenarios are analyzed to capture and quantify the hydrologic and economic implications of climatic and management uncertainties on refuge deliveries including (1) climate vulnerability: historical and warm-dry climates; (2) Delta regulations: high and existing Delta Outflows; (3) infrastructure: with and without isolated facility or peripheral tunnels; and (4) groundwater management: with and without long-term overdraft. A separate Spreadsheet Tool is also developed to explore the benefits and implications of inter-refuge trading and optimizing refuge land-use management practices.

This page is left blank intentionally.

Table of Contents

Abbreviations

AF	Acre-feet
BDCP	Bay Delta Conservation Plan
BiOp	Biological Opinion
CAA	California Aqueduct
CALVIN	California Value Integrated Network Model
CDFW	California Department of Fish and Wildlife
CESA	California Endangered Species Act
cfs	cubic feet per second
CVHJV	Central Valley Habitat Joint Venture
CVJV	Central Valley Joint Venture
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act of 1992
CWF	California Water Fix
CWP	California Water Plan
DMC	Delta-Mendota Canal
DWR	California Department of Water Resources
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
ESA	Endangered Species Act
FERC	Federal Energy Regulatory Commission
FKC	Friant-Kern Canal
GFDL	Geophysical Fluid Dynamics Laboratory
ID	Irrigation District
mth	month
MAF	million acre-feet
NAWMP	North American Waterfowl Management Plan
NMFS	National Marine Fisheries Service
NWR	National Wildlife Refuge

RCD	Resource Conservation District
SGMA	Sustainable Groundwater Management Act
SWAP	Statewide Agricultural Production Model
SWP	State Water Project
SWRCB	State Water Resource Control Board
TAF	thousand acre-feet
USBR	U.S. Bureau of Reclamation Mid-Pacific Region
USFWS	United States Fish and Wildlife Service
WA	Wildlife Area
WD	Water District
WEF	Water Education Foundation
WMP	Water Management Plan
WY [1]	Water Year
yr	year

[1] Two definitions of Water Year are used in this document: (1) DWR's definition, from October of previous calendar year to September of current calendar year; and (2) USFWS's definition, from March of current calendar year to February of following calendar year.

Chapter 1: Introduction

California's Central Valley is the most important waterfowl wintering area of Pacific Flyway, supporting about 60 percent of the total flyway migratory bird population (CVHJV, 1990). Wetlands provide ideal wintering and breeding habitat for waterfowl and other wildlife. Historically, the Central Valley had more than 4 million acres of wetland; however, 95 percent of wetlands have been permanently lost since 1900 as a result of flood control and navigation projects, and land conversion to sustain irrigated agricultural and population growth during the 20th century (CVJV, 2006). By mid-1980s bird flights were 30 percent below the long-term average. Even though the major focus of restoring wetlands is to sustain waterfowl, 50% of threatened and endangered species in California are also associated with wetlands (CVHJV, 1990).

Refuge management in California dates back to 1930s. The primary purpose was to provide a sanctuary to migrating waterfowl; however, it quickly evolved into managing for crop damage and providing public hunting opportunities. The Endangered Species Act (ESA) and California Environmental Species Act (CESA) further expanded the management responsibilities of these refuges to protect endangered and threatened species (USBR, 2010a-b; USBR, 2011a-l). Historically, refuges relied on agricultural return flows and when available, surplus Central Valley Project (CVP) water to sustain their operations. In 1992, Congress authorized Central Valley Project Improvement Act (CVPIA) which dedicated 800,000 acre-feet of the Central Valley Project water (project water) to meet minimum in-stream flow requirements and refuge demands. Section 3406(d)(6) of CVPIA guaranteed Full Level 2 refuge deliveries – average historic refuge deliveries prior to 1989 – and set targets towards acquiring 100 percent of incremental Level 4 refuge deliveries – additional water required for "optimal wetland and wildlife habitat development and management" – by 2002 (CVJV, 2006; USDOI, 2014).

With passage of CVPIA, Central Valley refuges became a direct competitor for managed water supply which left them vulnerable to challenges and uncertainties surrounding management of water resources in California. Environmental regulations enacted under Endangered Species Act (ESA) and California Endangered Species Act (CESA) curtailed the amount of water that can be exported south of the Delta. As a result, competition for water intensified while opportunities for capturing and exporting surplus Delta Outflows decreased. Some estimates indicate that, on average, the cost of acquiring water for wetlands increased by 400 percent since 1990s (CVJV, 2006). Only 89 percent of the Level 2 deliveries and 47 percent of incremental Level 4 have been met between 2001 and 2014 (*Table 2-2*).

While environmental regulations restrain water exports to protect endangered and threatened species in Delta and Sacramento River watershed, statewide warming alters the hydrologic pattern and widens the gap between periods of water supply and peak water demand. Reports published by Western Regional Climate Center confirm a temperature warming by 1.1 to 2 degree Fahrenheit in California over the last century (Abatzoglou *et al.*, 2009). Hydrologic implications of warmer conditions are already being observed in precipitation pattern: more precipitation is falling as rainfall in winter months when there is often surplus water with less of water stored as snowpack, reducing snowmelt runoff in spring (DWR, 2014). This trend contradicts with the intended design and management of California's surface water reservoirs. Historically, reservoirs are managed for flood control in winter, and for water supply during spring and summer. This shift in precipitation pattern has reduced the time window available for capturing flows for water supply use and is projected to continue at an accelerated rate (Cayan *et al.*, 2008; Hayhoe *el at.*, 2004; Pierce *et al.*, 2012; Pierce & Cayan, 2013).

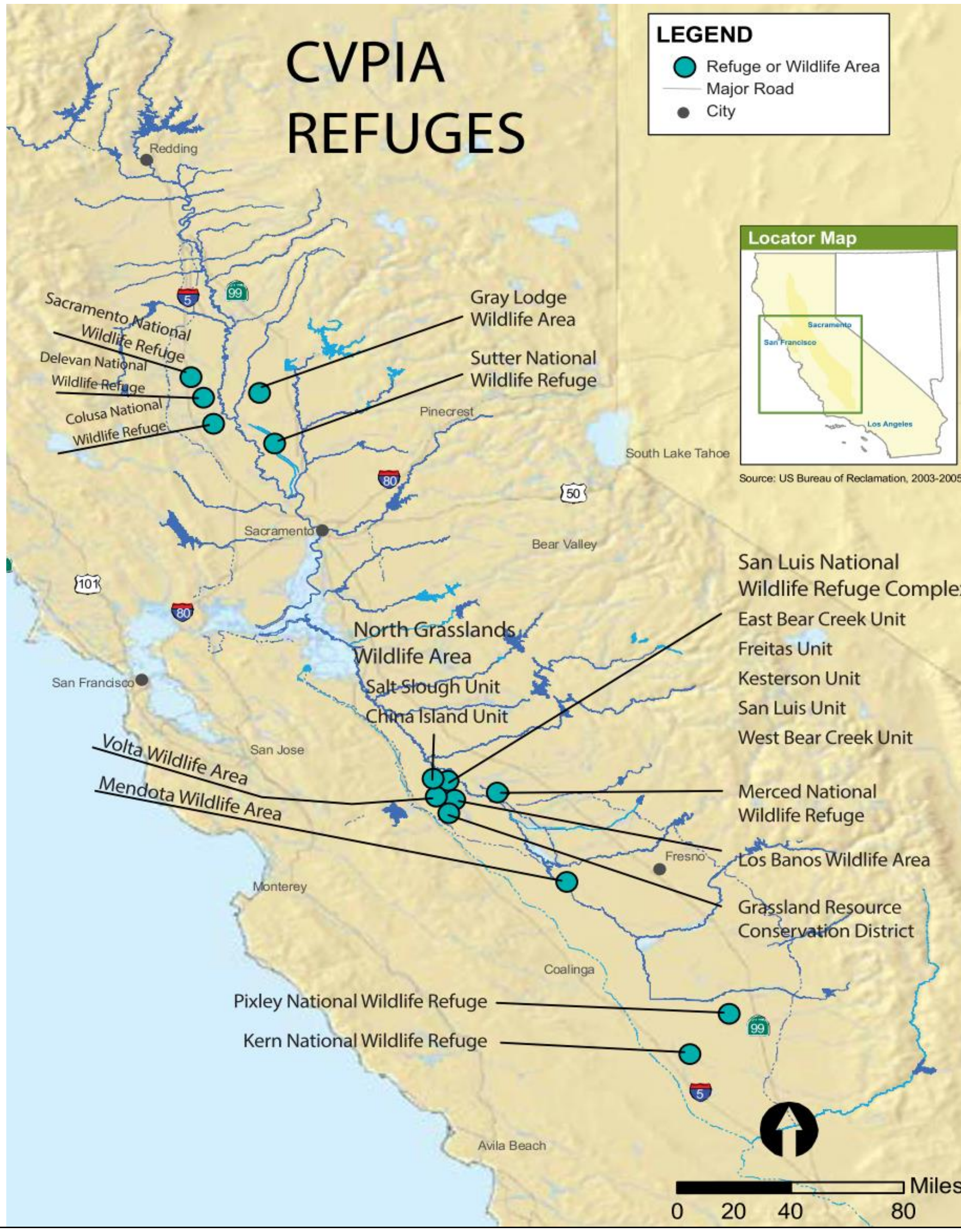


Figure 1-1. Managed wetlands and wildlife refuges included in the Central Valley Project Improvement Act of 1992. National Wildlife Refuges (NWRs) are managed by US Fish and Wildlife. Wildlife Areas (WAs) are managed by California Department of Fish and Wildlife (CDFW). Rest are privately managed (USDOI, 2014).

In addition to providing natural surface water storage, snowpack also supplies a natural source of groundwater recharge (DWR, 2014). On average, groundwater satisfies 40 percent state's consumptive use demand. Unsustainable management of groundwater resources results in 1 to 2 MAF overdraft each year. Reduced snowpack is expected to lower aquifer recharge in the Central Valley and increase the imbalance between groundwater recharge and pumping. To curb long-term groundwater overdraft, California's legislature enacted the Sustainable Groundwater Management Act (SGMA) in September 2014. The act mandates that local groundwater users manage and use groundwater without causing "undesirable results" such as chronic long-term lowering of groundwater levels. Limiting natural recharge opportunities coupled with SGMA will intensify competition for surface water, potentially increasing the cost of acquiring water (WEF, 2015).

Table 1-1. Hydrologic and management scenarios assessed using CALVIN

Scenario #	Abbreviation	Hydrology	Delta Export/ Outflow Regulations	Isolated Facility/ Peripheral Tunnels	Long-term Groundwater Overdraft	Refuge Deliveries
1	HEREC	Historic	Existing	No	Yes	Historic
2	HERIF	Historic	Existing	Yes	Yes	Historic
3	HHOEC	Historic	High Outflow	No	Yes	Historic
4	HHOIF	Historic	High Outflow	Yes	Yes	Historic
5	HERECG	Historic	Existing	No	No	Historic
6	HERIFG	Historic	Existing	Yes	No	Historic
7	HHOECG	Historic	High Outflow	No	No	Historic
8	HHOIFG	Historic	High Outflow	Yes	No	Historic
9	CEREC	Warm-Dry	Existing	No	Yes	Historic
10	CERIF	Warm-Dry	Existing	Yes	Yes	Historic
11	CHOEC	Warm-Dry	High Outflow	No	Yes	Historic
12	CHOIF	Warm-Dry	High Outflow	Yes	Yes	Historic
13	CERECG	Warm-Dry	Existing	No	No	Historic
14	CERIFG	Warm-Dry	Existing	Yes	No	Historic
15	CHOECG	Warm-Dry	High Outflow	No	No	Historic
16	CHOIFG	Warm-Dry	High Outflow	Yes	No	Historic

Historic Deliveries: Level 2 and incremental Level 4 deliveries to CVPIA refuges between March 2001 and February 2014.
Existing Delta Export and Outflow: D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp (and BDCP Alt 2a-H3 if tunnels are used to export water).
High Outflow Delta Export and Outflow: D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H4.

At the same time, California's population and urban footprint are projected to grow. Assuming statewide population and land development continue at the current trend, by 2050 California's population and urban footprint will increase by 40% and 29%, respectively, compared to 2006. Even though irrigated agricultural acreage is projected to decline over the same period, an equivalent reduction in agricultural water use is not anticipated. Recent cropping is shifting towards high-value, perennial crops like vine crops and orchards. Unlike seasonal crops, perennial crops require reliable water supplies year-after-year which limits system's flexibility to respond to extreme hydrologic events by reducing agricultural land available for flooding or fallowing (DWR, 2014). Several projects are being explored to develop resiliency and redundancy in the system, and increase opportunities for capturing flood flows. At the forefront is the Bay Delta Conservation Program (BDCP) or California Water Fix (CWF) project. The project proposes construction of peripheral tunnels, a conveyance facility that bypasses the Delta and diverts up to 9,000 cfs of water from Sacramento River directly to the pumps for export south of the Delta. Proponents argue that this project will reduce the impact of pumping operations on Delta habitat and provide increased opportunities for capturing and exporting surplus water to water users south of the Delta. However, the regulatory environment around the tunnels project is still evolving; use of best available science to quantify the project's impact on Delta habitat still remains a highly contentious discussion topic (DWR, 2015).

Table 1-2. CVPIA refuge representation in CALVIN and Spreadsheet Tool

CVPIA Refuge	CALVIN	Spreadsheet Tool
Sacramento Valley		
Sacramento NWR	Sacramento River West (SRW)	Sacramento NWR (SAC)
Delevan NWR		Delevan NWR (DEL)
Colusa NWR		Colusa NWR (COL)
Sutter NWR	Sutter NWR (SUT)	Sutter NWR (SUT)
Gray Lodge WA	Gray Lodge WA (GLD)	*- not included -*
San Joaquin Valley		
Volta WA	San Joaquin River West (SJW)	*- not included -*
Los Banos WA		
Grasslands RCD		
North Grasslands WA		
China Island Unit		
Salt Slough Unit		
San Luis NWR		West of Highway 165 (W165)
Kesterson Unit		
Freitas Unit		
San Luis Unit		East of Highway 165 (E165)
West Bear Creek Unit		
East Bear Creek Unit	San Joaquin River East (SJE)	East Bear Creek Unit (EBR)
Merced NWR		Merced NWR (MER)
Mendota WA	Mendota WA (MDT)	*- not included -*
Tulare Basin		
Pixley NWR	Pixley NWR (PIX)	Pixley NWR (PIX)
Kern NWR	Kern NWR (KER)	Kern NWR (KER)

NWR: National Wildlife Refuge; managed by US Fish and Wildlife Service (USFWS)
WA: Wildlife Area; managed by California Department of Fish and Wildlife (CDFW)
RCD: Resource Conservation Districts; managed by private owners

The uncertainties and changes surrounding the future of water management coupled with the increasing cost of and diminishing opportunities for acquiring water poses two critical challenges for the refuge managers: 1) do more with less and 2) secure reliable water supplies at affordable prices. Sixteen scenarios are analyzed using CALVIN, a hydro-economic model of State of California, to capture and quantify the hydrologic and economic implications of evolving climatic and management conditions on refuge water deliveries (Chapter 3) including (1) climate vulnerability: historical and warm-dry climates; (2) Delta regulations: high and existing Delta Outflows; (3) infrastructure: with and without isolated facility or peripheral tunnels; and (4) groundwater management: with and without long-term overdraft (*Table 1-1*). Only a subset of managed refuges is incorporated in CVPIA (*Figure 1-1*). This group is also referred to as CVPIA Refuges and comprises slightly more than half of the managed wetland acreage in the Central Valley including US Fish and Wildlife Service (USFWS) managed National Wildlife Refuges

(NWRs), California Department of Fish and Wildlife (CDFW) managed Wildlife Areas (WAs') and Grasslands Resource Conservation District (GRCD). Modeling results are limited to CVPIA refuges because only these refuges receive dedicated water supply and actively compete against the other water users in the state. A separate Spreadsheet Tool is also developed to find insights into optimizing refuge management practices (Chapter 4). This tool only focuses on USFWS managed refuges because of the scope of this research effort; however, it can be easily adapted to explore other managed refuges as well. To simplify computation, CVPIA refuges are aggregated by water supply source in CALVIN. Altogether, CVPIA refuges are represented as 8 aggregate demand areas in CALVIN and 10 demand areas in the Spreadsheet Tool (*Table 1-2*).

Three major scientific questions are explored in this research: (1) What are the hydrologic and economic impacts of climatic and management uncertainties on refuge management; (2) What are some promising adaptation strategies to mitigate for the hydrologic and economic impacts; and (3) What water trading opportunities exist to secure reliable supplies for refuge management? This thesis is divided in five chapters including this introductory chapter (Chapter 1). Chapter 2 provides background information on water resource management and refuge management in California. Challenges and uncertainties associated with water management, and their relation to scenarios explored in this research study are also discussed in this chapter. Chapter 3 provides a discussion on the hydro-economic analysis using CALVIN model. Results include (1) hydrologic and economic implications of climatic and management uncertainties on refuge deliveries, (2) infrastructure development opportunities, and (3) opportunities for and cost of acquiring additional water to realize Full Level 4 deliveries. Chapter 4 focuses on refuge management practices. Eight scenarios are analyzed using the Spreadsheet Tool to assess the implications of inter-refuge trading, and the differences between optimized and historic refuge management practices. Chapter 5 presents a summary of key insights from the research followed by a discussion on possible extensions of the work presented in this thesis.

References

Abatzoglou J. T., Redmond, K. T. & Edwards, L. M. (2009). Classification of regional climate variability in the State of California. *Journal of Applied Meteorology and Climatology, 48*, 1527-1541.

Cayan, D. R., Maurer, E. P., Dettinger, M. D., Tyree, M. & Hayhoe, K. (2008). Climate change scenarios for the California region. *Climatic Change, 87*(1), 21-42.

Central Valley Habitat Joint Venture (CVHJV). (1990). *Central Valley Habitat Joint Venture implementation plan: A component of the North American Waterfowl Management Plan*.

Central Valley Joint Venture (CVJV). (2006). *Central Valley Joint Venture implementation plan: Conserving bird habitat*. Sacrament, CA: U.S. Fish and Wildlife Service.

Department of Water Resources, California (DWR). (2014). *California Water Plan Update 2013 Bulletin 160-13: Investing in innovation and infrastructure* (Vol. 1). Sacramento, CA.

Department of Water Resources, California (DWR). (2015). *State Water Project Final Delivery Capability Report 2015*.

Hayhoe K., Cayan, D., Field, C. B., Frumhoffe, P. C., Maurer, E. P., Miller, N. L., … Cleland, E.E. (2004). Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Science, 101*(34), 12422–12427.

Pierce, D. W., Das, T. Cayan, D. R., Maurer, E. P., Miller, N. L., Bao, Y., … Tyree, M. (2012). Probabilistic emissions of future changes in California temperature and precipitation using statistical and dynamical downscaling. *Climate Dynamics*, *40* (3), 839-856.

Pierce, D. W. & Cayan, D. R. (2013). The uneven response of different snow measures to human-induced climate warning. *Journal of Climate, 26*, 4148-4167.

U.S. Department of Interior (USDOI). 2014. *Central Valley Project Improvement Act Public Law 102-575: Annual Report Fiscal Year 2013*.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010a). *Merced National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010b). *San Luis National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011a). *Colusa National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011b). *Delevan National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011c). *Grasslands Resource Conservation District Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011d). *Gray Lodge Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011e). *Kern National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011f). *Los Banos Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011g). *Mendota Pool Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011h). *North Grasslands Wildlife Area China Island Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011i). *North Grasslands Wildlife Area Salt Slough Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011j). *Pixley National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011k). *Sacramento National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011l). *Volta Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

Water Education Foundation (WEF). (2015). *The 2014 Sustainable Groundwater Management Act: A handbook to understanding and implementing the law*. Sacramento, CA.

This page is left blank intentionally.

Chapter 2: History of water and refuge management in California

Sixteen scenarios are analyzed using CALVIN to capture and quantify the hydrologic and economic implications of evolving climatic and management conditions on refuge water deliveries. These scenarios include (1) climate vulnerability: historical and warm-dry climates; (2) Delta regulations: high and existing Delta Outflows; (3) infrastructure: with and without peripheral tunnels; and (4) groundwater management: with and without long-term overdraft (*Table 1-1*). Chapter 2 provides background information on scenarios included in this analysis. This chapter is divided into two major sections: water resource management in California and Central Valley refuge management. Each section begins with a summary of historical management practices followed by challenges and uncertainties of water management.

Water Resource Management in California

Loucks et al. (1981) classifies water resource planning challenges into three broad categories: too much water, too little water, and too dirty water. The history of water resource management in California revolves around simultaneously planning for these three challenges while meeting the demands of "desired quantity and quality of water at particular locations and times" (1981).

Disparity between supply and demand

California has an arid to semi-arid Mediterranean climate. Precipitation falls between October and April, with half occurring from December through February. Rest of the year receives relatively little precipitation (DWR, 2003). On average, state receives about 200 MAF of water per year in form of rainfall and snow. About 65 percent of precipitation evaporates or is transpired by natural vegetation. The remaining 35 percent becomes streamflow runoff and aquifer recharge which is managed for agricultural, urban and environmental demands (Littleworth & Garner, 2007; Lund *et al.*, 2009). While statewide average annual rainfall is 23 inches, the range of annual rainfall varies from more than 140 inches in north-west to less than 4 inches in the south (*Figure 2-1*; Littleworth & Garner, 2007). *Figures 2-2* and *2-3* plot unimpaired runoff volume from state's two major river systems, Sacramento River and San Joaquin River for the entire period of historic record. Outflows from the Sacramento River vary between 5 MAF (1977) and 37 MAF (1983). Similarly, outflows from San Joaquin River system vary from 1 MAF (1977) to 15 MAF (1983). Bar colors correspond to five different Water Year[2] type classifications – wet, above normal, below normal, dry and critical – which represent the contemporary hydrologic conditions. In the last half century, California has experienced five prolonged droughts interspersed with five major flood events of 1983, 1986, 1995, 1997 and 2006 (*Figure 2-4*). In a given year, water managers are often faced with one of the two problems: not enough water to meet all demands or too much water that could cause flood damage. As a result of spatial, seasonal and inter-annual variability in precipitation, it is not uncommon for California's water managers to be preparing for flood and drought at the same time.

[2] California Department of Water Resources defines of Water Year as October of previous calendar year to September of current calendar year.

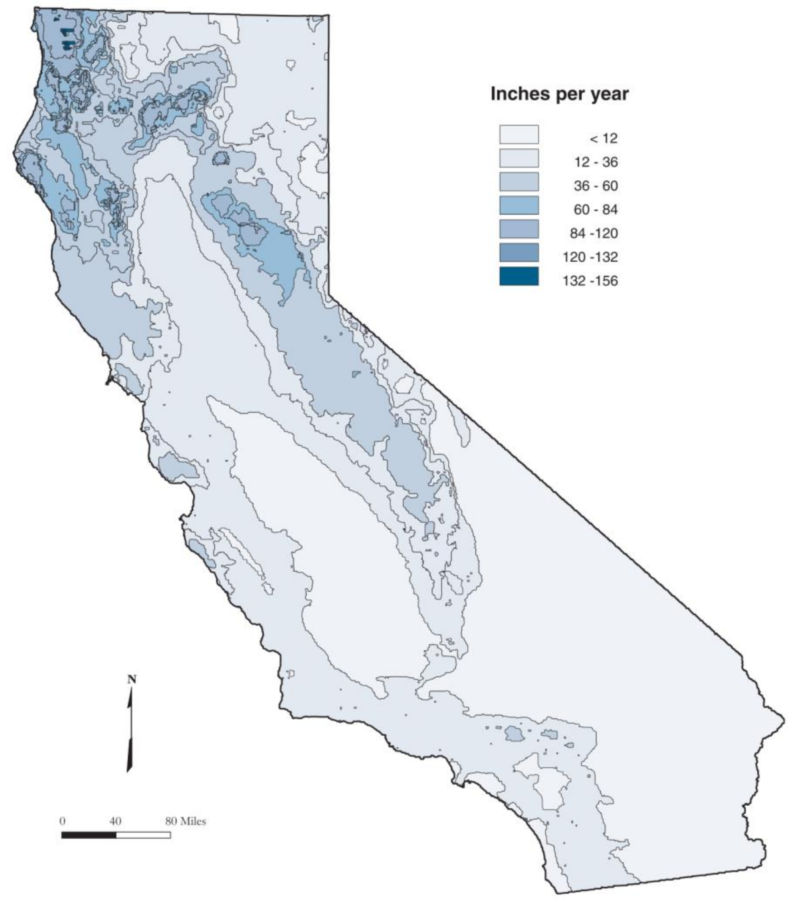


Figure 2-1. Average Annual Precipitation between 1961 – 1990 (DWR, 2003)

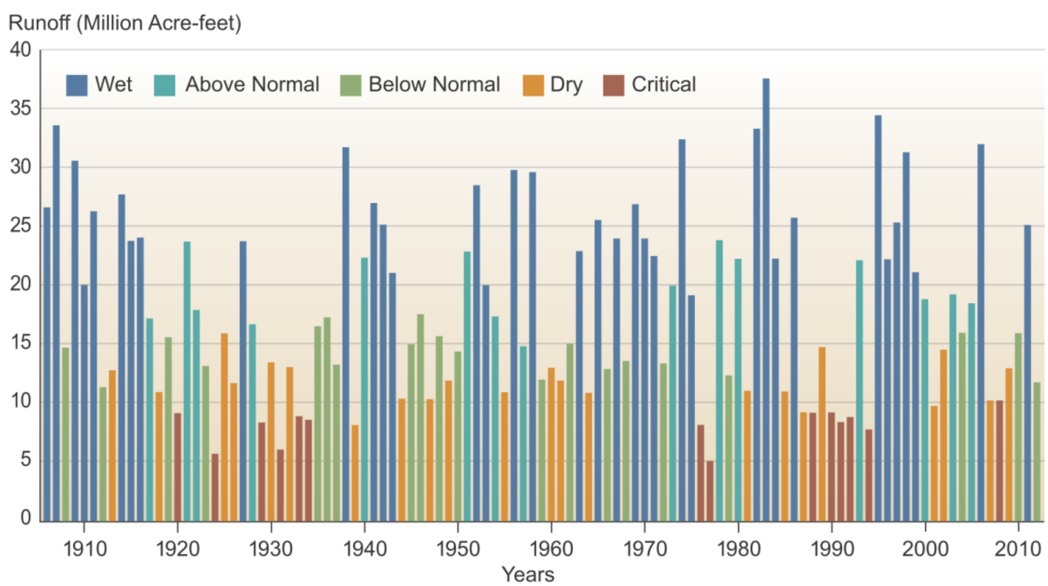


Figure 2-2. Unimpaired Runoff from the Sacramento River System, 1906 – 2012 (DWR, 2014)
Note: Runoff is calculated aggregate unimpaired flow of Sacramento River near Red Bluff, Feather River inflow to Lake Oroville, Yuba River at Smartville, and American River inflow to Folsom Lake.

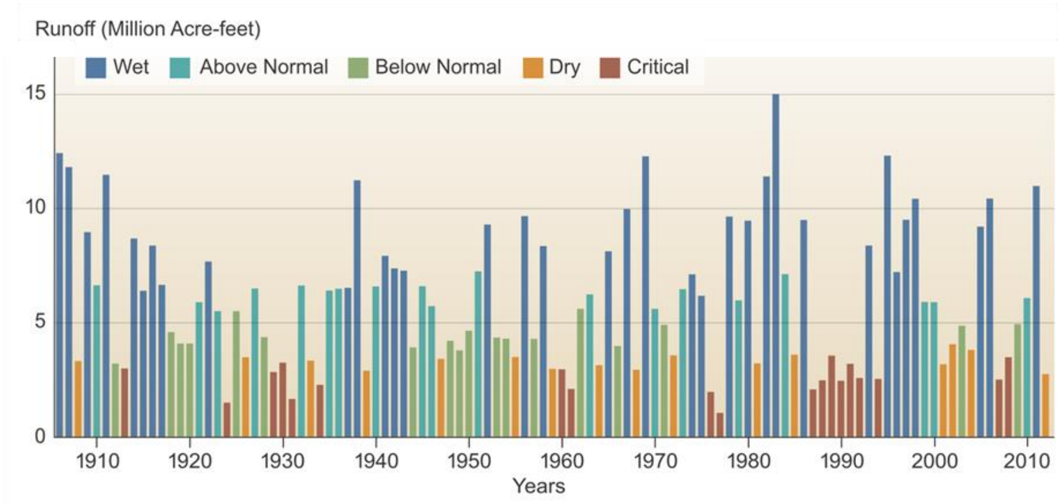


Figure 2-3. Unimpaired Runoff from the San Joaquin River System, 1906 – 2012 (DWR, 2014)

Note: Runoff is calculated aggregate unimpaired flow of Stanislaus River inflow to New Melones Reservoir, Tuolumne River inflow to New Don Pedro, Merced River inflow to New Exchequer Reservoir, and San Joaquin River inflow to Millerton Reservoir.

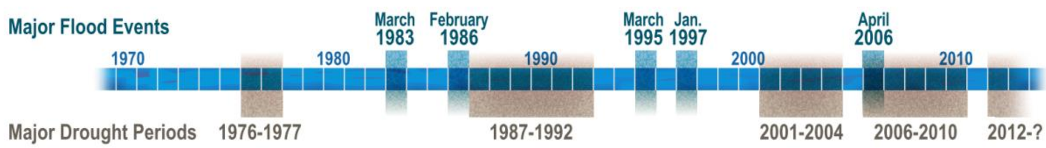


Figure 2-4. Extreme hydrologic events in California, 1970 - 2012 (DWR, 2014)

The most noticeable topographic features in California are the Coast Ranges on the west, Sierra Nevada mountain range on the east, and the alluvial valley floor called Central Valley that spans between the two mountain ranges (*Figure 2-5*). The Central Valley is separated into two major river systems, south flowing Sacramento River and north flowing San Joaquin River. The Sacramento River is single most significant water supply source in California contributing about 70 percent of state's average annual runoff (DWR, 2003). However, much of the demand exists outside the Sacramento Valley. Most of California's population resides along the coast and in Southern California, and most agriculture is in drier parts of the state, such as the San Joaquin Valley, Tulare Basin and desert regions of Southern California (Bachman *et al.*, 2005). Not only is there spatial mismatch between areas of supply and areas of demand, there is also temporal disconnect between periods of supply and period of peak demand. While most of the precipitation occurs between October and April, peak water demand is during summer (DWR, 2014).

History of water management

These limitations of geographic, seasonal and climatic variability led to development of intricate system of reservoirs, canals and pipelines under federal, state and local projects during the 20th century (*Figure 2-6*). Several major local water supply projects were completed during the first half of the 20th century including Hetch Hetchy Aqueduct, Mokelumne Aqueduct, Los Angeles Aqueduct and Colorado

River Aqueduct. Although these local projects secured reliable water supplies for urban areas, irrigated agriculture continued to rely on seasonal surface water supplies and groundwater pumping to meet its demands. Agriculture expanded drastically following the invention of centrifugal pumps in early 1900s which made it economically feasible to drill deeper. Uncontrolled groundwater pumping led to steady decline in the groundwater levels. By 1930s, farmers started looking for reliable surface water. The drought of 1928 – 1934 brought urgency to the problem as many wells went dry which resulted in construction of Central Valley Project (CVP) by US Bureau of Reclamation (USBR). CVP delivers about 7 MAF of water; more than 85 percent goes to agriculture in the San Joaquin Valley and Tulare Basin (Littleworth & Garner, 2007). Following the CVP, the state funded its own water supply project, State Water Project (SWP), with primary purpose of storing and distributing water statewide while providing flood control, recreation and hydropower generation. SWP has contracts to deliver 4.2 MAF of water; however, the project was never fully constructed and has dependable yield of only 2.8 MAF (DWR, 2014). Unlike the CVP, 70 percent of SWP water is delivered to urban areas (Bachman *et al.*, 2005).

Both the rivers merge at Sacramento-San Joaquin Delta (Delta), about 40 miles southwest of Sacramento, and drain westward into the Pacific Ocean. The Delta is an integral component of SWP and CVP projects; both projects rely on through Delta conveyance to move water from north to south. Flood flows and snowmelt runoff are captured in the rim dams in the foothills of the Sierras. Water from the rim dams is released into the Sacramento River to meet urban, agricultural and environmental demands within the Sacramento Valley and Delta. A portion of the leftover water is diverted into the Central Delta via the Delta Cross Channel, and pumped via Banks and Tracy pumping plants to meet urban and agricultural uses south of the Delta. Since both projects manage Sacramento River flows that would have otherwise flowed out to the Pacific Ocean, current operations of SWP and CVP create a direct competition for water between urban, agricultural and refuge uses, freshwater and anadromous fish habitat, and Delta water quality. Both, freshwater and anadromous, fish species are protected under Endangered Species Act (ESA) and California Endangered Species Act (CESA). As a result, operations of both projects have been modified to reduce environmental and water quality impacts of SWP and CVP operations. *Table 2-1* lists key regulatory constraints affecting the operations of major water supply projects in California. Environmental objectives are met by maintaining minimum threshold of in-stream flows, Delta Outflows and/or reservoir storage levels; limiting SWP and CVP exports; and placing maximum salinity standards at key locations within the Delta (DWR, 2015). These regulatory constraints vary by hydrologic conditions and time of the year. A peripheral conveyance has been discussed since the 1940s to bypass water around the Delta rather than through the Delta (Lund *et al.*, 2010). Proponents argue that bypassing the Delta will reduce stress on Delta levees which are vulnerable to floods and earthquakes, and provide better management of fish habitat and Delta water quality. The most recent effort is the development of Bay Delta Conservation Plan (BDCP) which proposes a dual conveyance system – through Delta and peripheral tunnels – to deliver water to Banks and Tracy pumping plants to be ultimately delivered to urban and agricultural users, and refuges south of the Delta. The process began in 2006. A state mandated Environmental Impact Report (EIR) and federally mandated Environmental Impact Statement (EIS) were released late 2013 and 2015 for public review (DWR, 2015). Two infrastructure set-ups are examined in this study to assess the impact of peripheral tunnels on refuge management. See *Scenarios* section of Chapter 3 for details.

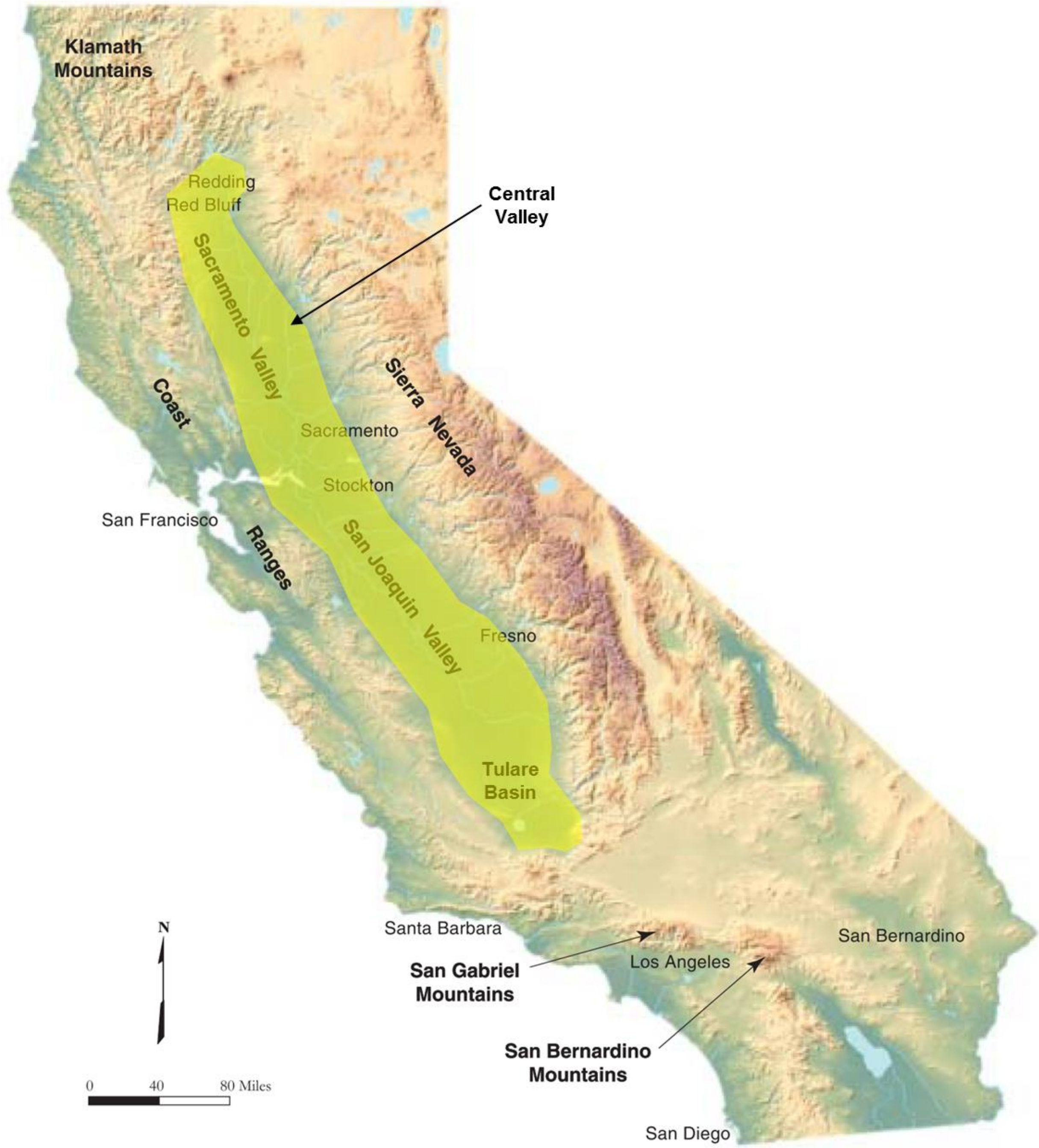


Figure 2-5. Topographic map of California (DWR, 2003)

Despite the challenges, California's water supply projects have mostly met their primary goals of providing reliable water supply for urban and agricultural use. Population grew from 30 million in 1990 to 37.3 million in 2010. Inflation-adjusted gross revenue for all of California's agriculture increased by 80 percent between 1967 and 2010, from $20.8 billion (in 2010 dollars) to $37.5 billion. California is one of the most productive agricultural regions the world. Nine of the top ten most productive agricultural counties in US are in Central Valley which generates 12 percent of the total US agricultural revenue (DWR, 2014). These successes, however, have come at a cost to the environment and state's groundwater resources. Changing climatic conditions, population growth and shifts towards high-value crops are expected to place additional stresses on system and exacerbate competition for water among urban, agricultural and environmental interests.

Figure 2-6. Map of California's major rivers and water supply facilities (DWR, 2014)

Table 2-1. Summary of key environmental regulatory constraint affecting California's water supply project operations (DWR & USBR, 2002; Ferreira et al., 2002)

River/ Watershed	Project Impacted	Location	Source
Trinity River	CVP	Minimum Flow below Lewiston Dam	Trinity EIS Preferred Alternative
		Trinity Reservoir End-of-September Minimum Storage	*(Same)*
Clear Creek	CVP	Minimum Flow below Whiskeytown Dam	Downstream water rights, 1963 USBR Proposal to USFWS and NPS, and USFWS discretionary use of CVPIA 3406(b)(2)
Upper Sacramento River	CVP	Shasta Lake End-of-September Minimum Storage	SWRCB WR 1993 Winter-run BiOp
		Minimum Flow below Keswick Dam	Flows for SWRCB WR 90-5 and 1993 Winter-run BiOp temperature control, and USFWS discretionary use of CVPIA 3406(b)(2)
Feather River	SWP	Minimum Flow below Thermalito Diversion Dam	1983 DWR, DFW Agreement
		Minimum Flow below Thermalito Afterbay outlet	*(Same)*
Yuba River		Yuba River at Marysville	SWRCB D-1644
		Yuba River at Smartville	*(Same)*
American River	CVP	Minimum Flow below Nimbus Dam	SWRCB D-893, and USFWS discretionary use of CVPIA 3406(b)(2)
		Minimum Flow at H Street Bridge	SWRCB D-893
Lower Sacramento River	SWP/CVP	Minimum Flow near Rio Vista	SWRCB D-1641
Mokelumne River		Minimum Flow below Camanche Dam	FERC 2916-029, 1996 (Joint Settlement Agreement)
		Minimum Flow below Woodbridge Diversion Dam	*(Same)*
Stanislaus River		Minimum Flow below Goodwin Dam	1987 USBR, DFW agreement, and USFWS discretionary use of CVPIA 3406(b)(2)
		Minimum Dissolved Oxygen	SWRCB D-1422
Merced River		Minimum Flow below Crocker-Huffman Diversion Dam	Davis-Grunsky (180 – 220 CFS, Nov – Mar), and Cowell Agreement
		Minimum Flow at Shaffer Bridge	FERC 2179
Tuolumne River		Minimum Flow at Lagrange Bridge	FERC 2299-024, 1995 (Settlement Agreement)
San Joaquin River		Maximum Salinity near Vernalis	SWRCB D-1641
		Minimum Flow near Vernalis	*(Same)*
Sacrameto River-San Joaquin River Delta	SWP/CVP	Minimum Required Delta Outflow for flow and salinity control	SWRCB D-1641, 2008 USFWS Bilogical Opinion, and 2009 NMFS BiOp
		Delta Cross Channel Gate Operation	*(Same)*
		Delta Exports	SWRCB D-1641, , 2008 USFWS Bilogical Opinion, 2009 NMFS BiOp, and USFWS discretionary use of CVPIA 3406(b)(2)
Mono Basin	Los Angeles Aqueduct	Aggregate of Rush, Parker, Walker and Lee Vining Creeks	SWRCB D-1631
Owens Valley	Los Angeles Aqueduct	Dust Mitigation Requirements	Great Basin Unified Air Pollution Control District, 1998

Abbreviations

BiOp	*Bilogical Opinion*
CVP	*Central Valley Project*
CVPIA	*Central Valley Project Improvement Act*
DFW	*Department of Fish and Wildlife, California*
DWR	*Department of Water Resources, California*
EIS	*Environmental Impact Statement*
FERC	*Federal Energy Regulatory Commission*
NMFS	*National Marines Fisheries Service*
SWP	*State Water Project*
SWRCB D-xxx	*State Water Resource Control Board Water Right Decision xxx*
USBR	*U.S. Bureau of Reclamation*
USFWS	*U.S. Fish and Wildlife Service*

Challenges

Water resource management challenges can be broadly separated into four categories: 1) population growth and land-use development; 2) groundwater overdraft in the Central Valley; 3) uncertain Delta regulations; and 4) climate change.

Population growth and land-use development

The California Water Plan (CWP) Update 2013 assessed nine different combinations of population growth and land-use development trends. Three population growth scenarios – low, current trend and high growth – were paired with three land-use development scenarios – slow, current trend and fast development. *Figure 2-7* shows the variability in irrigated crop area and population growth projected to 2050 for the nine different scenarios. Under all scenarios, California's population is expected to grow. Projected population increase varies from 7.8 million (22 percent) to 33.3 million (92 percent) compared to 2006 population of 36.1 million. Assuming current population growth and land-use development trends, California's population is expected to grow from 36.1 million in 2006 to 51.0 million (40 percent increase) by 2050. Subsequently, urban footprint is expected to increase from 5.2 million acres to 6.7 million acres (29 percent). Irrigated acreage is expected to decline regardless of the growth scenario. Under current population growth and land-use development trend, irrigated acreage is projected to decrease from 8.7 million acres in 2006 to 8.2 million acres (5 percent decline) by 2050. Even though irrigated acreage is declining, recent shift in cropping trends from low-value seasonal crops to high-value perennial crops like vines and orchards is expected to continue into the future (DWR, 2014). Unlike seasonal crops, perennial crops require more reliable inter-annual water supplies; therefore, reduce the system's flexibility to respond to extreme events. 2050 population and land-use projections are used in this study. See *Scenarios* section of Chapter 3 for details.

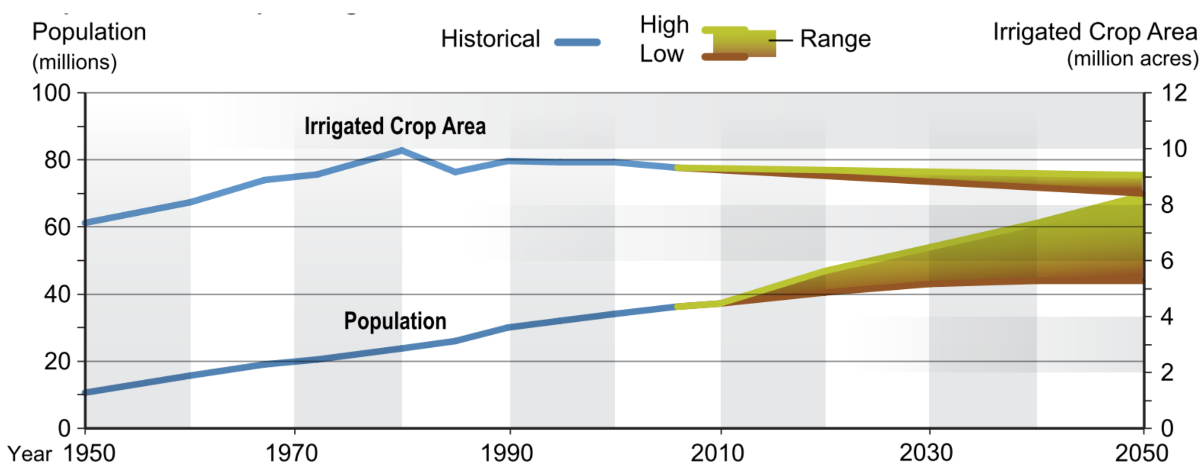


Figure 2-7. Historic and projected population growth and irrigated crop acreage, 1950 - 2050 (DWR, 2014)

Groundwater overdraft in Central Valley

Even with the intricate system of managing highly variable surface water supplies, the present growth could not be possible without harnessing state's groundwater. California is the nation's single largest groundwater user and accounts for 20 percent of groundwater extracted in the entire country. Groundwater is 40 percent of state's water supply in an average year and exceeds 60 percent in dry years. Some urban and agricultural communities depend entirely on groundwater for water supply. Overreliance on groundwater has resulted in overdraft: a net deficit in long-term groundwater storage. DWR estimates long-term annual rate of overdraft to be 1 – 2 MAF/yr in the Central Valley. A more recent study conducted by National Aeronautics and Space Administration (NASA)/ German Aerospace Center Gravity Recovery and Climate Experiment (Grace) revealed an even drastic decline in groundwater storage. The study estimates that between 2003 and 2009, the Central Valley groundwater aquifers and its water sources lost 26 MAF of water, that is, 3 – 4 MAF/yr or double the historic overdraft rate. Issues of overdraft led to discussions about statewide groundwater regulation. In September 16, 2014, Sustainable Groundwater Management Act (SGMA) – Senate Bill 1168, Assembly Bill 1739, and Senate Bill 1319 – was signed into law with intent to sustainably manage state's groundwater resources. The Act defined sustainable groundwater management as, "management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results." Undesirable results include: 1) chronic long-term lowering of groundwater levels, 2) significant and unreasonable reductions in groundwater storage and interconnected surface water sources, seawater intrusion, degradation of water quality, and land subsidence such that it interferes with overlying land-use (WEF, 2015). To assess the impacts of SGMA on refuge management, two groundwater overdraft scenarios are analyzed in this study. See *Scenarios* section of Chapter 3 for details.

Uncertain Delta regulations

The Endangered Species Act of 1973 (ESA) provided protection for endangered and threatened wildlife species as well as the ecosystems that these species depend on. Endangered species include species "in danger of extinction", and threatened species include species "likely to become endangered in the foreseeable future" (USFWS, 2013). The act assigned the responsibility for terrestrial and freshwater organisms to the US Fish and Wildlife Service (USFWS), and for marine wildlife, including anadromous fish, to the National Marines Fisheries Service (NMFS). Several endangered and threatened species depend on the Delta. As a result, both, USFWS and NMFS have issued several Biological Opinions (BiOps) since 1990s which affect SWP and CVP operations. BiOp provisions have become increasing restrictive over the years. Most recent BiOps were issued in 2004 by NMFS and 2005 by USFWS providing protection for anadromous fish – winter-run and spring-run Chinook salmon, steelhead, green sturgeon and killer whales – and delta smelt, respectively. The original BiOps were reviewed and updated in 2008 by USFWS and 2009 by NMFS. Both the BiOps were challenged in the federal court on various grounds including agencies' failure to use best available science to develop the BiOps. SWP and CVP operations are currently managed under the BiOps provisions; however, the future of these regulations remains uncertain (DWR, 2014). Two types of Delta regulations – high outflow/ low exports and existing outflows and exports – are included in the analysis to examine the impacts of stringent Delta regulations on refuge management. See *Scenarios* section of Chapter 3 for details.

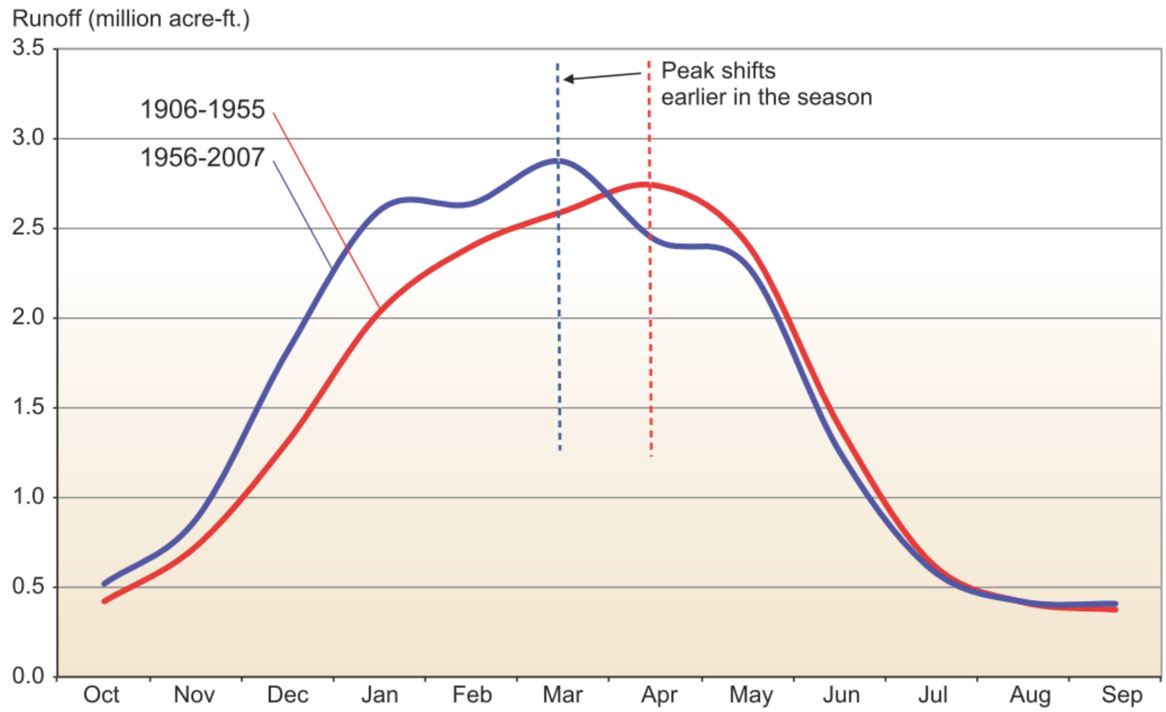


Figure 2-8. Monthly average runoff of Sacramento River system, 1906 - 2007 (DWR, 2014)

Climate change

Overlying these challenges is the concern about climate change and its impact on California's hydrology. Historical trends indicate that climate has been evolving over the past century. According to Western Regional Climate Center, California has experienced an increase of 1.1 to 2 degree Fahrenheit or 0.6 to 1.1 degree Celsius in the past century (Abatzoglou *et al.*, 2009). As a result, precipitation has shifted from snow to rainfall runoff. *Figure 2-8* compares average monthly runoff in the Sacramento River watershed between 1906-1955 and 1956-2007. The shifting trend provides a glimpse of anticipated effects of climate on California's hydrology: 1) the timing of peak monthly flow shifted nearly a month earlier in the year which indicates earlier snowmelt; and 2) two distinct peak flows begin to emerge in the latter half of the century representing the transition in precipitation from snowpack to rainfall runoff (DWR, 2014).

These hydrologic trends are at direct odds with current water management practices. Much of state's infrastructure was designed to capture the slow spring runoff and deliver it during summer and fall (DWR, 2014). Reservoirs are drawn down ahead of the flood season to provide flood protection to downstream communities. Some flood flows are captured for use in summer; however, the focus is on flood protection and safely routing the flows through the system during the winter. Spring snowmelt runoff replenishes surface water reservoirs and aquifers ahead of the summer months. Surface water and groundwater resources are conjunctively managed to meet the urban, agricultural and environmental demands throughout spring, summer and fall. These trends shorten the window to store surface water runoff, limit opportunities for natural groundwater recharge from snowpack and extend the temporal gap between peak water supply and peak demand. Warmer temperatures also increase evaporation losses from reservoirs, lakes and rivers.

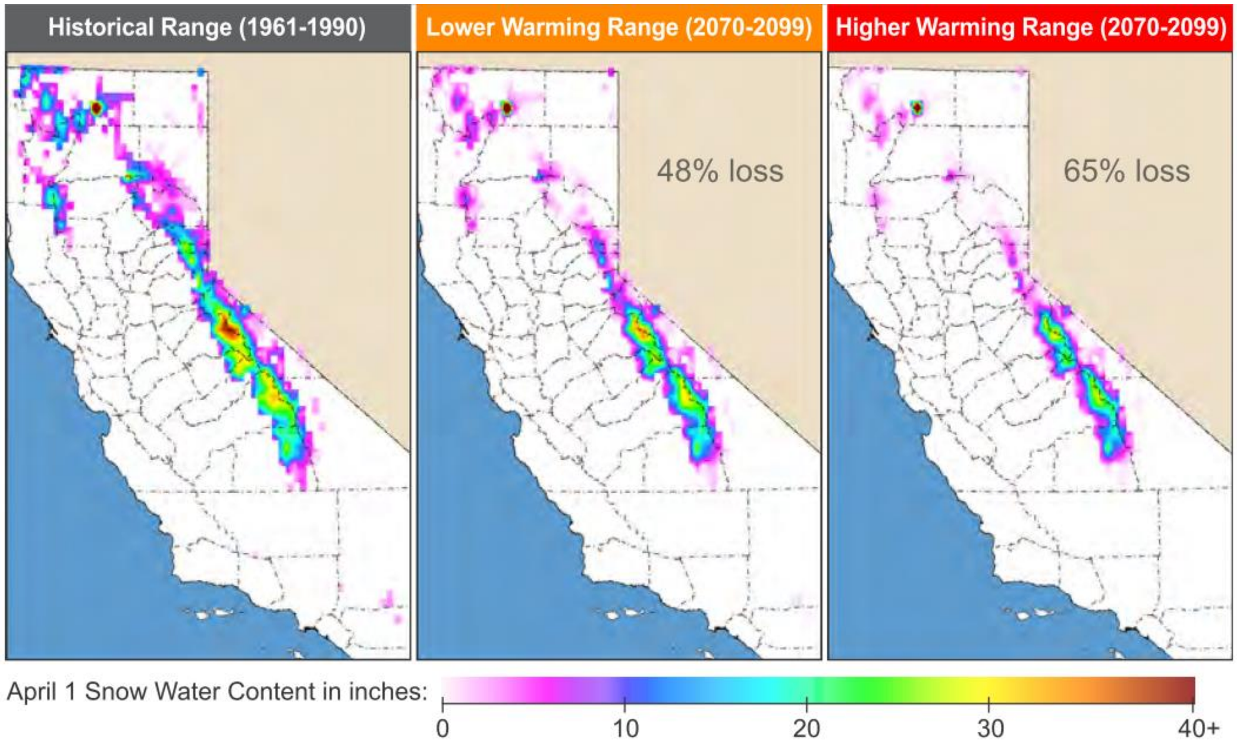


Figure 2-9. Effect of climate change on snowpack in Sierra-Nevada (DWR, 2014)

While observed trends indicate that California's climate is already changing, future climate change is anticipated to bring more dramatic changes. A study by Scripps Institute of Oceanography indicates an increase in mean temperature by 3.4 to 4.9 degree Fahrenheit (1.9 to 2.7 degree Celsius) across the state by 2060-2069 compared to 1985-94. Seasonal trends indicate more increase in the summer (4.1 to 6.5 degree Fahrenheit or 2.3 to 3.6 degree Celsius) than the winter months (2.7 to 3.6 degree Fahrenheit or 1.5 to 2.0 degree Celsius) (Pierce *et al.*, 2012). Another study by Scripps Institute of Oceanography finds that Sierra snowpack may reduce by 48 – 65 percent by the end of this century compared to the 1961-1990 average (*Figure 2-9*, Pierce & Cayan, 2013). Although climate change models ubiquitously predict increase in temperatures statewide, not all models are in agreement on precipitation projections. Most models anticipate drier conditions in southern California, and warmer, heavier bursts of precipitation without net increase in average total precipitation in northern California (Pierce *et al.*, 2012). To determine the impacts from climate change, warm-dry climate scenario is included in this study. See *Scenarios* section of Chapter 3 for details.

Summary

In a nutshell, climate change will limit state's ability to manage water, reduce total volume of water available for use and intensify competition for water, especially during summer and fall. Environmental water supplies are retained in reservoirs and released throughout spring, summer, and fall to maintain habitat for aquatic species. Currently, any requirements unmet by reservoir releases are met by reducing Delta exports. Climate change is likely to further reduce supplies available for import through SWP and CVP during non-winter months to meet water needs south of the Delta. (Cayan *et al.*, 2008; Hayhoe *et al.*, 2004). Historically, reduction in surface water supplies is substituted with groundwater pumping. Chronic overdraft and the provisions under SGMA will limit pumping opportunities. While growing population and expanding urban footprint will increase urban water demand, agricultural water demand is projected to have a mixed response. Declining irrigated crop acres will lower agricultural water demand; however, shift towards perennial, high-value crops will reduce flexibility to respond to extreme hydrologic events by reducing the agricultural land available for flooding or fallowing.

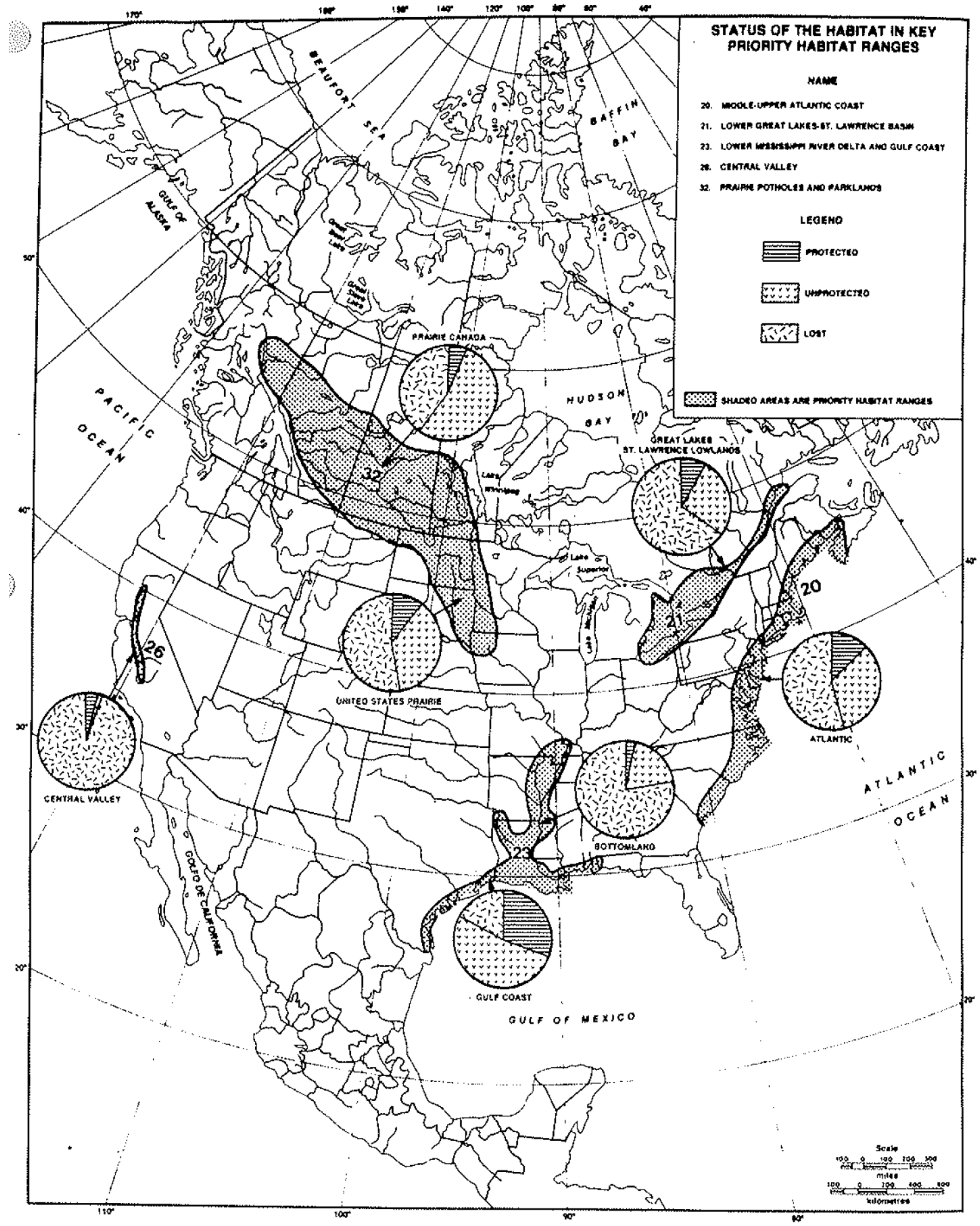


Figure 2-10. Status of wintering waterfowl habitat in priority breeding and nesting areas in North America continent (CVHJV, 1990)

Refuge Management in California

Wetlands – regions along natural streams seasonally inundated from flood flows – in the Central Valley of California are considered the most important wintering waterfowl area on the Pacific Flyway. These wetlands support about 60 percent of the total Pacific Flyway waterfowl population and more than 65 percent of pintail ducks in the entire US. In addition to waterfowl, wetlands along with adjacent riparian and uplands areas provide habitat for many species of plants, animals and birds. Several state and federally recognized threatened and endangered species – such as southern bald eagle, peregrine falcon, delta green beetle, greater sandhill crane, and giant garter snake – are also found in these wetlands, and associated riparian and upland habitats (CVHJV, 1990). About 70% of these wetlands are under private ownership; one-third of which are part of the Grasslands Resource Conservation District in the San Joaquin Valley. The remaining 30% are managed almost equally by federal, US Fish and Wildlife (USFWS), and state, California Department of Fish and Wildlife (CDFW), agencies (CVHJV, 1990; CVJV, 2006). *Figure 1-1* shows the geographic location of publically owned and managed wetlands in the Central Valley. National Wildlife Refuges (NWRs) are federally managed; Wildlife Areas (WAs) are state managed; and Resource Conservation District (RCD) is privately owned and managed wetlands.

History of refuge management

At the time of Gold Rush, more than 4 million acres of wetlands and 6,000 miles of riparian habitat existed in the Central Valley (CVHJV, 1990; CVJV, 2006). Estimates suggest that these wetlands supported 20 to 40 million waterfowl annually. *Figure 2-10* compares lost, protected, and unprotected wetlands in the North American continent in 1990. By far, the Central Valley has experienced the largest loss of wetland acreage. Discovery of gold followed by population boom and irrigated agriculture expansion led to permanent conversion of 95 percent of wetlands into agricultural and urban land (*Figure 2-11*). Moreover, construction of levees along the rivers for flood control purposes reduced the riparian habitat to less than 950 miles (CVHJV, 1990). As a result, by the 1970s waterfowl population were down to 6 to 7 million and declined still more in the 1980s. Today, just over 205,500 acres of managed wetlands remain in the Central Valley which along with adjacent riparian and upland habitat areas provide habitat for 5.5 million waterfowl annually (CVJV, 2006).

Publically managed refuges were established in the Central Valley of California as early as 1930s to provide wetland and waterfowl protection (*Table 2-2*). With the exception of Volta Wildlife Area (WA) in San Joaquin Valley, publically managed refuges were first established in the Sacramento Valley between 1930s and 1940s, followed San Joaquin Valley and Tulare Basin in 1950s, 1960s and 1990s. These refuges were primarily managed as wildlife sanctuaries through early 1950s. In 1948, the Lea Act was passed to fund purchase and management of state and federal public lands to attract waterfowl away from the adjacent agricultural lands. The Lea Act expanded refuge management scope to reduce crop depredation in addition to protecting wetlands and providing a sanctuary for wintering waterfowl. In 1953, publically managed wildlife refuges were enrolled in the Pittman-Roberson Program which further expanded management objectives to provide public hunting opportunities (USBR, 2010a-b; USBR 2011a-l). Finally, passage of Endangered Species Act (ESA) and California Endangered Species Act (CESA) in 1973 and 1977, respectively, expanded the responsibilities of USFWS and CDFW to conserve endangered and threatened aquatic and terrestrial wildlife species in addition to the waterfowl population.

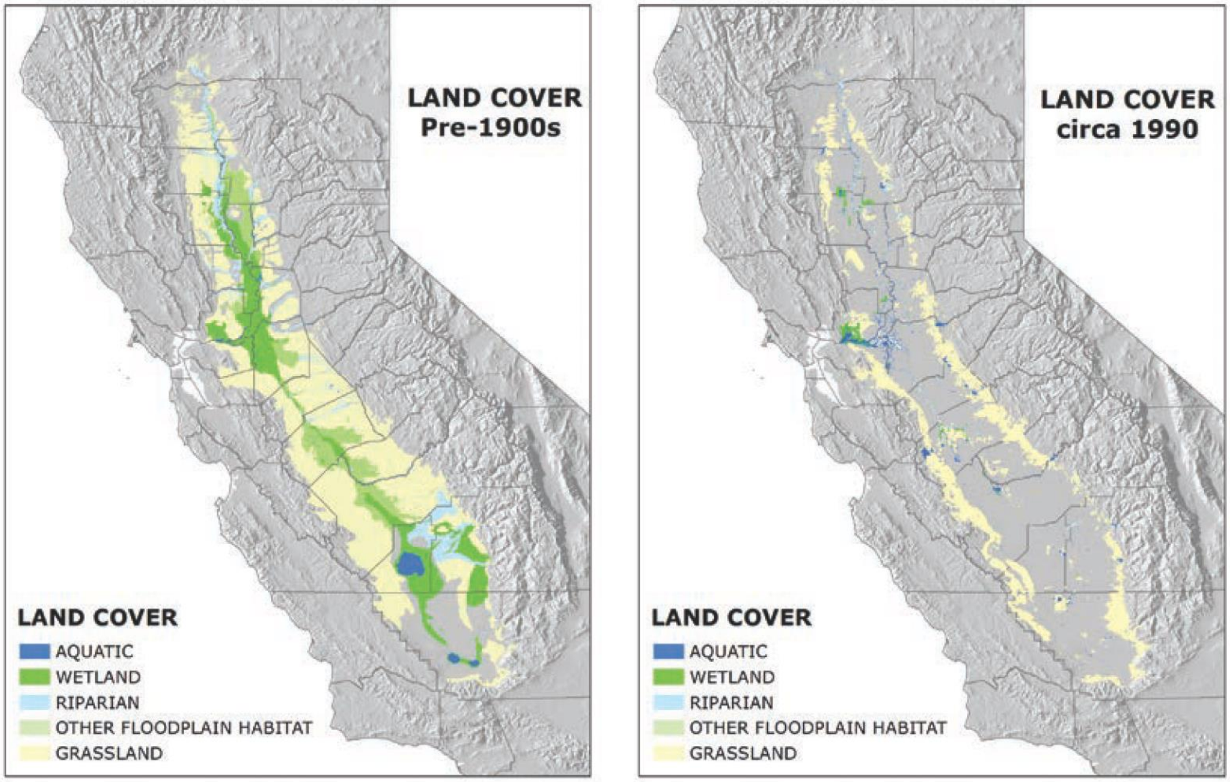


Figure 2-11. Land area of Central Valley wetlands and associated habitats before in 1900 (left) and in 1990 (right) (CVJV, 2006)

Prior to CVPIA, these refuges relied on agricultural return flow and surplus CVP water, when available. The 1976-1977 drought greatly reduced refuge water deliveries and in some cases, even completely eliminated all the deliveries. Drought combined with degrading agricultural return flow water quality led to a series of investigative reports by US Bureau of Reclamation (USBR) (CVJV, 2006). Around that time significant decreases in the North American duck population were also documented as a direct result of loss of wetlands throughout North America. The North American Waterfowl Management Plan (NAWMP), an international treaty, was signed US, Canada and Mexico in 1986 to "restore and maintain the diversity, abundance, and distribution of [wintering] waterfowl [to levels] that occurred in 1970-79" (CVHJV, 1990)[3]. NAWMP developed a framework for recovering waterfowl populations. Although the goals under NAWMP were continental in scope, its success relied on local public and private entities that came together and formulated six Joint Ventures (JVs). In 1988, Central Valley Habitat Joint Venture – later renamed to Central Valley Joint Venture (CVJV) in 2006 – was formed with partnership from California Waterfowl Association, National Audubon Society, The Nature Conservancy, Trust for Public Land, Waterfowl Habitat Owners Alliance, California Department of Fish and Wildlife, and US Fish and Wildlife Service. Original Central Valley waterfowl habitat conservation plan was formulated in 1990 with focus on wintering waterfowl. The plan was later revised in 2006 to broaden the conservation scope to shorebirds, waterbirds and riparian songbirds (CVJV, 2006).

[3] Mexico was not part of the 1986 NAWMP. It joined in as signatory a few years later when NAWMP was revised in 1994.

Table 2-2. Target and historic water deliveries to CVPIA refuges by refuge in acre-feet per year

CVPIA Refuge [a]	Year Established [b]	Full Level 2 [b]		Incremental Level 4 [b]	Full Level 4	
Sacramento Valley		**152,250**	**36%**	**26,750**	**179,000**	**32%**
Sacramento NWR	1937	46,400	11%	3,600	50,000	9%
Delevan NWR	1962	21,950	5%	8,050	30,000	5%
Colusa NWR	1945	25,000	6%	0	25,000	5%
Sutter NWR	1945	35,400	8%	8,600	44,000	8%
Gray Lodge WA	1931	23,500	6%	6,500	30,000	5%
San Joaquin Valley		**259,671**	**61%**	**85,745**	**345,416**	**62%**
Volta WA	1952	13,000	3%	3,000	16,000	3%
Los Banos WA	1929	16,670	4%	8,330	25,000	5%
North Grasslands WA	1990					
China Island Unit		*6,967*	*2%*	*3,483*	*10,450*	*2%*
Salt Slough Unit		*6,680*	*2%*	*3,340*	*10,020*	*2%*
San Luis NWR	1967					
Kesterson Unit		*10,000*	*2%*	-	*10,000*	*2%*
Freitas Unit		*5,290*	*1%*	-	*5,290*	*1%*
San Luis Unit		*19,000*	*4%*	-	*19,000*	*3%*
West Bear Creek Unit		*7,107*	*2%*	*3,603*	*10,710*	*2%*
East Bear Creek Unit		*8,863*	*2%*	*4,432*	*13,295*	*2%*
Merced NWR	1951	13,500	3%	2,500	16,000	3%
Grasslands RCD	1953	125,000	30%	55,000	180,000	32%
Mendota WA	1954	27,594	7%	2,057	29,651	5%
Tulare Basin		**11,230**	**3%**	**19,770**	**31,000**	**6%**
Pixley NWR	1959	1,280	0%	4,720	6,000	1%
Kern NWR	1960	9,950	2%	15,050	25,000	5%

[a] NWR: National Wildlife Refuge; managed by US Fish and Wildlife Service (USFWS)
WA: Wildlife Area; managed by California Department of Fish and Wildlife (CDFW)
RCD: Resource Conservation Districts; managed by private owners
[b] Source: (USBR, 2010a-b; USBR, 2011a-l)

Reports from USBR and NAWMP built enough political pressure to pass the Central Valley Project Improvement Act of 1992 (CVPIA). Section 3406(d)(6) of CVPIA recognized CVP's responsibility to provide water for environmental uses and set aside 800,000 acre-feet of water for environmental obligations, a portion of which was dedicated to securing water supply that is of "suitable quality and is delivered in a timely manner for use…" at state and federally managed refuges, and privately owned wetlands by Grasslands RCD. Grasslands RCD is within the administrative boundaries of Grasslands Water District (GWD) which is one of the several exchange contractors. After USBR finished construction of Friant Dam on the San Joaquin River and began diverting flows into Friant-Kern Canal for agricultural and urban uses in Tulare Basin, flows within the San Joaquin River system reduced significantly. These exchange contractors were instead allocated water from the Delta-Mendota Canal. As part of the settlement contract, Grasslands RCD received 50,000 acre-feet of CVP water for wetlands within GWD and was included in CVPIA. CVPIA established two water delivery levels: *Full Level 2*, "amount of water required for minimum wetland and wildlife habitat management based on historic average annual deliveries before 1989"; and *Full Level 4*, "total amount of water … required for optimum wetland and wildlife habitat development and management" (USDOI, 2014). The difference between Full Level 2 and Full Level 4 is called, *Incremental Level 4* deliveries. Full Level 2 was guaranteed under CVPIA. Incremental Level 4 deliveries were not guaranteed; however, the intent was to acquire these deliveries in 10 percent increments beginning 1993 from willing sellers at the market price (CVJV, 2006).

Table 2-3 enumerates Full Level 2, Incremental Level 4 and Full Level 4 deliveries allocated to CVPIA refuges. San Joaquin Valley refuges were allocated the largest portion; more than 60 percent of Full Level 2 and Full Level 4 water, half of which was allocated to Grasslands RCD. The remaining 39 percent was split between Sacramento Valley refuges and Tulare Basin with Sacramento Refuges getting 92 percent remaining Full Level 2 and 85 percent of the remaining Full Level 4 supplies. Tulare Basin refuges have the least developed water supply. They need to secure roughly double their Full Level 2 supplies to reach full management levels. Sacramento Valley refuges have the most developed and secure water supply; they are only 20 percent short of reaching their full management objective.

Table 2-3. Total target and historic water deliveries to CVPIA refuges by Water Year in acre-feet per year

Water Year	Level 2			Incremental Level 4			Full Level 4		
	Historic [a]	Target [b]	Percent Target Delivered	Historic	Target	Percent Target Delivered	Historic	Target	Percent Target Delivered
2001*	354,746	423,151	84%	62,615 [c]	119,039 [c]	53%	417,361	542,190	77%
2002*	370,342	423,151	88%	79,400	132,265	60%	449,742	555,416	81%
2003*	379,146	423,151	90%	77,471	132,265	59%	456,617	555,416	82%
2004*	372,232	423,151	88%	66,044	132,265	50%	438,276	555,416	79%
2005*	374,417	423,151	88%	82,911	132,265	63%	457,328	555,416	82%
2006	380,073	423,151	90%	89,345	132,265	68%	469,418	555,416	85%
2007	388,525	423,151	92%	45,049	132,265	34%	433,574	555,416	78%
2008	398,010	423,151	94%	37,066	132,265	28%	435,076	555,416	78%
2009	397,239	423,151	94%	41,313	132,265	31%	438,552	555,416	79%
2010	391,587	423,151	93%	71,743	132,265	54%	463,330	555,416	83%
2011	393,508	423,151	93%	99,038	132,265	75%	492,546	555,416	89%
2012	396,129	423,151	94%	51,356	132,265	39%	447,484	555,416	81%
2013	401,205	423,151	95%	42,141	132,265	32%	443,346	555,416	80%
2014[d]	257,847	423,151	61%	18,022	132,265	14%	275,869	555,416	50%
Average [e]	375,358	423,151	89%	61,608	132,265	47%	438,551	555,416	79%

* No Merced NWR historic delivery data available for these Water Years.
[a] Source: Rachael Esralew, USFWS Hydrologist
[b] Source: (USBR, 2010a-b; USBR, 2011a-l)
[c] Central Valley Project Improvement Act of 1992 stipulated that Incremental Level 4 deliveries will increase by 10 percent every water year beginning 1993 and reach 100 percent by 2002. Therefore, the target incremental Level 4 deliveries for 2001 are set at 90 percent.
[d] First year in recorded when the allocations were set below 100 percent.
[e] Incremental and Full Level 4 deliveries averaged over 2002 and 2014.

As a result of dedicated refuge water supply, about 65,200 acres of wetlands have been restored in perpetuity since 1990, increasing wetland acreage from 140,300 acres to 205,500 acres (CVJV, 2006). The 1990 plan set a goal of enhancing 332,300 acres of grain fields and 110,800 acres of upland habitat highlighting that wetlands alone are not enough to provide "food and cover for the desired populations of wintering waterfowl set forth in the NAWMP" (CVHJV, 1990). Grain fields and upland habitats provide food and breeding opportunities for waterfowl. No upland habitat restoration programs have been developed since 1990. Instead, efforts have been focused on improving waterfowl access to grain crops during migration season which corresponds with flooding of rice fields during winter months. Winter flooding of agricultural habitats is estimated to be over 384,000 acres, 52,000 acres above the 1990 objective. More than 90 percent of the habitat is provided by flooded rice fields.

Challenges

Even though CVPIA provided reliable water supplies for wetland management, the original targets have not yet been attained (*Table 2-3*). Long-term average of Level 2 deliveries and Incremental Level 4 is at 89 percent and 47 percent, respectively. Regulations passed under the auspice of Endangered Species Act curtailed the amount of water that can be exported south of the Delta which greatly increased demand for water in San Joaquin Valley and Tulare Basin, and reduced opportunities for exporting surplus water supplies. As a result, the cost of acquiring water escalated since 1990 and budgetary constraints prevent USBR from acquiring supplies to meet Full Level 4 delivery targets (CVJV, 2006). This creates an uncertain environment around long-term reliability and affordability of water supplies essential for meeting wetland management objectives. Another critical challenge comes from declining irrigated crop acreage (DWR, 2014). Wetlands rely on surrounding grain crops to provide food for wintering waterfowl. California's Central Valley ranks first among the twenty most threatened farming regions in US; is projected to lose nearly one million acres of agricultural land (CVJV, 2006). Loss of irrigated farmland will reduce food and habitat available for waterfowl which will place greater stress on managed wetlands. Finally, water quality could emerge as a challenge to refuge management in the near future. Managed wetland drainage flows are currently waived from meeting water quality standards under the Irrigated Lands Conditional Waiver Program. However, Regional Water Quality Control Boards (RWQCBs) are considering load restrictions for managed wetlands which would limit the concentration of mercury, salt and boron in the discharge flows (2006). Wetlands are usually located at the tail end of the delivery system; their water supplies are already diluted with agricultural return flows. Regulation of drainage flows from managed wetlands will require the refuge managers to be considerate of water quality of supply sources as well which will further limit the opportunities for securing reliable water supplies.

References

Abatzoglou J. T., Redmond, K. T. & Edwards, L. M. (2009). Classification of regional climate variability in the State of California. *Journal of Applied Meteorology and Climatology, 48*, 1527-1541.

Bachman, S., Hauge, C., McGlothlin, R., Neese, K., Parker, T., Saracino, A., Slater, S. (2005). *California groundwater management: A resource for future generations* (2nd ed.). Sacramento, CA: Groundwater Resources Association of California.

Cayan D. R., Maurer, E. P., Dettinger, M. D., Tyree, M., Hayhoe, K. (2008). Climate change scenarios for the California region. *Climatic Change, 87*(1), 21-42.

Central Valley Habitat Joint Venture (CVHJV). (1990). *Central Valley Habitat Joint Venture implementation plan: A component of the North American Waterfowl Management Plan*.

Central Valley Joint Venture (CVJV). (2006). *Central Valley Joint Venture implementation plan: Conserving bird habitat*. Sacrament, CA: U.S. Fish and Wildlife Service.

Department of Water Resources, California (DWR) & U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2002). *Benchmark Studies Assumptions and Appendices*. Retrieved from http://baydeltaoffice.water.ca.gov/modeling/hydrology/CalSim/Downloads/CalSimDownloads/CalSim-IIStudies/Benchmark/index2.cfm.

Department of Water Resources, California (DWR). (2003). *California's Groundwater: Bulletin 118 Update 2003*. Sacramento, CA.

Department of Water Resources, California (DWR). (2014). *California Water Plan Update 2013 Bulletin 160-13: Investing in innovation and infrastructure* (Vol. 1). Sacramento, CA.

Department of Water Resources, California (DWR). (2015). *State Water Project Final Delivery Capability Report 2015*.

Ferreira, I. C. & Tanaka, S. K. (2002). Appendix E: Environmental flow constraints. In *Climate warming and California's water future* (Report). Sacramento, CA: California Energy Commission.

Hayhoe K., Cayan, D., Field, C. B., Frumhoffe, P. C., Maurer, E. P., Miller, N. L., … Cleland, E.E. (2004). Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Science, 101*(34), 12422–12427.

Littleworth, A. L. & Garner, E. L. (2007). *California Water II* (2nd ed.). Point Arena, California: Solano Press Books.

Loucks, D. P., Stedinger, J. R. & Haith, D. A. (1981). *Water resources systems planning and analysis*. Englewood Cliffs, New Jersey: Prentice-Hall.

Lund, J.R., Howitt, R. E., Medellin-Azuara, J., & Jenkins, M.W. (2009). Water management lessons for California from statewide hydro-economic modeling: A Report for the California Department of Water Resources. In *California Water Plan Update 2009* (Vol. 4).

Pierce, D. W., Das, T. Cayan, D. R., Maurer, E. P., Miller, N. L., Bao, Y., … Tyree, M. (2012). Probabilistic emissions of future changes in California temperature and precipitation using statistical and dynamical downscaling. *Climate Dynamics*, *40* (3), 839-856.

Pierce, D. W. & Cayan, D. R. (2013). The uneven response of different snow measures to human-induced climate warning. *Journal of Climate, 26*, 4148-4167.

U.S. Department of Interior (USDOI). 2014. *Central Valley Project Improvement Act Public Law 102-575: Annual Report Fiscal Year 2013*.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010a). *Merced National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010b). *San Luis National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011a). *Colusa National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011b). *Delevan National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011c). *Grasslands Resource Conservation District Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011d). *Gray Lodge Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011e). *Kern National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011f). *Los Banos Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011g). *Mendota Pool Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011h). *North Grasslands Wildlife Area China Island Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011i). *North Grasslands Wildlife Area Salt Slough Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011j). *Pixley National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011k). *Sacramento National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011l). *Volta Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

Water Education Foundation (WEF). (2015). *The 2014 Sustainable Groundwater Management Act: A handbook to understanding and implementing the law*. Sacramento, CA.

Chapter 3: Hydro-economic analysis and results using CALVIN

The California Department of Water Resources (DWR) estimates that, on average, water users' statewide experience a shortage of 1.6 MAF/yr and 5.1 MAF/yr during drought years (DWR, 2014). Warming and sea level rise are likely to further reduce supplies available for import through the State Water Project (SWP) and Central Valley Project (CVP), especially during non-winter months as more of the water previously exported south of the Delta will be diverted for Delta water quality needs (Cayan *et al.*, 2008; CVJV, 2006; DWR, 2014; Hayhoe *et al.*, 2004). Refuge managers are already encountering challenges in securing water supplies with increasing costs and diminishing water trading opportunities in the Central Valley (CVJV, 2006). By some estimates, the cost of water has increased by 400 percent since 1993 (CVJV, 2006). Between 2001 and 2014, only 89% of the Level 2 deliveries and 47 percent of incremental Level 4 have been met (*Table 2-2*). Two critical challenges remain for the refuge managers: (1) how to do more with less; and 2) how to secure reliable water supplies at affordable prices?

Central Valley refuges are managed as part of the integrated water management system; therefore, compete against other environmental, urban and agricultural water users. An integrated water resource model is required to obtain a holistic understanding of the effects of changing climatic and management conditions on refuge management. The California Value Integrated Network Model (CALVIN), an integrated water resource model developed and maintained by the Center for Watershed Sciences, UC Davis, is used to assess vulnerabilities and explore adaptation strategies for refuge management over a range of climatic and management scenarios. Findings include hydro-economic impacts of peripheral tunnels, high outflow/low export Delta regulations, Sustainable Groundwater Management Act (SGMA) and a warm-dry hydrology on refuge deliveries. Promising adaptation strategies, such as, management of existing water supply resources, conveyance expansion opportunities and open market water trading are also explored. Background information and data used to develop tables and figures presented in chapter are included in *Appendices 1* through *10*.

CALVIN Overview

Simulation versus Optimization Models

Integrated water resource modeling can be classified into two broad categories: simulation and optimization models. Simulation models are useful for exploring *what-if* questions. These models compute system's behavior time-step by time-step for each of the predefined alternatives. Mathematical structure allows simulation models to represent non-linear physical and institutional processes with greater detail and complexity. Optimization models, on the other hand, are useful for exploring the alternative water management strategies given a set of physical, legal and management constraints. Unlike simulation models, optimization models compare numerous alternatives and identify the alternative that either maximizes or minimized a user-defined objective function. However, optimization models are seldom able to efficiently handle nonlinearities and complexities that can be easily incorporated into simulation models. Moreover, due to vast number of alternatives to be explored, mathematical representation of physical and institutional processes is often simplified to reduce the computational effort. Ideally, both modeling approaches should be used together: optimization models to identify promising solution strategies and simulation models to further test and refine the strategies (Harou *et al.*, 2009; Loucks *et al.*, 1981; Lund *et al.*, 2009).

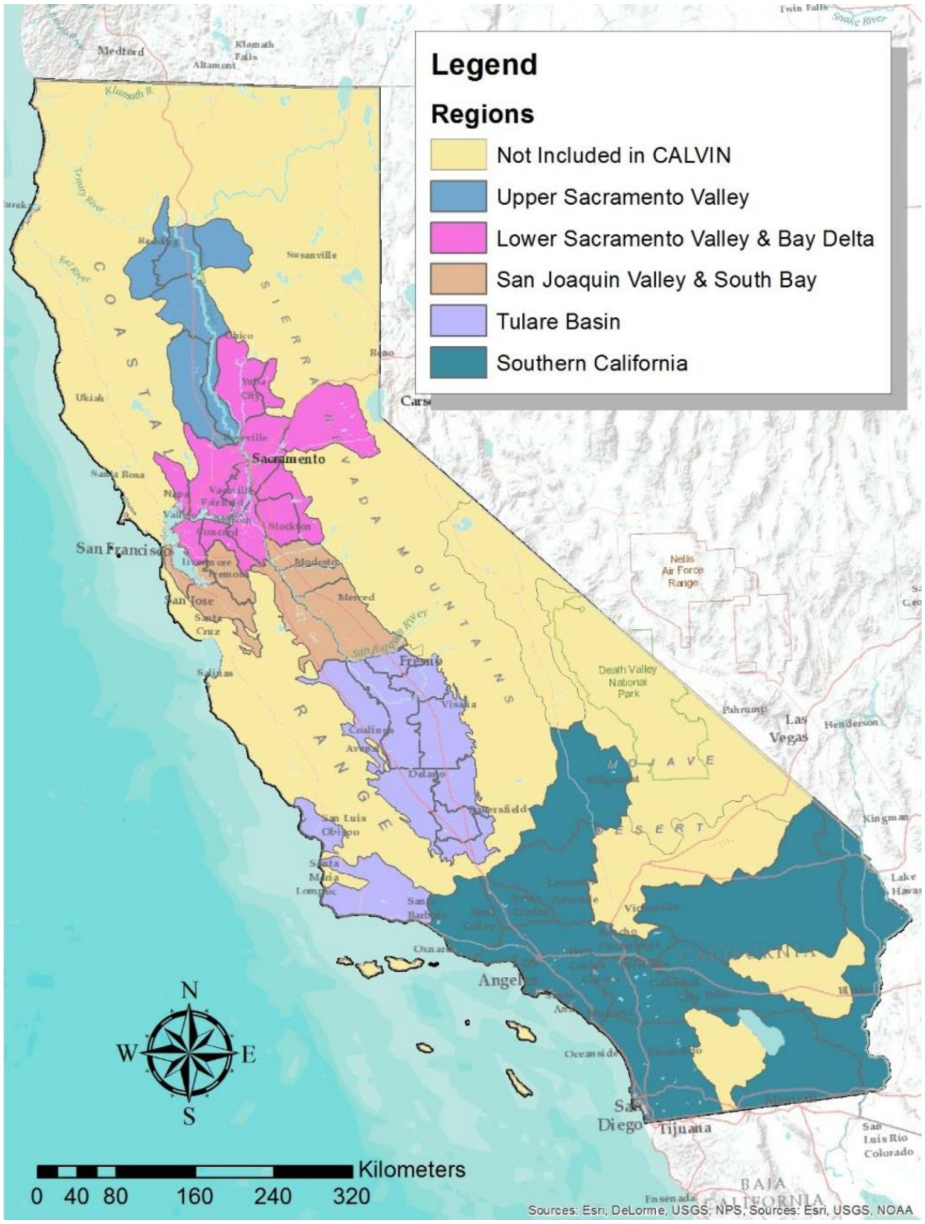


Figure 3-1. Regions included in CALVIN (Dogan, 2015)

Incorporating economic principles into optimization problems provides an added benefit. Non-economic water resource optimization models commonly represent demands as fixed deliveries based on allocation priorities set by water rights. Contrary to reality, this static view assumes that water users are incapable of responding to changing hydrologic and regulatory conditions by engaging in water trading or changes in use and local operations. Integrating hydrologic and economic principles allow optimization models to move away from the static view. Water users are assigned a value based on quantity and type of use. These values generally reflect economic output generated from the water delivered. This allows the optimization model to dynamically respond to changing conditions (Harou *et al.*, 2009). As water scarcity grows, the system re-operates to accommodate economically superior uses. This restructuring is similar to the real-life response where low-value agricultural land is fallowed to provide water for urban communities and/or high-value crops during periods of water scarcity. Hydro-economic models assume rational response to economic incentives. The results are purely economics-driven; however, in reality water rights and other institutional constraints also factor into the decision-making process.

Table 3-1. Agricultural and urban areas included in CALVIN

CALVIN Region		SWAP Agricultural Regions *	Major Urban Centers
Upper Sacramento Valley	*1*	CVP Users: Anderson Cottonwood ID, Clear Creek CSD, Bella Vista WD, and misc. Sacramento River water users	Redding and urban areas in CVPM regions 2 - 4
	2	CVP Users: Corning Canal, Kirkwood WD, Tehama, and misc. Sacramento River water users	
	3a	CVP Users: Glenn Colusa ID, Provident ID, Princeton-Codora ID, Maxwell ID, and Colusa Basin Drain MWC 3b Tehama Colusa Canal Service Area. CVP Users: Orland-Artois WD, most of Colusa County, Davis WD, Dunnigan WD, Glide WD, Kanawha WD, La Grande WD, and Westside WD	
	4	CVP Users: Princeton-Codora-Glenn ID, Colusa IC, Meridian Farm WC, Pelger Mutual WC, RD 1004, RD 108, Roberts Ditch IC, Sartain MWC, Sutter MWC, Swinford Tract IC, Tisdale Irrigation and Drainage Co., and misc. Sacramento River water users	
Lower Sacramento Valley and Delta	*5*	Most Feather River Region riparian and appropriative users	Yuba City, Sacramento, Napa, Stockton, service areas of Contra Costa WD and EBMUD, and urban areas in CVPM 5, 6, 8 and 9
	6	Yolo and Solano Counties. CVP Users: Conaway Ranch and misc. Sacramento River water users	
	7	Sacramento County north of American River. CVP Users: Natomas Central MWC, misc. Sacramento River water users, MWC, and Placer County WA	
	8	Sacramento County south of American River and northern San Joaquin County	
	9	Direct diverters within the Delta region. CVP Users: Banta Carbona ID, West Side WD, and Plainview	
San Joaquin Valley and South Bay	*10*	Delta Mendota service area. CVP Users: Panoche WD, Pacheco WD, Del Puerto WD, Hospital WD, Sunflower WD, West Stanislaus WD, Mustang WD, Orestimba WD, Patterson WD, Foothill WD, San Luis WD, Broadview, Eagle Field WD, Mercy Springs WD, San Joaquin River Exchange Contractors	Service areas of SFPUC and Santa Clara Valley WD, and urban areas in CVPM 10 - 13
	11	Stanislaus River water rights: Modesto ID, Oakdale ID, and South San Joaquin ID	
	12	Turlock ID	
	13	Merced ID CVP Users: Madera ID, Chowchilla WD, and Gravely Ford	
Tulare Basin	*14a*	CVP Users: Westlands WD	San Bernadino, San Luis Obispo, Bakersfield and urban areas in CVPM 14, 15, 17 - 21
	14b	Southwest corner of Kings County	
	15a	Tulare Lake Bed. CVP Users: Fresno Slough WD, James ID, Tranquillity ID, Traction Ranch, Laguna WD, and RD 1606	
	15b	Dudley Ridge WD and Devils Den (Castaic Lake)	
	16	Eastern Fresno County. CVP Users: Friant-Kern Canal, Fresno ID, Garfield WD, and International WD	
	17	CVP Users: Friant-Kern Canal, Hills Valley ID, Tri-Valley WD, and Orange Cove	
	18	CVP Users: Friant-Kern Canal, County of Fresno, Lower Tule River ID, Pixley ID, portion of Rag Gulch WD, Ducor, County of Tulare, most of Delano-Earlimart ID, Exeter ID, Ivanhoe ID, Lewis Creek WD, Lindmore ID, Lindsay-Strathmore ID, Porterville ID, Sausalito ID, Stone Corral ID, Tea Pot Dome WD, Terra Bella ID, and Tulare ID	
	19a	SWP Service Area, including Belridge WSD, Berrenda Mesa WD	
	19b	SWP Service Area, including Semitropic WSD	
	20	CVP Users: Friant-Kern Canal. Shafter-Wasco, and South San Joaquin ID	
	21a	SWP Users and CVP Users served by Cross Valley Canal and Friant-Kern Canal	
	21b	Arvin Edison WD and portions of Wheeler Ridge–Maricopa WSA	
	21c	SWP service area: Wheeler Ridge–Maricopa WSD	
Southern California		Production areas in Ventura County, Antelope Valley, Coachella, Palo Verde, East and West MWD, Imperial ID, San Diego, and Bard WD	Santa Barbara, service areas of Castaic Lake WA and MWD, and urban areas in Ventura County, Antelope Valley, Coachella, Blythe, El Centro and San Diego

* SWAP (Statewide Agricultural Production Model) is an improved and extended version of the Central Valley Production Model (CVPM). Sometimes, SWAP regions are referred to as CVPM regions. This report will also refer to SWAP regions as CVPM to maintain consistentcy with previous CALVIN studies. (USBR, 2012)

The California Value Integrated Network model, CALVIN, is a hydro-economic optimization model of State of California designed to provide technical and economic insights into integrated water resource management problems in California (Draper *et al.*, 2003; Lund *et. al.*, 2009). It optimizes system-wide operations over the 82-year period, from October 1921 to September 2003, using monthly time-step. The model covers 88% of the total statewide irrigated acreage and 92% of state's total population, and with recent updates, includes more than 50% of the managed wetlands or all of the CVPIA refuges in the Central Valley. *Figure 3-1* shows the spatial extent of the model and *Table 3-1* lists out all major agricultural and urban water districts included in CALVIN.

Conceptual Set-up and Data flow

CALVIN is a node-link network flow model. Demands regions, surface water reservoirs, and aquifers are represented as nodes. Reservoirs and aquifers are a special kind of nodes, called storage nodes, which can regulate flow of water by capturing it during times of availability and releasing it during times of need. Capacity constraints and initial and ending storage targets guide the management of storage nodes. Demand regions are divided into three categories: urban, agricultural and refuge water users. Demands are represented as either *hard* or *soft* constraints. *Hard* constraints require the model to deliver a fixed quantity of water. Deliveries to refuges and a few urban areas are represented as *hard* constraints. The model delivers water to these demand nodes before delivering water to the remaining agricultural and urban nodes. *Soft* constraints allow model to determine deliveries based on availability of water and economic output generated from the water delivered. A piecewise linear penalty curve is assigned to each urban and agricultural node with *soft* constraints (*Figure 3-2*). The penalty curves vary spatially and temporally, and increase with increasing scarcity, where scarcity is defined as the difference between delivery target and amount delivered. Penalty curves relate allocated amount to scarcity cost, loss of economic output from delivering less than target amount to urban and agricultural uses. These nodes are connected by links which mimic the existing water conveyance infrastructure to the extent possible. Flows on these links are bounded by channel capacity and minimum in-stream flow requirements, and assigned an operating cost, such as cost of pumping or treating water, where applicable. The objective function is set to minimize scarcity cost and operating cost while satisfying all the constraints. *Equations 3-1* through *3-4* represent the mathematical formulation of the network flow model (Draper, 2001).

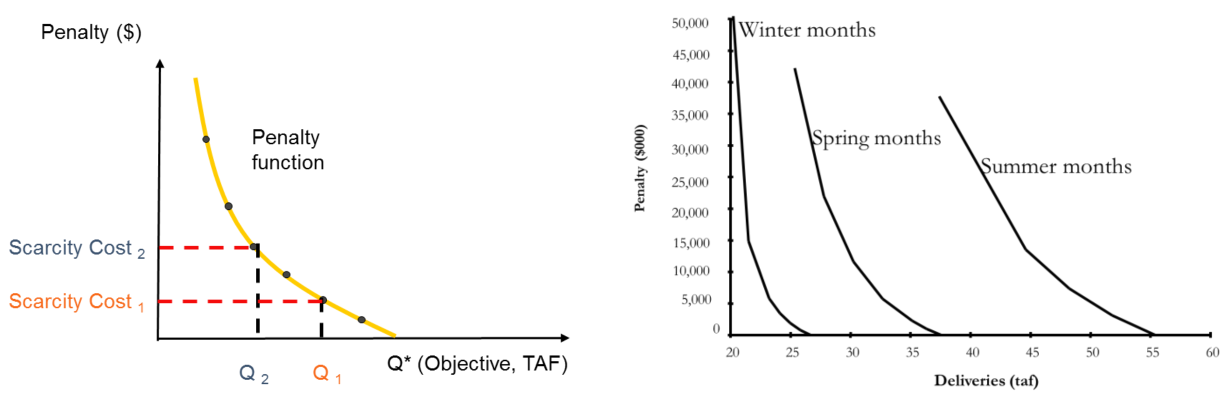


Figure 3-2. Penalty curves used to assign economic value to agricultural and urban water use in CALVIN
These curves vary monthly and spatially to reflect spatial and temporal variability in water demand.

Objective Function: $\min\{\sum_i \sum_j c_{ij} X_{ij}\}$ (3-01)

Subject to: $\sum X_{ji} = \sum a_{ij} X_{ij} + b_j$ (3-02)

$X_{ij} \leq u_{ij}$ (3-03)

$X_{ij} \geq l_{ij}$ (3-04)

Variable	Description	Units
c_{ij}	Economic costs	*$/Acre-Foot*
X_{ij}	Flow from node i to node j	*Acre-Feet/ mth*
a_{ij}	Gains or losses on flow arc, ij	*Acre-Feet/ mth*
b_j	External flows to node j	*Acre-Feet/ mth*
u_{ij}	Upper bound on flow arc, ij	*Acre-Feet/ mth*
l_{ij}	Lower bound on flow arc, ij	*Acre-Feet/ mth*

There are five types of inputs to CALVIN: 1) hydrologic inputs including surface water inflows, groundwater inflows, gains to and losses from stream due to groundwater-surface water interaction, and seepage and evaporative losses from canals and reservoirs ; 2) regulatory requirements such as minimum in-stream flows, required Delta outflows, and limitations on south of the Delta exports; 3) physical inputs such as reservoir and channel capacity; 4) agricultural, urban and refuge water demands represented as either *hard* or *soft* constraints; and 5) economic inputs represented by penalty curves and operating cost. Outputs are also categorized into hydrologic outputs and economic outputs. Hydrologic outputs include channel flows, water deliveries to urban, agricultural and refuge demand nodes, and reservoir and groundwater storages. Economic outputs include Lagrange multipliers or shadow prices which represent change in the objective function from unit relaxation of a constraint. Lagrange multipliers are interpreted as system-wide economic benefit from expanding a conveyance facility, opportunity cost of providing water to refuges or opportunity cost of meeting minimum in-stream flow requirements (Draper, 2001). Results can be further post-processed to assess agricultural and urban scarcity cost, and willingness to pay (WTP). Willingness to pay represents equilibrium market price or cost of trading water in a competitive, unregulated market (Draper, 2000). *Figure 3-3* outlines the data flow in CALVIN.

Limitations

Possible limitations include data quality, representation of refuge deliveries as *hard* constraints, simplified groundwater representation, operations' optimization assuming perfect foresight, and mathematical formulation of network flow models. Implications from these limitations must be factored in when interpreting results for insights into refuge management. Although these limitations have a significant effect on results of an individual model run, their impact is often muted in comparative analysis since all runs equally represent these limitations.

Data quality

Input data quality limits the quality of data output. CALVIN has been continuously managed and updated by graduate students since its inception. Most recent improvements include extension of simulation period by another 10 years to capture hydrologic variability between 1994 and 2003 (Dogan, 2015); refined agricultural and urban water use demand, and groundwater representation (Bartolomeo, 2011;Chou, 2012; Zikalala, 2013; Dogan, 2015); and expanded and improved representation of refuge representation as part of this research.

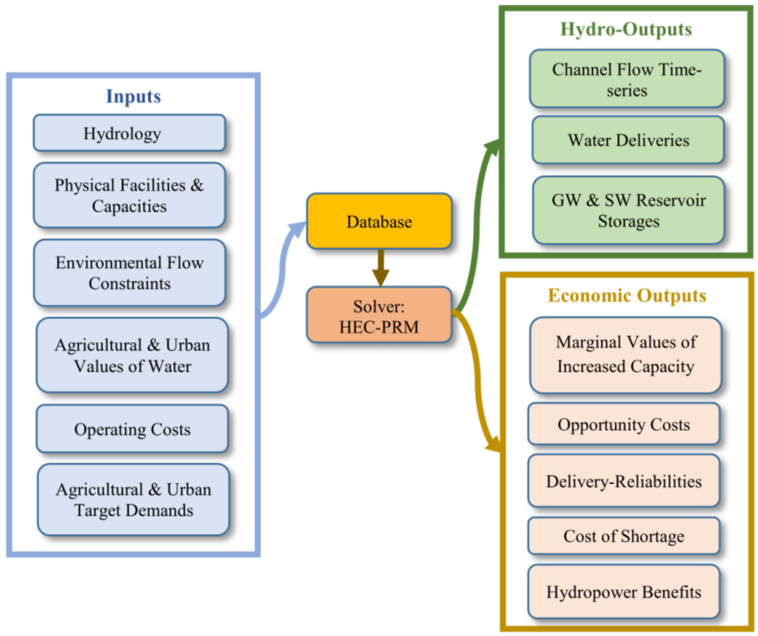


Figure 3-3. CALVIN inputs, outputs and data flow (Dogan, 2015)

Refuge demand representation

Environmental water use demands are represented as *hard* constraints or fixed deliveries in CALVIN. Fixed deliveries are given priority over urban and agricultural deliveries. As a result, (1) environmental uses are always met unless the model cannot find a feasible solution within the confines of defined upper and lower bound constraints, and (2) refuges do not directly compete with agricultural and urban water users. This limitation can be addressed by assigning economic value to environmental water use; however, this is still a field of on-going research and no credible statewide estimates for economic valuation of environmental use are available (Draper, 2001). Instead Lagrange multipliers or opportunity costs are used as surrogates to determine competition for the water delivered to the refuges or left in-stream to meet environmental uses. Implicit valuation techniques could be also used to estimate the economic value of environmental water use by comparing system-wide scarcity costs with and without the environmental constraints (2001). This technique is used in this analysis to assess potential water trading partners and the cost of acquiring additional supplies to realize Full Level 4 refuge deliveries.

Simplified groundwater representation

Groundwater storage is affected by four mechanisms: (1) lateral groundwater flows through which a given basin exchanges flows with adjacent basins, (2) interaction with natural streams and unlined canals, (3) recharge through deep percolation and (4) pumping. In CALVIN, first three mechanisms are combined into one, called *net groundwater inflows*, and included as pre-processed timeseries imported from California Central Valley Simulation Model (C2VSim). To represent the surface water counterpart of the stream flow interaction, a pre-processed local depletion and local accretion timeseries are used. These timeseries largely reflect losses from and gains to streams as a result of the surface water-groundwater interaction. Although CALVIN covers all groundwater flows in theory, these components are not dynamically connected in the model. Moreover, water quality is usually not explicitly factored in when model determines the composition of surface water and groundwater supplies to meet urban, agricultural and refuge water needs. An operating cost ($/AF) is assigned to pumping which sometimes include treatment cost; however, these cost are fixed and do not vary with the head.

Perfect foresight

CALVIN operates reservoirs and manages groundwater basins with perfect foresight, an assumption that that operators have perfect knowledge of all hydrologic events included in the simulation period and can adjust operations in anticipation of a flood or a drought. In reality, the system is managed with imperfect knowledge of future hydrologic events. Perfect foresight assumption can result in large carryover storage in surface water reservoirs ahead of a drought and a very little carryover storage ahead of a wet period (Draper, 2000).

Network flow models

Mathematical structure of network flow models limits model's ability to represent complex physical and operational constraints. These constraints must be pre-processed and represented as either upper bound, lower bound or constrained timeseries. This limitation affects CALVIN's ability to represent the complex water quality standards and operational constraints that play a critical role in determining required Delta Outflow and allowable Delta Exports. To mitigate for this limitation, CALVIN directly employs minimum in-stream flow requirements, required Delta Outflow and Delta export timeseries from CalSim II.

CalSim II is a water resource planning model jointly developed by California Department of Water Resource (DWR) and US Bureau of Reclamation Mid-Pacific Region (USBR). Similar to CALVIN, it is a network flow model which uses a node link configuration. However, CalSim II uses sequential linear programming with limited foresight which is significantly different than the many time-step optimization usually used in CALVIN. CalSim operates with limited knowledge of future hydrologic conditions to resemble real-time reservoir management operations. Sequential linear programming allows the model to conduct conditional analysis by simulating multiple cycles in a pre-defined order time-step by time-step. Environmental regulations and water exports depend on existing and forecasted hydrologic conditions of the system. Sequential linear programming allows CalSim to use state variables from previous, current or future time-steps to determine appropriate regulatory requirements in the current time-step, and therefore, more accurately determine minimum in-stream flows, required Delta Outflows, and allowable Delta exports (DWR, 2003).

Previous applications

G.E.P Box famously said, "All models are wrong, but some are useful." This is certainly true of CALVIN. Simplifications of a real system are inevitable in modeling of a complex system. Despite its simplifications, modeling studies using CALVIN have highlighted promising water management actions that have been actually adopted by water management agencies. For example, CALVIN studies indicated a great economic and water supply reliability potential from Contra Costa Water District (CCWD) and East Bay Municipal Utility District (EBMUD) intertie. The intertie became operational in 2009 where EBMUD gains from having a reliable water supply during dry years and CCWD benefits from using surplus EBMUD's Mokelumne River water to mix with CCWD's Delta diversions to improve water quality and lower treatment costs. CALVIN studies also indicated economic and reliability benefits from water transfers between SWP contractors north and south of the Delta which was achieved as part of the Monterey Agreements (Lund, et. al., 2009)

CALVIN has been used to gain insights into a large spectrum of climatic and regulatory scenarios. Draper and Jenkins used CALVIN to compare historic and optimized integrated water management operations, and to explore potential water markets at regional and statewide scales (Draper *et al.*, 2003; Jenkins *et al.*, 2001; Jenkins *et al.*, 2004). Pulido-Velazquez et al. applied CALVIN to assess conjunctive use potential in Southern California (2004). Null et al. focused on using CALVIN for ecosystem management (2006). Multiple researchers used CALVIN to assess the effects of climate change on agricultural, urban and environmental water uses (Connell, 2009; Lund *et al.*, 2003; Medellin-Azuara *et al.*, 2008; Medellin-Azuara *et al.*, 2009; Tanaka *et al.*, 2006; Tanaka *et al.*, 2011). Tanaka and Harou investigated the impact increasing Delta Outflows and ending Tulare Basin overdraft on the statewide economy (Harou & Lund, 2008; Tanaka *et al.*, 2011).

Refuge representation

A total of 8 nodes are used in CALVIN to represent 19 CVPIA refuges located in the Central Valley. *Figure 3-4* includes a high-level, simplified network flow schematic of CVPIA refuges and their respective *project water* delivery sources. Project water represents Level 2 and incremental Level 4 deliveries allocated and delivered to the refuges as mandated by Central Valley Project Improvement Act of 1992 (CVPIA). These deliveries are procured by USBR and made available to refuges by local irrigation districts (*Table 3-2*). CVPIA refuges may also have riparian water rights to local sources, but the model only focuses on project deliveries. *Table 3-3* outlines the correlation between CVPIA refuges, CALVIN refuge nodes, SWAP agricultural regions, and underlying groundwater basins. Surrounding SWAP agricultural regions represent the irrigation districts responsible for delivering water to the refuges. Underlying groundwater basin represent potential or existing source of groundwater deliveries to the refuge.

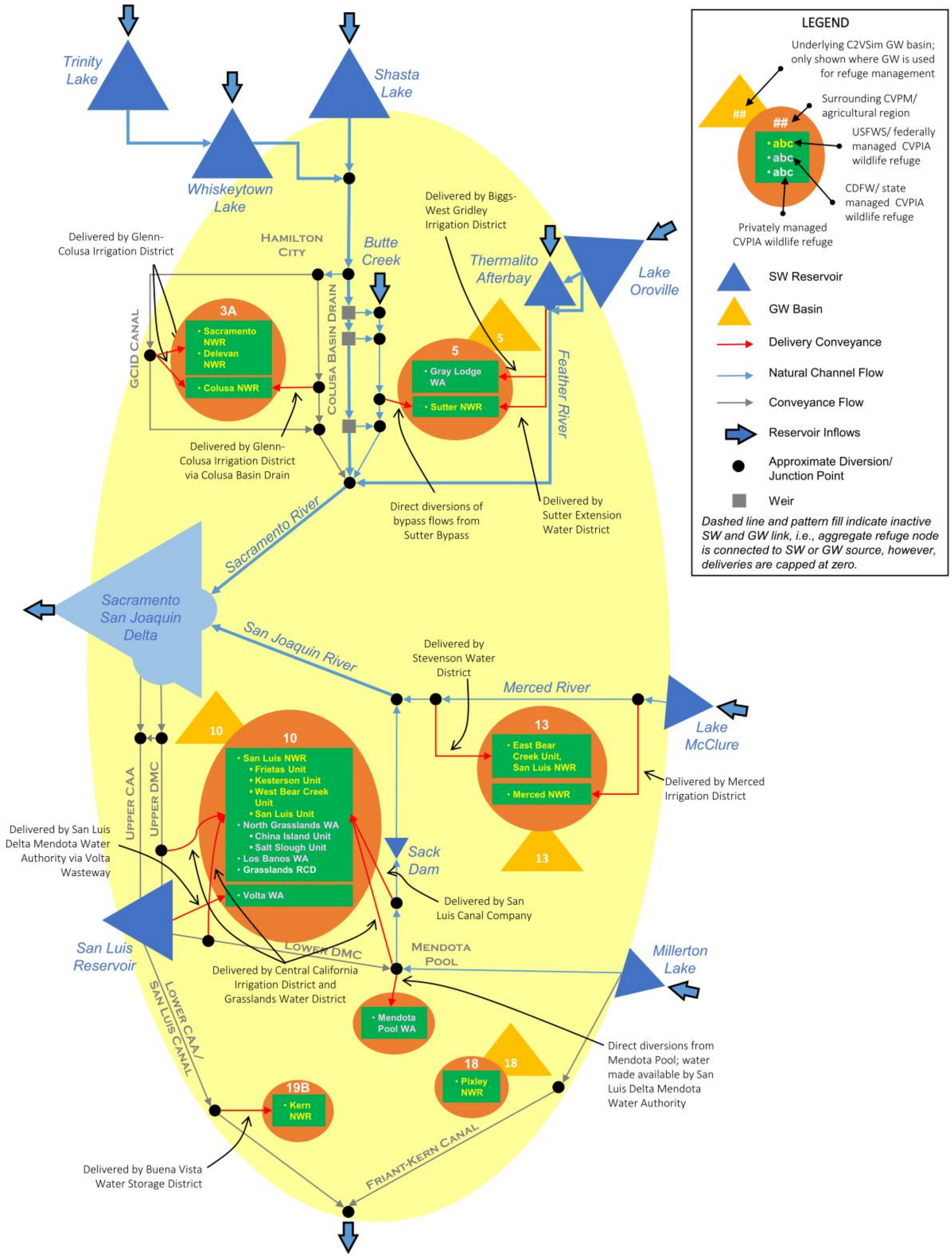


Figure 3-4. Simplistic representation of on-the-ground network flow schematic of Central Valley CVPIA refuge management

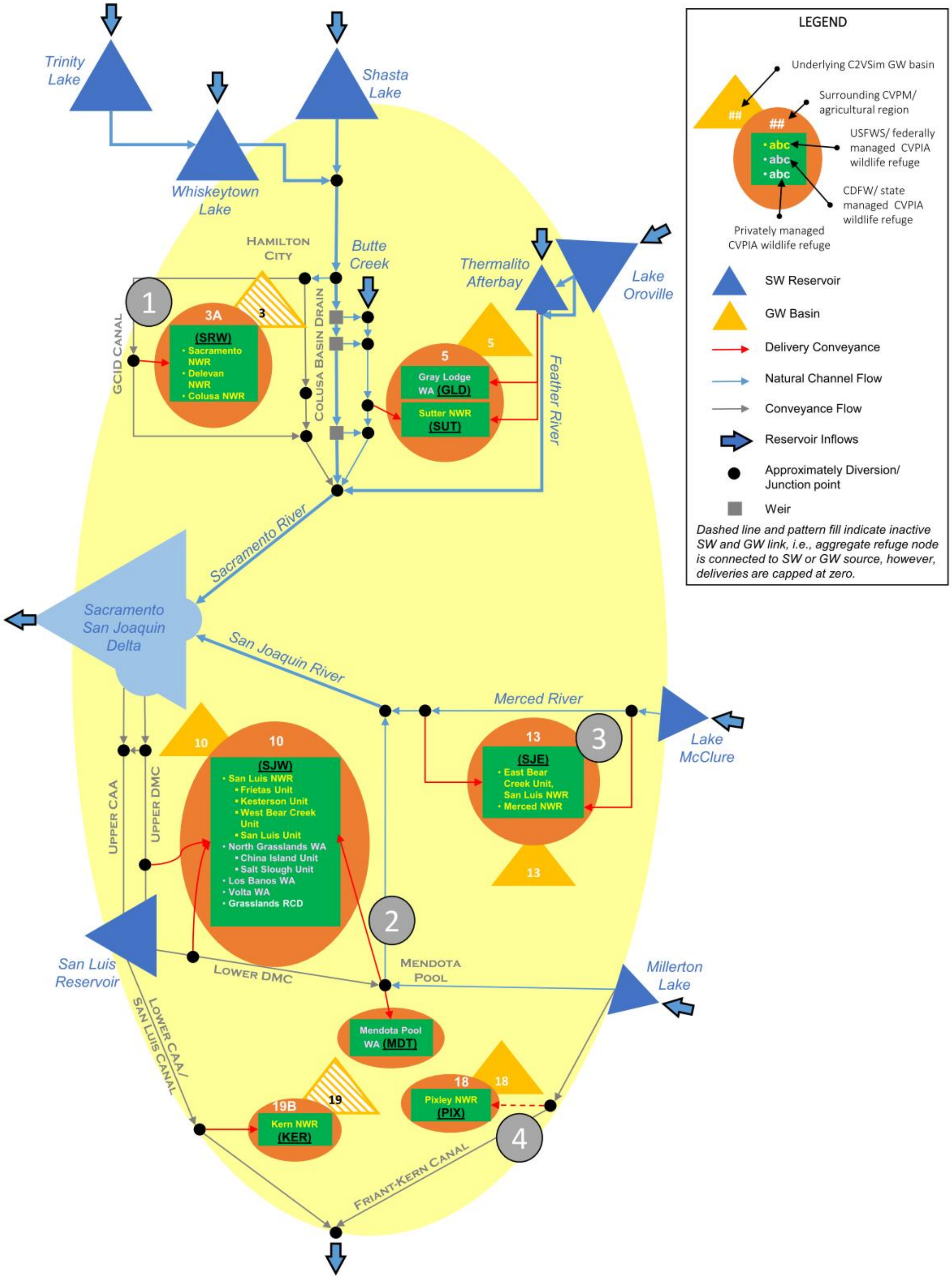


Figure 3-5. Network flow schematic of CVPIA refuges as represented in CALVIN.

Conveyance infrastructure was consolidated to reduce complexity; however, the source of water was still retained (# 1, 2 and 3). Potential future sources of water are connected to the refuge nodes with an upper bound of zero (# 4 and pattern-filled groundwater basins).

Table 3-2. CVPIA refuge water delivery portfolio [a]

CVPIA Refuge [b]	Surface Water Service District [c]	Groundwater Pumping [d]	Operational Loss Recovery System [d]
Sacramento Valley			
Sacramento NWR	Glenn-Colusa Irrigation District	-	-
Delevan NWR	"	-	-
Colusa NWR	"	-	-
Sutter NWR [e]	Sutter Extension Water District	Yes	n/a
Gray Lodge WA	Biggs West Gridley Water District	Yes	Yes
San Joaquin Valley			
Volta WA	San Luis Delta Mendota Water Authority	-	-
Los Banos WA	Grasslands Water District San Luis Canal Company	Yes	Yes
North Grasslands WA			
China Island Unit	Central California Irrigation District	Yes	Yes
Salt Slough Unit	Grasslands Water District	Yes	Yes
San Luis NWR			
Kesterson Unit	Grasslands Water District	-	-
Freitas Unit	"	-	-
San Luis Unit	San Luis Canal Company	Yes	Yes
West Bear Creek Unit	"	Yes	Yes
East Bear Creek Unit	Stevenson Water District	-	-
Merced NWR	Merced Irrigation District	Yes	Yes
Grasslands RCD	Grasslands Water District	- [f]	-
Mendota WA	San Luis Delta Mendota Water Authority	-	Yes
Tulare Basin			
Pixley NWR	-	Yes	-
Kern NWR	Buena Vista Water Storage District	- [g]	Yes

[a] Source: Section A3, D4 and D5 of Water Management Plans (USBR, 2010a-b; USBR 2011a-l)
[b] NWR: National Wildlife Refuge; managed by US Fish and Wildlife Service (USFWS)
WA: Wildlife Area; managed by California Department of Fish and Wildlife (CDFW)
RCD: Resource Conservation Districts; managed by private owners
[c] Only the Service Water Districts commissioned by USBR to deliver CVP water are listed. In addition to CVPIA surface water deliveries, refuges rely on runoff flows, local streams and pre-CVPIA contracts with surrounding agricultural Water Districts.
[d] CVPIA also provided funding to develop on-site water supply infrastructure such as groundwater wells or lift pumps to capture and reuse drainage flows to contribute towards meeting the Full Level 2 responsibility using project water.
[e] Water Management Plan is not available for Sutter NWR. Water supply portfolio information was provided by Rachael Esralew, USFWS Hydrologist. Sutter NWR historically relied on Sutter Bypass flows and limited groundwater pumping. Recently, they started receiving surface water supplies from Sutter Extension Water District as part of a pilot project.
[f] Grasslands RCD engaged in a 3-year pilot project to test viability of groundwater as water supply source, however, no long term decision was made at the time. Therefore, it is assumed that no groundwater is used within RCD to satisfy Level 2 and incremental Level 4 demand (USBR, 2011c).
[g] Water Management Plan lists nine groundwater wells. However, all of them have been abandoned due poor water quality and inaccessibility.

Nodes

Figure 3-5 highlights the simplifications made to the CVPIA refuge network flow schematic as represented in CALVIN. Similar to agricultural and urban water user representation in CALVIN, refuges sharing same water supply source are aggregated into a single node (see ① and ③ in *Figure 3-5*). Sometimes the delivery infrastructure is simplified to match the resolution of network flow schematic included in CALVIN (see ① and ② in *Figure 3-5*). Lastly, potential sources of water are also connected to the refuge nodes to examine the opportunity cost of expanding these sources of water in the future (see ④ and pattern-filled groundwater basins in *Figure 3-5*). These sources are bounded by an upper bound capacity of zero.

Table 3-3. CVPIA refuges' representation in CALVIN

CVPIA Refuge	CALVIN	Surrounding Ag Region	Underlying GW Basin
Upper Sacramento Valley			
Sacramento NWR	Sacramento River West (SRW)	CVPM 3A	GW-3
Delevan NWR			
Colusa NWR			
Lower Sacramento Valley and Delta			
Sutter NWR	Sutter NWR (SUT)	CVPM 5	GW-5
Gray Lodge WA	Gray Lodge WA (GLD)		
San Joaquin Valley and South Bay			
Volta WA	San Joaquin River West (SJW)	10	GW-10
Los Banos WA			
Grasslands RCD			
North Grasslands WA			
China Island Unit			
Salt Slough Unit			
San Luis NWR			
Kesterson Unit			
Freitas Unit			
San Luis Unit			
West Bear Creek Unit			
East Bear Creek Unit	San Joaquin River East (SJE)	13	GW-13
Merced NWR			
Mendota WA	Mendota WA (MDT)	-	-
Tulare Basin			
Pixley NWR	Pixley NWR (PIX)	18	GW-18
Kern NWR	Kern NWR (KER)	19B	GW-19

Five of the 19 CVPIA refuges are north of the Delta which include Sacramento NWR, Delevan NWR, Colusa NWR, Sutter NWR and Gray Lodge WA. Sacramento, Delevan and Colusa are on the west side of the Sacramento River and overlie groundwater basin GW-3. All three refuges receive their project deliveries from Glenn-Colusa Irrigation District (GCID) which is included in SWAP region 3A or

CALVIN agricultural demand node 103A. Even though these refuges receive their supplies from GCID, delivery mechanism varies among the three refuges. GCID uses Colusa Basin Drain as a delivery conveyance to deliver water to Colusa NWR in addition to district's canals whereas Sacramento NWR and Delevan NWR solely rely on district canals for water supplies (USBR, 2011a-b; 2011k). Since all refuges share the same supplier, all three refuges are aggregated into a single demand, Sacramento River West (SRW) and for simplification, the points of diversion are also consolidated into one. All supplies are diverted from CALVIN node C13, the same node from where CVPM 3A diverts surface water. None of the refuges have active wells and do not receive water from GW-3.

The remaining two, Gray Lodge WA and Sutter NWR are east of the Sacramento River in the Feather River Service Area (FRSA) and overlie groundwater basin GW-5. Both refuges actively pump groundwater for a portion of their project deliveries and are connected to GW-5. Surface water portion of the project deliveries comes from separate sources, however. As a result, the two refuges are represented as two distinct nodes, Gray Lodge WA (GLD) and Sutter NWR (SUT). Gray Lodge WA is allocated Feather River water which is diverted and delivered by Biggs-West Gridley Water District (BWGWD), included in SWAP region 5 or CALVIN agricultural demand node 202. Gray Lodge WA is also a landowner within the jurisdictional boundaries of BWGWD and continues to receive dependable supplies from BWGD per year which are also used towards the 35,400 acre-feet of Level 2 allocations. In addition to Feather River water, the refuge captures agricultural return flows from upstream rice farmers located in Reclamation District 2054 (RD 2054) and Reclamation District 833 (RD 833) which adds up to a considerable amount. Based on the refuge's Water Management Plan (WMP), between WY 2001 and 2010, on average, 70 TAF is delivered to the refuge per year, of which 36 TAF is upslope drainwater, 19 TAF is local water supply, 9 TAF is Level 2 water and 6 TAF is groundwater (USBR, 2011d). Since more than 50% of the deliveries are from agricultural return flow and measurable data is available, GLD is the only refuge that receives agricultural return flows. Even though agricultural return flows represent a portion of the project water delivered by the irrigation district, no measureable data is available at other refuges and do not receive any return under current configuration. Sutter NWR is largely within Sutter Bypass and owns a small portion of land within the boundary of Sutter Extension Water District (SEWD) which is also included in SWAP region 5 or CALVIN agricultural demand node 202. Even though Sutter NWR is a CVPIA refuge, USBR has been unable to secure reliable surface water deliveries and the area of the refuge within the bypass relies on bypass flows and groundwater. The portion located within SEWD is served by SWED.

Twelve of the CVPIA refuges are in the San Joaquin Valley and are represented using three refuge demands. Grasslands Resource Conservation District (RCD), Volta WA, Los Banos WA, China Island and Salt Slough units of North Grasslands WA, and Kesterson, Freitas, San Luis and West Bear Creek units of San Luis NWR are west of the San Joaquin River. These refuges receive project deliveries from Delta-Mendota Canal (DMC) and Mendota Pool which are diverted and delivered by Exchange Contractors including Central California Irrigation District (CCID), Grasslands Water District (WD), and San Luis Canal Company (SLCC) represented by SWAP region 10 or CALVIN agricultural demand area 303 (USBR, 2010b; 2011c; 2011f-i). Unlike other refuges in west of San Joaquin River, Volta WA receives its project deliveries directly from Volta Wasteway which captures any operational spills from San Luis Reservoir and diverts additional water from Delta-Mendota Canal (USBR, 2011l). Since all these refuges ultimately divert water from Delta-Mendota Canal, these refuges are aggregated into a single node called San Joaquin River West (SJW) and connected to two points of diversion: lower DMC (CALVIN node

D731) and Mendota Pool (CALVIN node C30). With the exception of Volta WA and Grasslands RCD, all SJW refuges actively use groundwater wells to meet their refuge needs and are connected with the underlying groundwater basin GW-10 (USBR, 2010b; 2011c; 2011f-i; 2011l). Grasslands RCD started using groundwater in 2007 as part of a three-year pilot project, but the WMP did not comment on the future use of groundwater at Grasslands RCD and current configuration assumes no groundwater use at Grasslands RCD (USBR, 2011c).

East Bear Creek unit of San Luis NWR and Merced NWR are east of the San Joaquin River in the Merced River watershed. These refuges rely on Merced River water to meet their management needs. Merced Irrigation District diverts and delivers water to Merced NWR from the Upper Merced River watershed (USBR, 2010a). Stevenson Water District diverts and delivers water to East Bear Creek unit from the Lower Merced River watershed, just before Merced River merges with San Joaquin River (USBR, 2010b). Both the water providers are included in SWAP region 13 or CALVIN agricultural demand area 306. Since both refuges divert water from Merced River, these are combined into a single demand, San Joaquin River East (SJE) and are connected to two points of diversion: Upper Merced River (CALVIN node D645) and Lower Merced River (CALVIN node D649). Since Merced NWR actively pumps groundwater to supply some of its use, the refuge node is connected to the underlying groundwater basin GW-13.

The third refuge node represents Mendota Wildlife Area (MDT). Mendota WA is part of the Mendota Pool and diverts water directly from Mendota Pool. USBR has contracted with San Luis Delta Mendota Water Authority (SLDMWA) which is a group of 29 different water contractors which divert CVP water from Delta Mendota Canal or from San Luis Reservoir via Pacheco Tunnel. These contractors leave water in DMC which is eventually delivered to Mendota Pool. No active groundwater wells are used for the refuge water supply (USBR, 2011g).

The last two CVPIA refuges, Kern NWR and Pixley NWR, are in the Tulare Basin which are represented as two separate refuge areas in CALVIN: Kern NWR (KER) and Pixley NWR (PIX). Kern is located on the west side of the valley and relies on the California Aqueduct for its water supply. Buena Vista Water Storage District diverts and delivers water via Goose Lake canal. There are no active groundwater wells at the refuge and it does not receive any deliveries from underlying groundwater basin GW-19 (USBR, 2011e). Pixley NWR located in the east side of the valley. Even though Pixley is a CVPIA refuge, it does not have access to secure surface water deliveries. Currently, it relies completely on groundwater. The refuge is connected to the underlying groundwater basin GW-18. USBR is negotiating with Delano-Earlimart Irrigation District (DEID) to divert and deliver water from Friant-Kern Canal (FKC); however, no agreement has been reached yet (USBR, 2011j). The refuge node is connected to FKC in the model, but the upper bound is set to zero.

Network flow

A refuge demand area representing an individual or a group of refuges is not just a single node, instead it a collection of nodes with its own network flow schematic. A standard network flow schematic represented within a refuge node is included in *Figure 3-6* and more individualized network flow schematics for the eight refuge nodes are included in *Appendix 2*. At the center is the *aggregate node* which collects water from all applicable sources: upstream surface water diversions, agricultural return flows and groundwater. Operating cost and capacity associated with each water source is defined as model input. If a source is inactive or unavailable, capacity is set to zero. Operating costs are only assigned to groundwater pumping at the moment to deter the model from over-relying on groundwater to meet refuge water needs. The aggregate node is connected to the *refuge node*. Flows on the link connecting the two nodes are constrained to pre-determined refuge delivery timeseries. In addition to diverting surface water or pumping groundwater, most of these refuges have an operation loss recovery system to capture and re-use refuge return flows (*Table 3-2*). In CALVIN, link amplitude can be set to more than 1 to represent on-site reuse. However, not enough information is available at the time to determine on-site reuse. As a result, the current calibration assumes no on-site reuse. Finally, a link connects the *refuge node* to a downstream surface water node to route the return flows from the refuges back into the conveyance system. Return flows are represented by setting the link amplitude less than 1; same proportions as previous versions of CALVIN are used.

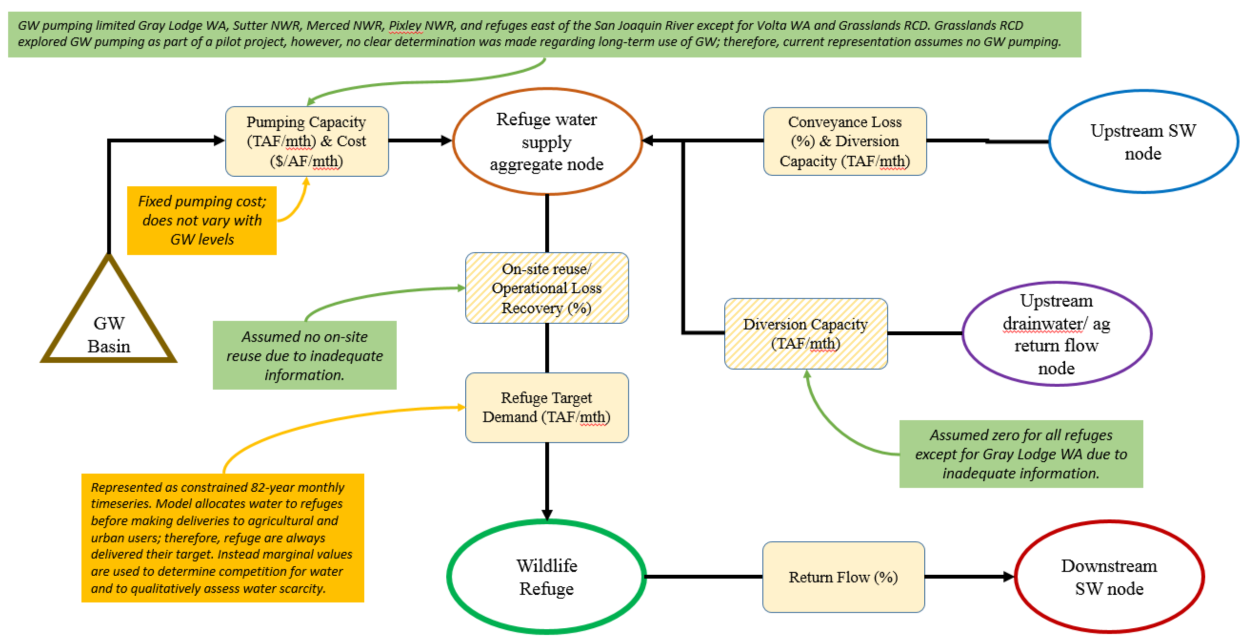


Figure 3-6. Detailed network flow schematic within each CALVIN refuge node
See *Appendix 2* for detailed network flow schematics of individual refuge nodes.

Demands

Refuge demands in CALVIN are represented using pre-processed timeseries. Two sets of refuge demand timeseries are prepared as part of this study: historical refuge deliveries and Full Level 4 deliveries. The first set, historical refuge deliveries, includes historical Level 2 and incremental Level 4 refuge deliveries between March 2001 and February 2015 to CVPIA refuges. To create 82-year monthly timeseries, two different sets of monthly averaged timeseries are prepared using historical deliveries to represent hydrologic variability in refuge deliveries: (1) refuge deliveries under drier conditions and (2) refuge deliveries under wetter conditions. California Department of Water Resources (DWR) uses two indices, namely, Sacramento River Index and San Joaquin River Index, to represent hydrologic conditions in Sacramento River and San Joaquin River watersheds, respectively. These indices categorize a given water year[4] as either wet (W), above normal (AN), below normal (BN), dry (D) or critical (C). Drier conditions include monthly averaged historical refuge deliveries during dry and critical water years. Wetter conditions represent monthly averaged historical refuge deliveries during wet, above normal and below normal water years. Refuges north and south of the Delta are mapped to Sacramento River Index and San Joaquin River Index, respectively. A synthetic 82-year historical refuge delivery timeseries is generated by mapping the two sets of monthly averaged historic refuge deliveries over the entire simulation period – October 1921 through September 2003 – using the water year types.

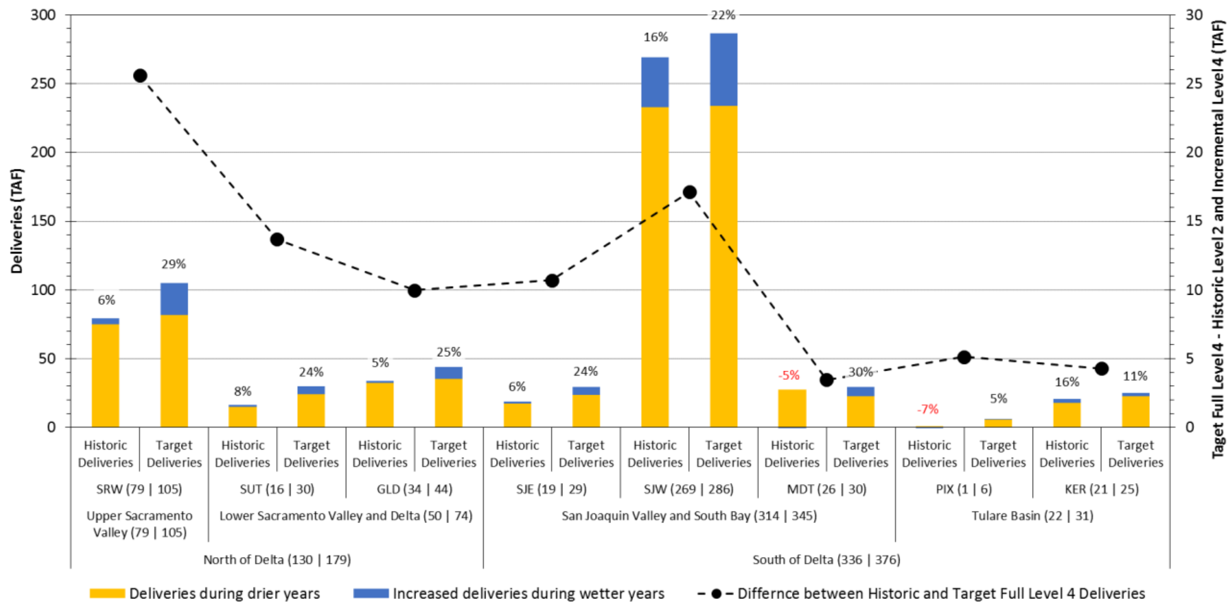


Figure 3-7. Historic Level 2 and incremental Level 4 vs Full Level 4 refuge deliveries

The second set represents Full Level 4 deliveries which include Full Level 2 and 100% of incremental Level 4 water allocated to CVPIA refuges (*Table 2-2*). For USFWS managed refuges, Rachel Esralew, a USFWS hydrologist, provided monthly Full Level 4 delivery timeseries. For remaining refuges, monthly Full Level 4 timeseries is determined using refuges' Water Management Plan (WMP). WMPs include annual Full Level 2 and incremental Level 4 targets. To convert from annual to monthly delivery targets, annual targets are distributed using monthly delivery pattern of historical refuge deliveries. Similar to historical deliveries, Full Level 4 deliveries are also adjusted to reflect hydrologic variability. A provision under CVPIA allows USBR to reduce Full Level 2 deliveries by 25% when there are critical conditions at Shasta Lake (defined by Shasta Lake Index of 4) which is equivalent to drier conditions under historical refuge deliveries. Therefore, Full Level 4 delivery timeseries is also divided into two sets: (1) refuge deliveries under drier conditions and (2) refuge deliveries under wetter conditions. The 82-year Full Level 4 delivery timeseries used in the model runs is created by mapping monthly Full Level 4 allocations over the entire simulation period, and reducing Full Level 2 deliveries to 75% when Shasta Lake Index is critical. Monthly averaged historic and Full Level 4 timeseries to individual CVPIA refuges and to CALVIN refuge nodes under drier and wetter hydrologic conditions is summarized in *Appendix 4*.

[4] DWR defines water year as October of previous calendar to September of existing calendar year

The water year types associated with the Sacramento River Index, San Joaquin River Index and Shasta Lake Index are summarized in *Appendix 3*.

Table 3-4. Summary of historic and Full Level 4 refuge deliveries (TAF/yr)

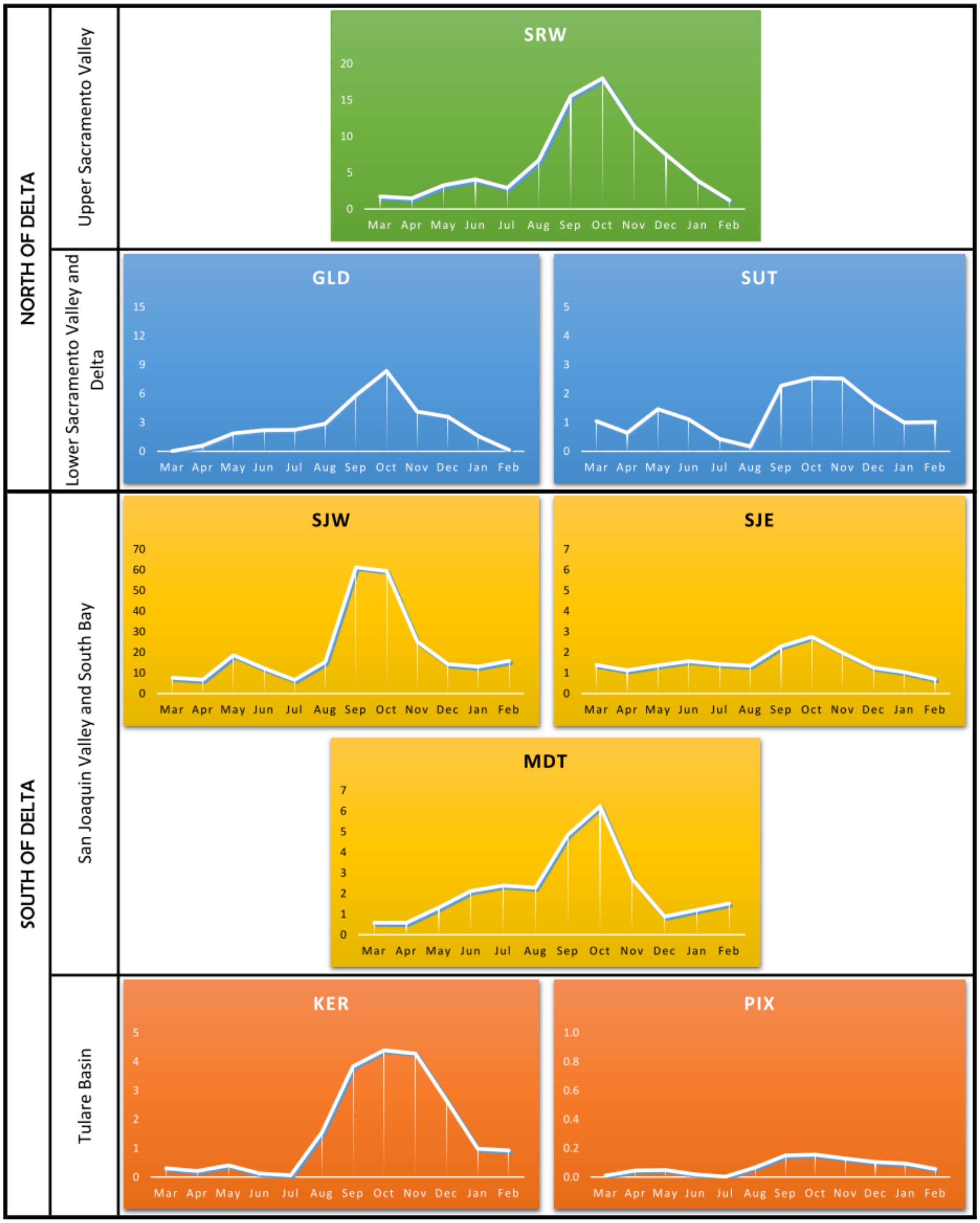
		Wetter Conditions			Drier Conditions			82-year Average		
		Historic	Full Level 4	Δ	Historic	Full Level 4	Δ	Historic	Full Level 4	Δ
NOD	SRW	79	105	*26*	75	82	*7*	78	102	*25*
NOD	GLD	34	44	*10*	32	35	*3*	33	43	*10*
NOD	SUT	16	30	*14*	15	24	*9*	16	29	*14*
SOD	SJE	19	29	*11*	18	24	*6*	18	29	*10*
SOD	SJW	269	286	*17*	233	234	*1*	256	281	*24*
SOD	MDT	26	30	*3*	28	23	*-5*	27	29	*2*
SOD	PIX	1	6	*5*	1	6	*5*	1	6	*5*
SOD	KER	21	25	*4*	18	23	*5*	20	25	*5*
NOD		130	179	*49*	123	141	*18*	127	175	*48*
SOD		336	376	*41*	297	309	*12*	322	369	*47*
CA		465	555	*90*	419	450	*30*	449	544	*95*

Note: For south of the Delta (SOD) summary, difference between historic and Full Level 4 deliveries averaged over 82-years exceeds the difference between the historic and Full Level 4 deliveries averaged over wetter and drier conditions. This is due to difference in the definition of wetter and drier conditions used for historic and Full Level 4 deliveries. For historic deliveries, Water Year types defined based on Sacramento Valley Index and San Joaquin Valley Index are used; whereas, for Full Level 4, Shasta Lake Index is used to determine wetter and drier conditions. Since Shasta Lake conditions are more representative of Upper Sacramento Valley, use of Shasta Lake index to categorize hydrologic conditions in the San Joaquin Valley results in a mismatch between drier conditions defined using San Joaquin Valley index and Shasta Lake index (*Appendix 1*). The total volume of historic and Full Level 4 averaged over 82-years is still bounded by historic and Full Level 4 deliveries averaged over wetter and drier conditions.

Figure 3-7 and *Table 3-4* highlight the spatial and temporal variability in historical and Full Level 4 deliveries. More than 65% of the historical deliveries are allocated to refuges in the San Joaquin Valley with 85% of these delivered to refuges west of the San Joaquin River (SJW). Roughly 30% of the historical deliveries are allocated to refuges in the Sacramento Valley with 60% of these going to refuges west of the Sacramento River and remaining 40% to refuges east of the Sacramento River. Less than 5% of historical deliveries are allocated to refuges in the Tulare Basin. Temporally, there is 5 – 8% variation in historical deliveries north of the Delta and 5 – 16% variation south of the Delta with Mendota WA and Pixley NWR even experiencing a reduction in their historical project deliveries as a result of wetter conditions. Pixley NWR completely relies on groundwater for its project deliveries. Wetter conditions generate substantial local runoff that the refuge is able to cut down its groundwater use. Mendota WA diverts its project water directly from Mendota Pool which receives flood flows from Kings River via James Bypass. Similar to Pixley NWR, during wetter conditions Mendota WA substitutes some of its project deliveries with excess runoff from Kings River.

On average, gains from Full Level 4 deliveries are split almost equally between refuges located north and south of the Delta: 48 TAF to refuges in the north and 47 TAF to refuges in the south. Refuges west of Sacramento River (Δ = 25 TAF) and west of San Joaquin River (Δ = 24 TAF) experience the highest volumetric gain in their deliveries and Pixley NWR experiences the highest percent gain in its deliveries

(500% increase). Hydrologic variability also increases with Full Level 4 deliveries. The average percent difference in refuge deliveries between drier and wetter conditions increases from 6% to 21%.



NOTE: Figures are **not** drawn to same scale.

Figure 3-8. Monthly averaged historic Level 2 and incremental Level 4 refuge deliveries

In addition to spatial and inter-annual variability, there is also seasonal variability in refuge deliveries (*Figure 3-8*). Peak demand occurs during September – October preceded by smaller peak demand earlier in the year between May – June and at some refuges, around February. Three different wetlands types are managed at the CVPIA refuges: seasonal wetlands, semi-permanent wetlands and permanent wetlands. Seasonal wetlands provide habitat and food for the greatest number of wildlife species, and cover the largest portion of managed wetland acreage at the refuges. The peak demand during September – October and May – June coincide with the flood-up and irrigation season of seasonal wetlands, respectively. Semi-permanent wetlands are managed to provide food and habitat during summer when seasonal wetlands are out of production. The influx in refuge demands around February corresponds with the flooding of semi-permanent wetland units. In addition to wetlands, a portion of Merced NWR is also managed to grow crops that provide food and/or habitat that naturally does not grow in the wetlands. Three crop types with different irrigation schedules are grown. First is irrigated pasture which provides dense nesting habitat for ducks. This crop type is periodically irrigated between March and September. The last two crop types are grain crops which provide high energy foods for the migratory birds. Corn is a summer grain crop and is irrigated May through August. Small grain crops like wheat, barley and sunflower are winter grain crops, and are irrigated during fall. The flatter demand from March through August at refuge node SJE corresponds with the irrigation season of various crop types sustained at Merced NWR (USBR, 2010a-b; USBR, 2011a-l).

Scenarios

Sixteen scenarios are analyzed using CALVIN to capture and quantify the hydrologic and economic implications of evolving climatic and management conditions on refuge water deliveries including (1) historical and warm-dry climate; (2) high outflow/low export and existing Delta regulations; (3) with and without peripheral tunnels; and (4) with and without long-term groundwater overdraft (*Table 1-1*). This section describes the sixteen scenarios, and agricultural and urban demands as represented in the model. For background information on these scenarios, refer to Chapter 2.

Table 3-5. Urban, agricultural and refuge demands included in CALVIN (MAF/yr)

	Urban	Agricultural	Historic Refuge Deliveries	Full Level 4 Refuge Deliveries
Upper Sacramento Valley	0.4 (3%)	2.6 (11%)	0.08 (17%)	0.1 (19%)
Lower Sacramento Valley and Delta	1.9 (15%)	4.6 (20%)	0.05 (11%)	0.07 (13%)
San Joaquin Valley and South Bay	1.7 (14%)	4.9 (21%)	0.3 (67%)	0.34 (62%)
Tulare Basin	1.5 (12%)	9.6 (41%)	0.02 (5%)	0.03 (6%)
Southern California	6.8 (55%)	1.4 (6%)	-	-
Statewide Total	12.4	23.1	0.45	0.54

Urban and agricultural demand

Urban and agricultural demands corresponding to year 2050 level of development are used in the model runs (*Table 3-5*). Statewide urban demand is 12.4 MAF/yr with more than half occurring in Southern California (6.8 MAF/yr or 55%). Statewide agricultural demand is 23.1 MAF/yr, roughly twice as much as the urban demand. More than 40% (9.6 MAF/yr) of the agricultural water use demand is in Tulare Basin followed by 4.6 MAF/yr in Lower Sacramento Valley and Delta, and 4.9 MAF/yr in San Joaquin Valley. Refuge demands are just 2% (0.5 MAF/yr) of the total water use demand which mostly is in the San Joaquin Valley.

Climate change

A downscaled version of NOAA GFDL CM2.1 A2 climate change scenario is used in the modeling runs (Delworth *et al.*, 2006). This represents a warm-dry scenario. Warming is represented by average monthly temperature increase of 7.38 degree Fahrenheit. Magnitude of temperature change varies regionally and seasonally, but the entire state sees an increase in temperature in all months (*Figure 3-9*). The drier hydrology is characterized by an average annual reduction of 26% in precipitation (*Figure 3-10*). Unlike temperature, precipitation trends are not ubiquitous statewide.

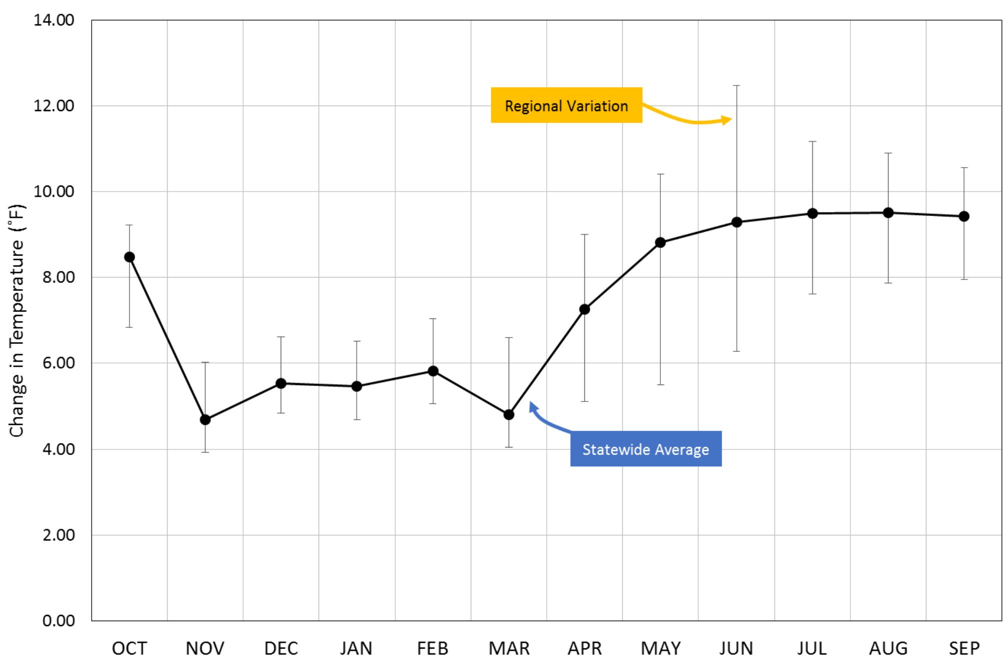


Figure 3-9. Projected temperature change under warm-dry (GFDL CM2.1 A2) climate scenario

Increase in temperature and decrease in precipitation cumulatively represents a warm-dry hydrology. As a result, a reduction and a seasonal shift in runoff flows is observed (*Figure 3-11*). Under historical hydrology, reservoir inflow peaked during May representing spring snowmelt runoff. Runoff from local streams had two peaks: a major peak during winter indicative of rainfall runoff and a smaller peak in May from snowmelt runoff during spring. Under warm-dry hydrology, reservoir inflows and local streamflow runoff reduce 28% and 22%, respectively. Peak flow shifts to winter months representing shift in precipitation pattern with much of the precipitation falling during winter months as rainfall and less of it stored as snowpack. Even though average monthly runoff decreases under the warm-dry scenario, runoff during month of January exceeds historical runoff flows reflecting extreme hydrologic conditions as a result of the warming trend.

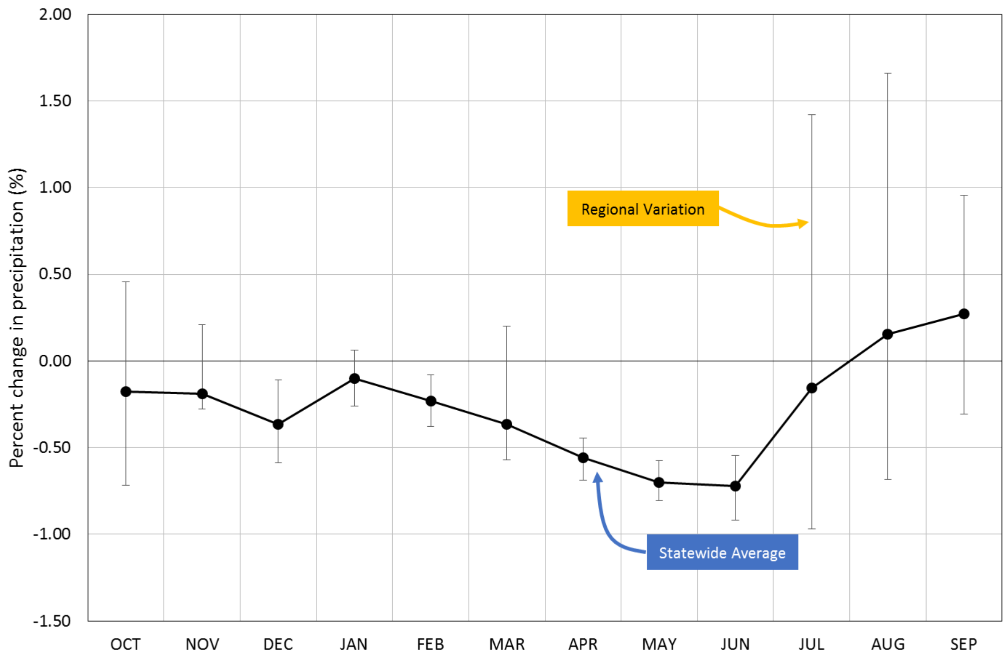


Figure 3-10. Percent change in precipitation under warm-dry (GFDL CM2.1 A2) climate scenario

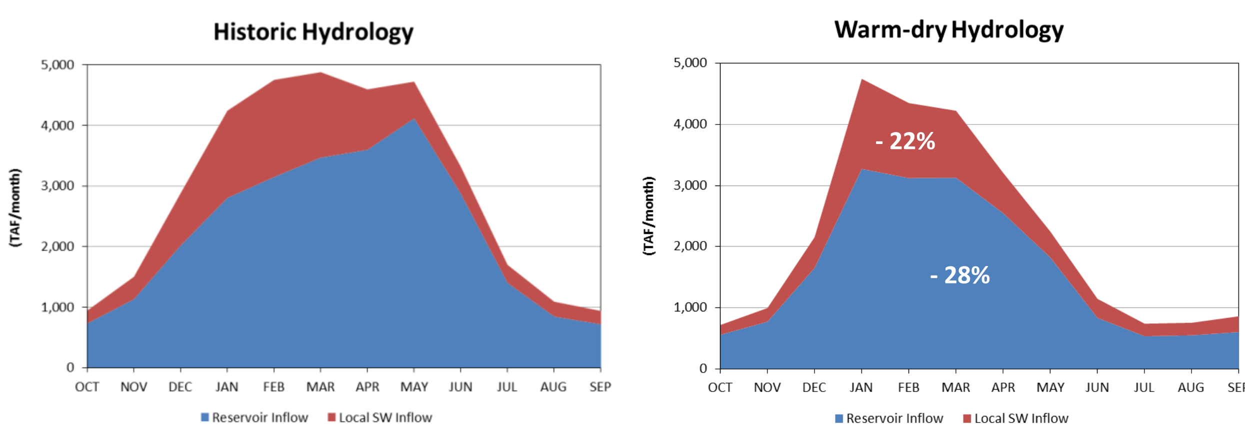


Figure 3-11. Reservoir inflows and local surface water runoff (rim inflows)

Results are aggregated for all rim nodes represented in CALVIN.

Figure 3-12 and *Appendix 8* summarize the impact of warm-dry hydrology region by region. Largest decrease in reservoir runoff occurs in Tulare Basin (44%) and San Joaquin Valley (37%). Upper and Lower Sacramento Valley experiences the greatest loss in streamflow runoff, 23% and 26%, respectively. Reduced runoff also impacts the local accretion, local depletion and groundwater inflows. As stated previously, local accretion and local depletion flows largely represent surface water-groundwater interaction. Local depletion doubles statewide and more than quadruples in the San Joaquin Valley. Local accretion flows decrease by 28% statewide with greatest decrease in San Joaquin Valley (42% reduction).

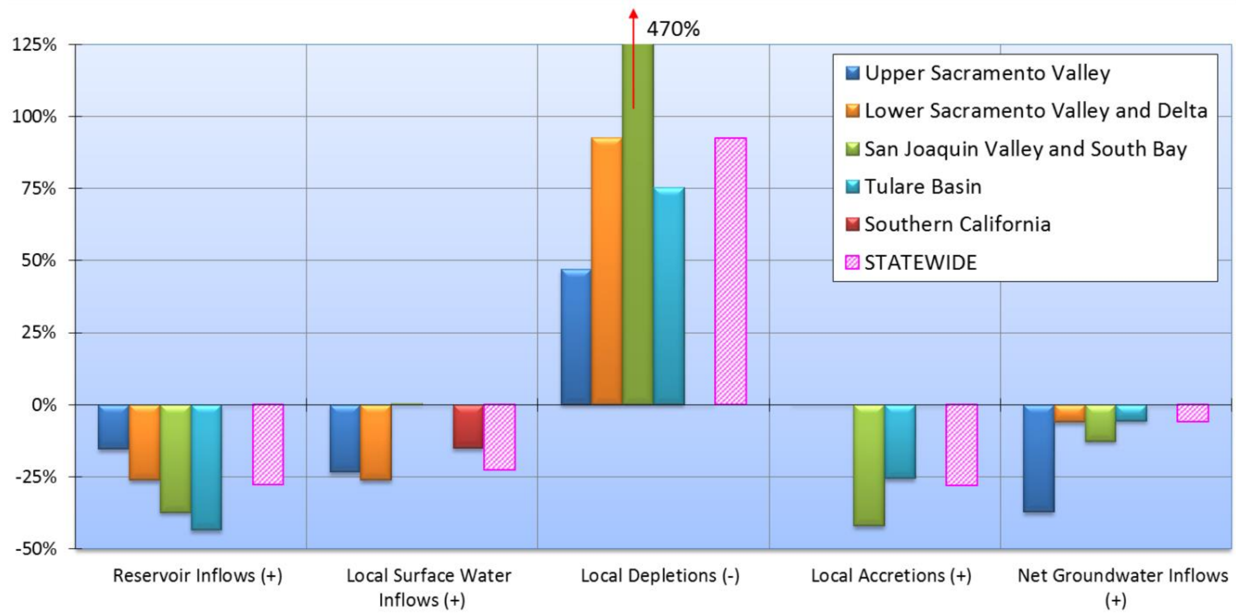


Figure 3-12. Impact of warm-dry climate scenario on hydrologic inputs into CALVIN

Net groundwater inflows – combination of lateral flows and deep percolation – decrease by 6% with majority of the reduction concentrated in Upper Sacramento Valley (37%) (*Figure 3-13*). Collectively, warm-dry trend represents a significant decrease in surface water inflows available for use as a result of reduced precipitation and increased loss from stream. San Joaquin and Tulare Basin experience the largest reduction in their water supplies, estimated around 40%, followed by Lower Sacramento Valley and Delta (35%). Since these regions represent more than 80% of agricultural water demand in California, competition for water is expected to increase dramatically in these parts of California. Even though Southern California, an urban hub of California with more than half of statewide urban water use, only experiences 6% reduction in water supplies, it also becomes a major competitor for water since penalty cost from urban scarcity is significantly more than for agricultural scarcity.

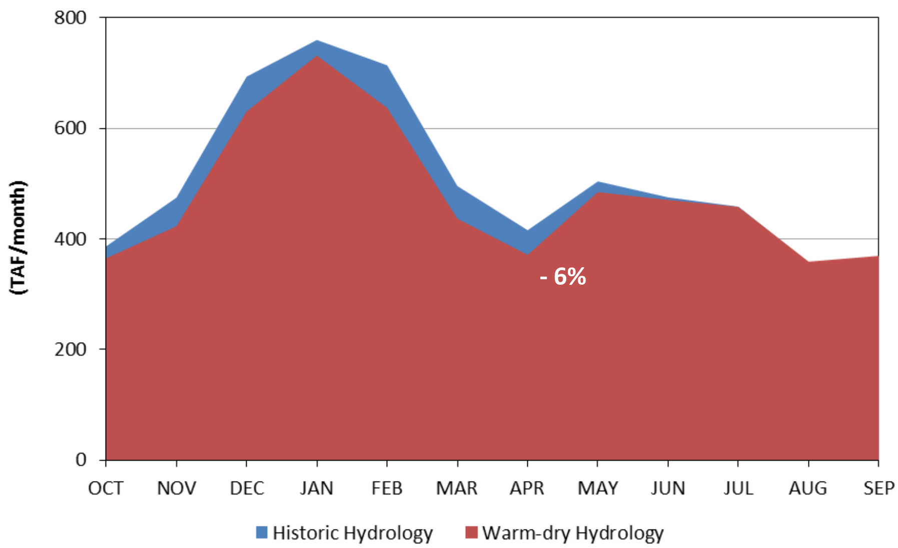


Figure 3-13. Net groundwater inflows

Results are aggregated across all groundwater basins represented in CALVIN.

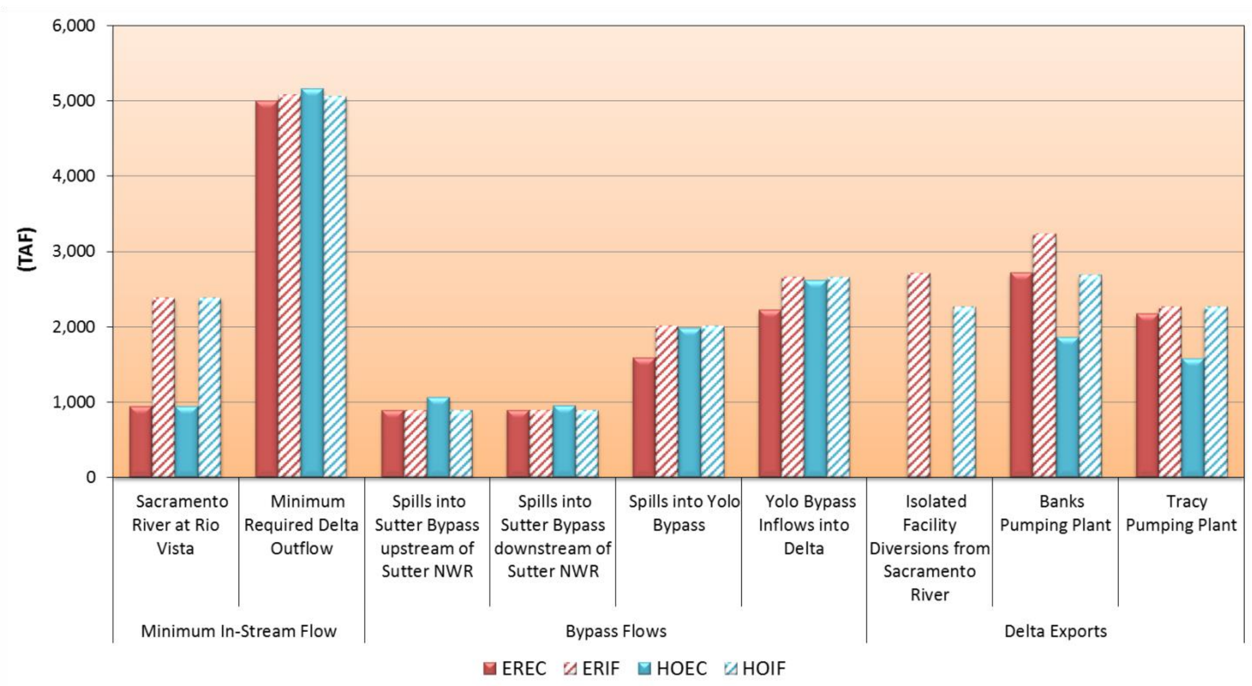


Figure 3-14. BDCP scenario comparison.
See *Appendix 7* for more details.

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Delta regulations and peripheral tunnels

South of the Delta exports and required Delta Outflows are largely driven by salinity conditions in the Delta. Operators rely on reservoir releases and export cutbacks to manage water quality and meet minimum flow requirements within Delta, which combined affect required Delta outflow. As explained previously, mathematical structure of network flow models, such as, CALVIN, limit them from representing complex physical and operational constraints regulating flow within the Sacramento-San Joaquin Delta. Instead, minimum in-stream flow requirements, required Delta Outflow and Delta export timeseries are imported directly from CalSim II. Four CalSim II runs are used to represent two infrastructure scenarios – with and without the peripheral tunnels – and two Delta regulatory scenarios, high outflow/ low export, and existing regulations. These runs were completed as part of the Bay Delta Conservation Plan Environmental Impact Report and Environmental Impact Statement (BDCP EIR/EIS) prepared in 2013. Four runs include: 1) No Action Alternative (NAA) with D-1641, and 2008 and 2009 Biological Opinions (BiOps) issued by USFWS and NMFS which represents Existing Regulations, Existing Conveyance (EREC) scenario; 2) Preferred Alternative (PA) with 9,000 cfs tunnels intake capacity and 2a-H3 operational criteria which represents Existing Regulations, Isolated Facility (ERIF) scenario; 3) 2a-H4 operational criteria without the tunnels which represents High Outflow, Existing Conveyance (HOEC) scenario; and 4) 2a-H4 operational criteria with 9,000 cfs tunnels intake capacity which represents High Outflow, Isolated Facility (HOIF) scenario. The mapping of CalSim II timeseries into CALVIN is outlined in *Appendix 6*.

Figure 3-14 highlights major differences among the four scenarios outlined above. A bypass flow criteria is introduced to synchronize tunnels' operations with anadromous fish migration pattern protected under Endangered Species Act. Tunnels are operated to maintain a threshold of Delta Outflows to preserve pulse flows during flood season and sweeping velocities during fish migration to minimize predatory losses. These requirements are reflected by increases in minimum flow requirements at Rio Vista under ERIF and HOIF compared to the no tunnels, EREC and HOEC, scenarios (BDCP, 2013). Additionally, an alternate fish migration passage through Yolo Bypass is proposed under BDCP to reduce incidental take at the tunnel intakes and increase spawning and rearing habitat for fish (2013). As a result, inflows and outflows from Yolo Bypass are higher under ERIF and HOIF scenarios. Existing Delta outflows are determined by flow and operational criteria prescribed under State Water Resource Control Board Decision 1641 (D-1641), 2008 USFWS BiOp, and 2009 NMFS BiOp. The high outflow scenario places additional Delta outflow requirements from March through May to protect longfin smelt, and adopts an increasingly restrictive Old and Middle River reverse flow criteria than originally proposed under 2008 and 2009 BiOps. As a result, required Delta outflows increase marginally, and exports are curtailed by 30% under HOEC compared to EREC scenario (2013). However, the peripheral tunnels provide more flexibility in managing surplus flows. Any losses in exports under HOEC are gained back in HOIF scenario, and Delta outflows and exports in HOIF are roughly same as EREC. Finally, due to export curtailments under the HOEC scenario, less water can be moved south of the Delta and more is spilled into Sutter and Yolo Bypass.

Table 3-6. CALVIN – CalSim II channel flow comparison (%)

	EREC	ERIF	HOEC	HOIF
Sacramento River Valley				
Sacramento R below Keswick	1%	1%	1%	1%
Clear Creek below Whiskeytown	1%	1%	0%	1%
Sacramento R @ Red Bluff	4%	4%	3%	4%
Sacramento R @ Hamilton City	0%	0%	-1%	0%
Feather R @ Confluence	5%	5%	3%	5%
American R below Nimbus Dam/ Lake Natoma	11%	11%	11%	10%
Sacramento R @ Hood (upstream of IF)	1%	1%	-1%	1%
Sacramento R @ Rio Vista	0%	1%	-1%	1%
Eastside Streams				
Mokelumne R Inflows into Delta	30%	17%	17%	16%
Calaveras R Inflows into Delta	44%	34%	30%	35%
San Joaquin River Valley				
San Joaquin R below Merced R	19%	9%	-13%	4%
San Joaquin R below Tuolumne R	9%	-1%	-4%	0%
San Joaquin R below Stanislaus R	11%	4%	5%	5%
San Joaquin R @ Vernalis	11%	2%	2%	3%
James Bypass Inflows*	0%	0%	0%	0%
Delta Outflow				
Required *	0%	0%	0%	0%
Surplus	7%	4%	1%	4%

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Constrained operations: CALVIN runs use the same timeseries as CalSim runs.

CalSim II runs are only available for the historical hydrology. Even though multiple climate change scenarios are explored as part of BDCP EIR/EIS, hydrology is perturbed differently than in CALVIN. Moreover, groundwater overdraft scenarios were not explored during the EIR/EIS analysis. As a result, minimum in-stream flows, required Delta outflow, bypass inflows and south of the Delta exports vary only by the Delta export and outflow scenario, but are independent of the hydrologic or groundwater overdraft scenario unless constraints had to be relaxed to obtain a feasible solution space (see discussion under *Calibration summary* section of this chapter). Therefore, model runs, under current set-up, represent an optimistic exports scenario for a warm-dry hydrology. Warming is projected to increase required Delta outflow demands during non-winter months to maintain suitable fish habitat and water quality within the Delta which will reduce the amount of water available for export (Cayan *et al.*, 2008; Hayhoe *et al.*, 2004). Sustaining the same level of Delta exports as under historical hydrology overestimates the amount of water available to meet urban, agricultural and refuge needs south of the Delta.

CALVIN and CalSim results from the four scenarios are compared at key locations in the Sacramento River and San Joaquin River watershed for the historical hydrology and groundwater overdraft case in *Table 3-6*. There are three major outlet points in the system: Sacramento River at Rio Vista, San Joaquin River at Vernalis and outflow from the Delta. Differences are about 10% or less at these three major outlet points. Within a watershed, differences can be more pronounced as a result of variances in optimization routines and representation of demands. Smaller watersheds tend to have more pronounced differences. CALVIN uses perfect foresight to optimize the system that is equivalent of operating the system if all the hydrologic information was available for the entire period of simulation. CalSim, on the other hand, uses limited monthly foresight. Operators make decisions based on hydrologic forecasts of next three to six months (DWR, 2003). Secondly, CALVIN aggregates demands into nodes and all the potential sources of water are connected to a demand area. In CalSim II, demands are represented as delivery arcs. As a result, a demand area in CALVIN could be represented by several arcs in CalSim which allows for a more explicit connection between supply source and demand. Despite these differences, the results at major outlets in the system are within 10% margin of error. Combined with other limitations, differences and scopes of the models, this is considered an acceptable difference.

Groundwater overdraft management

The Sustainable Groundwater Management Act (SGMA) mandates that groundwater must be managed to prevent chronic, long-term groundwater overdraft. This regulatory constraint was represented by setting the ending storage, storage at the end of the simulation period, that is, September 2003, to be same as the initial storage, storage at the beginning of the simulation period, October 1921 (*Table 3-7*). Collectively, groundwater use, as represented in CALVIN, results in 1.03 MAF of overdraft per year. Over 82 years of operations between October 1921 and September 2003, water use practices in Tulare Basin generated 55.9 MAF (700 TAF/yr) of overdraft followed by 15.1 MAF (185 TAF/yr) in San Joaquin Valley and 13.1 MAF (160 TAF/yr) in Lower Sacramento Valley and Delta. Under no groundwater overdraft, CALVIN optimizes system-wide operations such that no net groundwater overdraft is occurs over the simulation period. As a result, ending long-term groundwater overdraft has the largest impact in Tulare Basin.

Results

"The purpose of computing is insights, not numbers." – R.W. Hamming (1962)

CALVIN is a large-scale planning model; it is not an ideal tool to assess impact on year-to-year refuge operations. Instead, insights from the modelling studies are used to determine trends across the hydrologic and management scenarios outlined in the previous section of this chapter. Results are aggregated by five CALVIN regions: 1) Upper Sacramento Valley, 2) Lower Sacramento Valley and Delta,

3) San Joaquin Valley and South Bay, 4) Tulare Basin, and 5) Southern California (*Figure 3-1*). Upper Sacramento Valley region include refuges west of the Sacramento River (SRW): Sacramento, Delevan and Colusa NWRs. Lower Sacramento Valley and Delta region includes Gray Lodge WA (GLD) and Sutter NWR (SUT). San Joaquin Valley and South Bay region includes Mendota WA (MDT), refuges west of the San Joaquin River (SJW) – Volta WA, Los Banos WA, North Grasslands WA, San Luis NWR Complex except for East Bear Creek Unit, and Grasslands RCD – and refuges east of the San Joaquin River (SJE) which includes East Bear Creek Unit of San Luis NWR Complex and Merced NWR. Tulare Basin includes Kern NWR and Pixley NWR, and no CVPIA are located in Southern California (*Table 3-3*).

Table 3-7. Representation of no long-term groundwater overdraft scenario in CALVIN

CALVIN Groundwater Basin		Initial Storage	Ending Storage	
Abb.	Description		With Groundwater Overdraft	No Groundwater Overdraft
GW-01	C2VSim subregion 1	38,447	39,437	39,437 *
GW-02	C2VSim subregion 2	136,494	136,494	136,494
GW-03	C2VSim subregion 3	132,687	131,748	132,687
GW-04	C2VSim subregion 4	60,728	60,508	60,728
GW-05	C2VSim subregion 5	91,113	90,457	91,113
GW-06	C2VSim subregion 6	174,968	175,275	175,275 *
GW-07	C2VSim subregion 7	56,539	51,210	56,539
GW-08	C2VSim subregion 8	190,665	182,829	190,665
GW-09	C2VSim subregion 9	139,472	139,843	139,843 *
GW-10	C2VSim subregion 10	90,210	87,055	90,210
GW-11	C2VSim subregion 11	58,838	58,246	58,838
GW-12	C2VSim subregion 12	42,602	40,865	42,602
GW-13	C2VSim subregion 13	138,216	128,560	138,216
GW-14	C2VSim subregion 14	178,840	172,009	178,840
GW-15	C2VSim subregion 15	309,643	306,666	309,643
GW-16	C2VSim subregion 16	64,696	64,438	64,696
GW-17	C2VSim subregion 17	97,214	93,653	97,214
GW-18	C2VSim subregion 18	321,375	321,375	321,375
GW-19	C2VSim subregion 19	141,750	128,223	141,750
GW-20	C2VSim subregion 20	137,073	125,136	137,073
GW-21	C2VSim subregion 21	341,142	324,302	341,142
GW-AV	Antelope Valley	20,000	20,000	20,000
GW-CH	Coachella Valley	3,500	3,500	3,500
GW-EW	East-West MWD	7,000	7,000	7,000
GW-IM	Imperial Valley	930	930	930
GW-MJ	Mojave River Valley	2,580	2,580	2,580
GW-OW	Owens Valley	30,000	30,000	30,000
GW-SBV	San Bernardino Valley	2,500	2,500	2,500
GW-SC	Santa Clara Valley	425	425	425
GW-SD	San Diego	7,000	7,000	7,000
GW-VC	Ventura County	275	275	275

* Ending groundwater storage exceeds initial storage.

The sixteen scenarios are analyzed in this study which include (1) historical and warm-dry climate; (2) high outflow/ low export and existing Delta regulations; (3) with and without peripheral tunnels; and (4) with and without long-term groundwater overdraft. All model runs assume historical refuge deliveries, and year 2050 urban and agricultural demands. Results are averaged annually or monthly across the 82-year period. Existing Conveyance, Existing Regulations (EREC) scenario with historical hydrology and long-term groundwater overdraft is used as the base case, and the remaining scenarios are compared against the base case.

The section begins with a brief discussion of calibration or relaxation of model constraints needed to obtain a physically feasible solution. Next, hydrologic and economic impacts from the climate and regulatory uncertainties are summarized. Hydrologic impacts are determined by comparing flows at or just upstream of key diversion points. Economic impacts are indirectly evaluated from opportunity cost of delivering water to refuge nodes. Finally, adaptation strategies are outlined near the end of this section. These strategies include optimal management of existing resources, benefits and challenges from expanding existing or constructing new water sources, and identification of potential partners and cost of trading in water market to reach Full Level 4 deliveries targets.

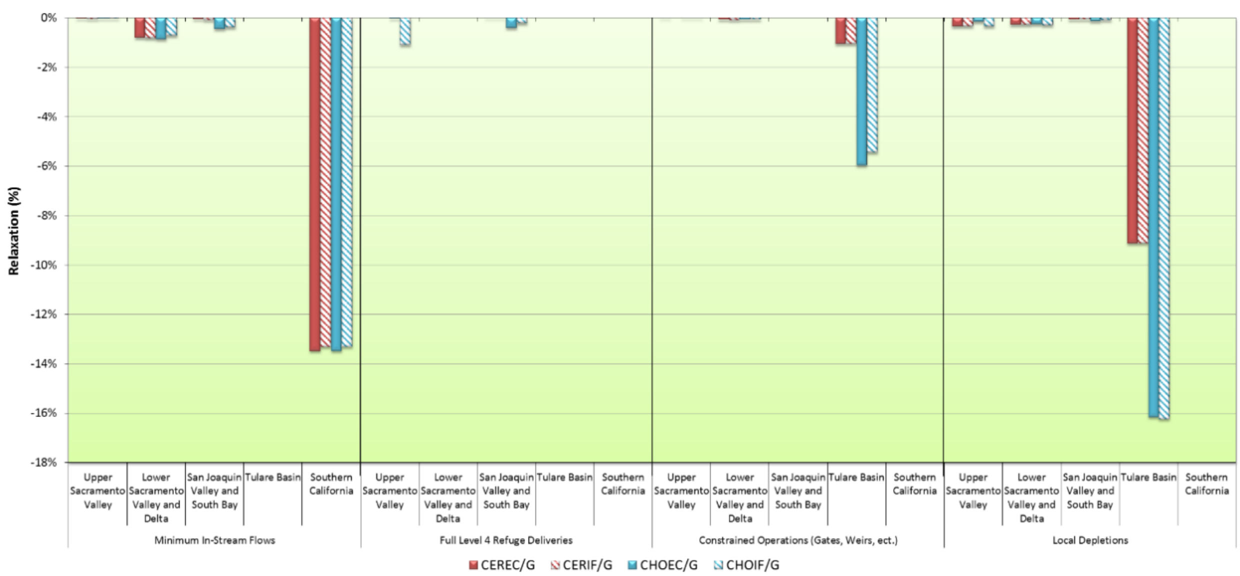


Figure 3-15. Percent relaxation of constrained flows in CALVIN

Only scenarios and categories of constrained flows which were relaxed to obtain a feasible solution are presented in this figure. For more information, refer to *Appendix 9.*

CEREC/G: Warm-dry hydrology; Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp); Existing Conveyance (no Peripheral Tunnels); with and without long-term groundwater overdraft

CERIF/G: Warm-dry hydrology; Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3); Isolated Facility (or Peripheral Tunnels)); with and without long-term groundwater overdraft

CHOEC/G: Warm-dry hydrology; High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4); Existing Conveyance (no Peripheral Tunnels)); with and without long-term groundwater overdraft

CHOIF/G: Warm-dry hydrology; High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4); Isolated Facility (or Peripheral Tunnels)); with and without long-term groundwater overdraft

Calibration summary

Sometimes constraints become very restrictive and model is unable to find a physically feasible solution that satisfies all the constraints. Under these circumstances, constraints are relaxed to obtain a feasible solution space. These constraints include minimum in-stream flow requirements, required Delta Outflows, local depletion flows, local accretion flows, constrained operations including bypass flows and south of the Delta exports, and fixed refuge deliveries. Only the model runs with warm-dry hydrology are re-calibrated which was expected since environmental flows and constrained operations are representative of historical hydrology, not warm-dry hydrology. *Figures 3-15* and *3-16* summarize the percent change and volumetric change in the constraints to obtain a feasible solution space. Results are also tabulated in *Appendix 9*.

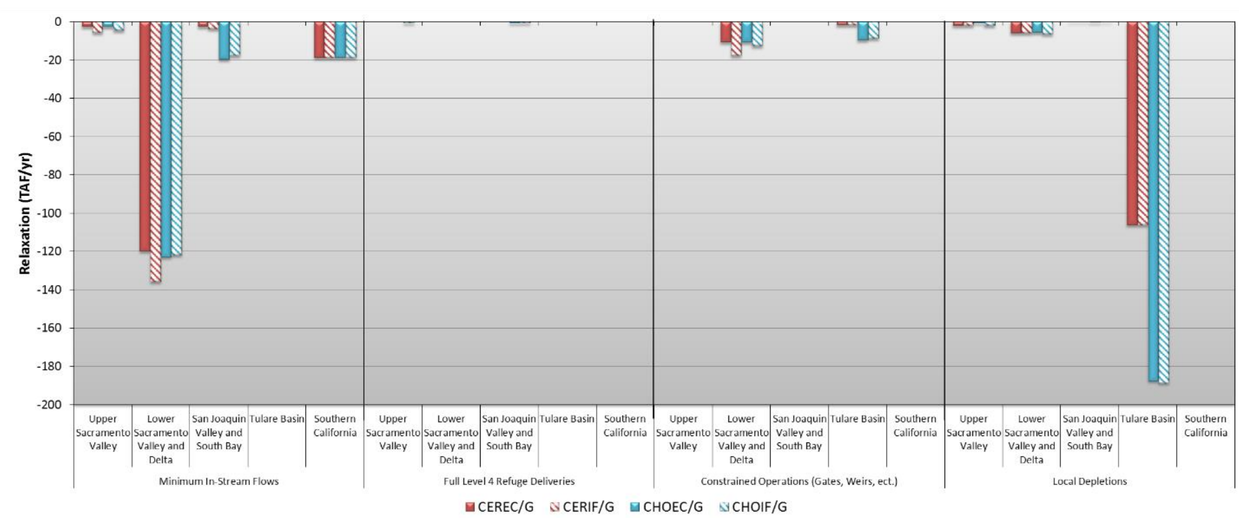


Figure 3-16. Volumetric relaxation of constrained flows in CALVIN

Only scenarios and categories of constrained flows which were relaxed to obtain a feasible solution are presented in this figure. For more information, refer to *Appendix 9*.

CEREC/G: Warm-dry hydrology; Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp); Existing Conveyance (no Peripheral Tunnels); with and without long-term groundwater overdraft
CERIF/G: Warm-dry hydrology; Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3); Isolated Facility (or Peripheral Tunnels)); with and without long-term groundwater overdraft
CHOEC/G: Warm-dry hydrology; High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4); Existing Conveyance (no Peripheral Tunnels)); with and without long-term groundwater overdraft
CHOIF/G: Warm-dry hydrology; High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4); Isolated Facility (or Peripheral Tunnels)); with and without long-term groundwater overdraft

Minimum in-stream flows are reduced by less one percent in Sacramento and San Joaquin Valley, and around 13% in Southern California. This translates to less than 20 TAF/yr reductions in minimum in Upper Sacramento, San Joaquin Valley and Southern California, and between 120 and 140 TAF/yr in Lower Sacramento Valley and Delta region. Historical refuge deliveries were not impacted under warm-dry hydrology; however, Full Level 4 deliveries to SRW and SJE refuge nodes are reduced by less than one percent or 1 TAF/yr. South of the Delta exports and James Bypass flows are lowered by 20 TAF/yr and 10 TAF/yr, respectively, which is equivalent of less than one percent reduction in exports and 6% reduction in James Bypass inflows into San Joaquin Valley. Finally, local depletion flows are reduced for all CALVIN regions except for Southern California. Most significant reductions are in Tulare Basin.

Local depletion flows are reduced by 9% to 16% or 100 to 190 TAF/yr in Tulare Basin. In summary, no infeasibilities occurred in historical hydrology runs. South of the Delta exports and refuge deliveries are not impacted by the warm-dry hydrology. Minimum in-stream flows in the Mono Basin and local depletions flows within Tulare Basin are significantly re-calibrated to obtain feasible warm-dry hydrology runs.

Vulnerability to changing conditions

Two metrics are used to assess vulnerability of refuge deliveries to changing climatic and regulatory conditions: (1) changes in channel flows and inter-basin exports to determine hydrologic impact and (2) changes in opportunity cost of refuge deliveries to determine economic impact. Agricultural water users represent nearly 65% of the total demand represented in CALVIN whereas refuges claim less than 2% of the total demand (*Table 3-5*). Much of the hydro-economic trends highlighted in this section are driven by agricultural scarcity in the Central Valley of California. Percent agricultural scarcity and corresponding Willingness to Pay (WTP) is tabulated in *Tables 3-8* and *3-9*.

Under historical hydrology, impacts on agricultural scarcity from various regulatory scenarios are limited to Lower Sacramento Valley, San Joaquin Valley and Tulare Basin. Peripheral tunnels reduce agricultural scarcity by 50% throughout the Central Valley. Export curtailments under the high Delta Outflow scenario trap previously exported water in the north. As a result, agricultural scarcity reduces by 25% in Lower Sacramento Valley and increases by 25 – 50% south of the Delta. Combined, tunnels and high Delta Outflow requirements, still reduce agricultural scarcity in the entire valley; however, the gains from additional supplies are cut in half south of the Delta (agricultural scarcity only reduces by 25% instead of 50%). No groundwater overdraft scenario diminishes any gains from peripheral tunnels and when combined with high Delta Outflow requirements, further increases agricultural scarcity by 40% south of the Delta resulting in highest scarcity among agricultural users in San Joaquin Valley and Tulare Basin across all the regulatory scenarios under the historical hydrology.

The warm-dry hydrology increases scarcity among all agricultural users in the Central Valley. Upper Sacramento Valley experiences the largest increase in scarcity from less than 1% to about 25%. Lower Sacramento Valley and south of the Delta farmers see 500% and 300% increase in scarcity, respectively. Under this warm-dry hydrology, scenario impacts extend throughout the entire Central Valley including the previous insulated Upper Sacramento Valley. North-South divide begins to emerge with peripheral tunnels while the gains from tunnels diminish significantly. Agricultural scarcity increases by 40% north of the Delta and reduces by a mere 15% south of the Delta compared to 50% reduction under historical hydrology. Due to five-fold increase agricultural scarcity south of the Delta, farmers in San Joaquin Valley and Tulare Basin are willing to pay two – three times more than farmers in Sacramento Valley for the same amount of water. As a result, agricultural scarcity increases in the north since tunnels provide additional opportunities to export water to users south of the Delta. High Delta Outflow requirements also create a North-South divide, but the effects are reversed compared to the peripheral tunnels scenario and are almost entirely concentrated on San Joaquin Valley in the south. Agricultural scarcity falls by 30% in the north and increases by 45% in the San Joaquin Valley compared a mere 3% increase in Tulare Basin. By combining tunnels and high Delta Outflow requirements, any gains north of the Delta are lost and scarcity increases by 40% instead. South of the Delta scarcity reduces by just 10% reduction compared to 15% and 25% in absence of high Delta Outflow requirements under warm-dry and historical hydrology, respectively. The no overdraft scenario has the same impact south of the Delta as it had with the historical hydrology: any gains from peripheral tunnels are lost and when combined with high Delta Outflow requirements, scarcity further increases by 40%, resulting in highest scarcity south of the Delta among all the regulatory scenarios. Ending overdraft increases scarcity by 7%, on average, north of the Delta regardless of the peripheral tunnels.

Table 3-8. Percent scarcity to agricultural water users

	EREC				ERIF				HOEC				HOIF				
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	
Upper Sacramento Valley	0.4%	0.4%	26%	28%	0.5%	0.5%	40%	40%	0.3%	0.4%	15%	17%	0.4%	0.4%	39%	39%	North of Delta
Lower Sacramento Valley and Delta	5%	8%	28%	31%	3%	5%	39%	44%	4%	6%	21%	24%	3%	5%	35%	39%	North of Delta
San Joaquin Valley and South Bay	12%	14%	41%	58%	5%	12%	35%	41%	15%	21%	59%	65%	8%	13%	37%	48%	South of Delta
Tulare Basin	10%	13%	47%	49%	5%	11%	38%	47%	14%	20%	48%	50%	8%	12%	42%	48%	South of Delta
Southern California	3%	3%	4%	4%	3%	3%	4%	4%	3%	4%	4%	4%	3%	3%	4%	4%	South of Delta

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Table 3-9. Willingness to pay for agricultural water use assuming historic refuge deliveries ($/AF)

	EREC				ERIF				HOEC				HOIF				
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	
Upper Sacramento Valley	5	5	395	398	5	5	507	523	5	5	270	308	5	5	469	491	North of Delta
Lower Sacramento Valley and Delta	63	90	463	484	30	59	507	543	42	77	333	428	30	70	508	544	North of Delta
San Joaquin Valley and South Bay	346	487	1,280	1,498	139	347	1,113	1,307	517	727	1,463	1,686	281	420	1,189	1,369	South of Delta
Tulare Basin	309	440	1,055	1,175	108	331	890	1,075	466	659	1,152	1,333	216	406	955	1,127	South of Delta
Southern California	257	257	388	394	252	257	367	387	257	336	396	413	257	257	386	388	South of Delta

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Channel flows and inter-basin exports

Hydrologic impacts from the sixteen hydrologic and regulatory scenarios are summarized in *Table 3-10*. Channels flows at Hamilton City represent Sacramento River just upstream of GCID's diversion point, the irrigation district that serves refuges west of the Sacramento River (SRW). In-stream flows are reduced by 20% across all regulatory scenarios under warm-dry hydrology. Inflows into Sutter Bypass upstream of the Sutter NWR combine inflows from Butte Creek, Mouton Weir and Colusa Weir into the bypass. Channel flows fall by 7% with the warm-dry hydrology, but increase during the HOEC scenario by 15% with the historical hydrology and 9% with the warm-dry hydrology. Export curtailments under HOEC scenario trap previously exported water north of the Delta which creates a surplus water conditions in the north and as a result, excess flows are routed through the bypass system.

Changes in south of the Delta exports affect deliveries to refuges in the San Joaquin Valley and Tulare Basin. Under Existing Regulations, Existing Conveyance (EREC) scenario, roughly 400 TAF per month is exported for use south of the Delta. Exports increase by 12% with peripheral tunnels (ERIF); decrease by 30% under high Delta Outflow regulations (HOEC); and remain same when high Delta Outflow scenario is combined with tunnels (HOIF). Since exports and Delta Outflows are represented as constrained flows for each conveyance and outflow scenario, south of the Delta exports do not vary with warm-dry hydrology or groundwater overdraft cases[5].

Table 3-10. Hydrologic impact summary (TAF/mth)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Sacramento R upstream of Red Bluff Diversion Dam (TCID Diversion point)	714	714	578 (-19%)	578 (-19%)	715	715	579 (-19%)	580 (-19%)	714	714	578 (-19%)	578 (-19%)	714	714	580 (-19%)	580 (-19%)
Sacramento R @ Hamilton City (upstream GCID Diversion)	750	750	604 (-19%)	603 (-20%)	750	750	606 (-19%)	606 (-19%)	749	749	603 (-20%)	603 (-20%)	750	750	607 (-19%)	607 (-19%)
Sutter Bypass Inflows Upstream of Sutter NWR	95	94	88 (-7%)	88 (-7%)	95	96 (1%)	88 (-7%)	89 (-6%)	109 (15%)	111 (17%)	103 (9%)	103 (9%)	94	95	88 (-7%)	88 (-7%)
Total South of Delta Exports *	408	408	408	408	457 (12%)	457 (12%)	443 (9%)	457 (12%)	287 (-30%)	287 (-30%)	287 (-30%)	287 (-30%)	413 (1%)	413 (1%)	413 (1%)	413 (1%)
*Banks Pumping Plant Exports **	*227*	*227*	*227*	*227*	*269 (19%)*	*269 (19%)*	*269 (19%)*	*269 (19%)*	*156 (-31%)*	*156 (-31%)*	*156 (-31%)*	*156 (-31%)*	*224 (-1%)*	*224 (-1%)*	*224 (-1%)*	*224 (-1%)*
*Tracy Pumping Plant Exports **	*181*	*181*	*181*	*181*	*188 (4%)*	*188 (4%)*	*175 (-4%)*	*188 (4%)*	*131 (-28%)*	*131 (-28%)*	*131 (-28%)*	*131 (-28%)*	*189 (4%)*	*189 (4%)*	*189 (4%)*	*189 (4%)*
Friant-Kern Canal Exports	119	116 (-2%)	58 (-51%)	59 (-50%)	122 (2%)	122 (3%)	67 (-44%)	60 (-49%)	119	116 (-3%)	50 (-58%)	55 (-54%)	121 (2%)	120 (1%)	59 (-51%)	54 (-54%)
Upper Merced R (upstream R-SJE diversion)	77	77	49 (-37%)	49 (-37%)	76 (-1%)	77	49 (-37%)	49 (-37%)	77	77 (1%)	49 (-37%)	49 (-37%)	77	77	49 (-37%)	49 (-37%)
Lower Merced R (upstream R-SJE diversion)	55	47 (-15%)	27 (-50%)	26 (-52%)	43 (-23%)	44 (-20%)	24 (-56%)	25 (-55%)	49 (-11%)	57 (3%)	28 (-49%)	29 (-48%)	47 (-15%)	42 (-25%)	27 (-50%)	27 (-51%)
Inflows into Mendota Pool	38	31 (-18%)	151 (296%)	162 (328%)	47 (24%)	39 (4%)	125 (230%)	139 (265%)	21 (-45%)	24 (-36%)	113 (199%)	114 (201%)	36 (-6%)	24 (-37%)	124 (225%)	131 (245%)

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Operations constrained across climatic and overdraft scenarios, but vary by conveyance and Delta Outflow scenarios.

[5] Only exception is the ERIF scenario with warm-dry hydrology and long-term groundwater overdraft where exports from Tracy pumping plant were calibrated to obtain a feasible solution.

Friant-Kern Canal (FKC) exports surface water from Millerton Lake into Tulare Basin. USBR is in process of negotiating an agreement with Delano-Earlimart Irrigation District to secure surface water from FKC for Pixley NWR (USBR, 2011j). Therefore, variations in FKC exports could directly impact deliveries to Pixley NWR. Under historical hydrology and no overdraft, FKC exports fall by 2 to 3% to provide additional surface water deliveries to users within San Joaquin Valley. Peripheral tunnels increase south of the Delta exports which increase FKC exports 2 – 3% to Tulare Basin. However, all gains are lost under warm-dry conditions and exports decrease 45 – 60% across all conditions. Therefore, there may be short term benefits from connecting Pixley NWR with Friant-Kern Canal, but deliveries would be less reliable in the future under warm-dry hydrologic conditions.

Refuges east of San Joaquin River (SJE), East Bear Creek Unit and Merced NWR, rely on diversions from Merced River watershed to meet their water demand. Agricultural water users, who divert water from Merced River, also divert water from San Joaquin River downstream of Mendota Pool, Millerton Lake via Madera Canal, and groundwater basins GW-12 and GW-13. Upper Merced River, diversion point for Merced Irrigation District, is unaffected by peripheral tunnels, high Delta Outflow requirements and no groundwater overdraft scenario. Flows reduce by 37% under warm-dry hydrology, consistent with the 40% reduction in available water supplies in the San Joaquin Valley (*Figure 3-12*). Lower Merced River which is the diversion point for Stevenson Water District is affected by both hydrologic and regulatory scenarios due to increased competition for water among the upstream users and lack of available water supplies under the warm-dry hydrology. Under the historical hydrology, inflows into Mendota Pool fall by 45% due to export curtailment (HOEC). As a result, local water users switch to Merced River water and channel flows fall by 10%. Ending overdraft limits access to groundwater supplies and further reduces channel flows by 10 – 15%. Even though peripheral tunnels lower agricultural scarcity by 50% south of the Delta, channel flows in Lower Merced River are still reduced by 15 – 25%. To distribute benefits from increased exports in the entire San Joaquin Valley and Tulare Basin, the system re-operates and increases FKC exports to agricultural users on the east side of Tulare Basin. Increased FKC exports reduce surface water supplies available to local water users from Millerton Lake via Madera Canal, so users switch to Merced River water. With the warm-dry hydrology, channels flows fall by half and marginally vary with regulatory scenarios. Since flows in lower Merced River fall regardless of the hydrologic and regulatory case due to increased competition among upstream users, it may be beneficial to secure long-term surface water deliveries from irrigation districts in the upper Merced River watershed to ensure reliable source of water supply to refuges east of the San Joaquin River (SJE).

Mendota Pool is the primary point of diversion for refuges west of the San Joaquin River (SJW) and Mendota Wildlife Area (MDT). In addition to CVPIA refuges, agricultural water users on both sides of the San Joaquin Valley and in Tulare Basin divert water from Mendota Pool. Similar to the Merced River watershed, inflows into Mendota Pool also have an integrated response to hydrologic and regulatory conditions. Under historical hydrology, export curtailments (HOEC) lower Mendota Pool inflows by 45%. Peripheral tunnels increase Mendota Pool inflows by 25%; however, when combined with high Delta Outflow requirements, inflows reduce by 5%. No groundwater overdraft further reduces Mendota Pool inflows by 10 – 30%. Tulare Basin water users are severely affected by SGMA. Groundwater basins in Tulare Basin are four times more depleted than groundwater basins in San Joaquin Valley or Lower Sacramento Valley (*Table 3-7*). As a result, with no overdraft, surface water supplies previously available to users in San Joaquin Valley are left in Delta-Mendota Canal or California Aqueduct to be diverted by

Tulare Basin water users. However, San Joaquin Valley has the largest volumetric change in their water supplies with the warm-dry hydrology. Subsequently, more surface water supplies are delivered into Mendota Pool via Delta-Mendota Canal and inflows increase by 200 – 300% across all cases with the warm-dry hydrology. Increased inflows, however, do not reduce competition for water in San Joaquin Valley. Agricultural scarcity increases by more than 300% in San Joaquin Valley and increased inflows are diverted by local farmers to offset losses from reduced local inflows.

Opportunity cost of refuge deliveries

Refuge deliveries are represented as *hard* constraints or fixed deliveries in CALVIN. These deliveries have priority over urban and agricultural deliveries and are always met unless the model cannot find a physically feasible solution. As a result, refuges do not directly compete with agricultural and urban water users. In the model runs, historical refuge deliveries are always met; full Level 4 deliveries to refuges west of the Sacramento River (SRW) and east of the San Joaquin River (SJE) are reduced by 1% or 1 TAF/yr under warm-dry scenario. Opportunity costs of refuge deliveries are used as an alternative metric to determine competition for water under different scenarios. The opportunity cost ($/AF) represents system-wide economic output lost as a result of delivering water to the refuge. Higher opportunity cost indicates more valuable use for water and therefore, more intensified competition for water.

Table 3-11 summaries the opportunity cost of refuge deliveries. Results indicate: (1) with historical hydrology, there is abundant water supply north of the Delta to meet refuge needs; (2) opportunity cost of refuge deliveries increase as water travels further south in the Central Valley; (3) tunnels marginally increase competition for water north of the Delta and significantly reduce competition south of the Delta; (4) ending overdraft (SGMA) increases competition for water throughout the Central Valley; (5) warm-dry hydrology drastically intensifies competition for water both, north and south of the Delta, but dampens the effects of tunnels and ending overdraft; and (6) the High Outflow, Existing Conveyance (HOEC) scenario magnifies the north-south divide and provides a net system-wide benefit to deliver more water to refuges west of Sacramento River (SRW) (*Figure 3-17*).

Similar to the trend in channel flows, under historical hydrology, opportunity cost of refuge deliveries is unresponsive to regulatory scenarios in regions north of the Delta. The opportunity cost increases dramatically with the warm-dry hydrology – from $2 to $30 per acre-foot in Upper Sacramento Valley and to $290 per acre-foot in Lower Sacramento Valley – and fluctuates with conveyance, Delta Outflow and groundwater overdraft scenarios. Peripheral tunnels, under ERIF and HOIF scenarios, provide additional opportunities to capture and export surplus water south of the Delta and as a result, increase competition for surface water north of the Delta. Opportunity cost on refuge deliveries increases three to four times (from $30 to $130 - $170 per acre-foot) in Upper Sacramento Valley and up to 22% in Lower Sacramento Valley (from $290 to $350 per acre-foot). The HOEC scenario curtails Delta exports 30% below the base case which creates a water surplus north of the Delta, lowers opportunity cost on refuge deliveries by 17% - 33% in Lower Sacramento Valley, and even generates a negative opportunity cost on deliveries to refuges west of Sacramento River – Sacramento, Delevan and Colusa NWRs (*Figure 3-17*). Finally, ending overdraft increases the opportunity cost by $4 - $70 per acre-foot.

Table 3-11. Opportunity cost* of historic refuge deliveries ($/AF)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	2	2	30	44	3	3	131	198	2	2	-76	-30	2	2	174	195
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	2	2	289	291	2	2	327	394	1	1	195	219	2	2	353	365
Gray Lodge Wildlife Area (GLD)	4	4	292	293	4	4	283	274	3	3	242	264	4	4	268	272
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	254	377	808	998	141	263	742	927	381	498	896	1,115	196	354	745	890
West of San Joaquin River (SJE)	235	347	708	785	130	242	576	702	370	490	821	995	182	330	637	747
Mendota Wildlife Area (MDT)	248	366	814	930	138	257	657	815	381	502	929	1,125	193	347	723	854
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	339	494	926	926	223	374	926	926	499	637	926	926	273	473	926	926
Kern National Wildlife Refuge (KER)	320	464	948	1,059	187	331	769	940	491	643	1,094	1,321	255	444	851	999

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Since refuges deliveries are represented as constrained flows in CALVIN, model allocates water to refuges before delivering water to agricultural and urban water users. Opportunity cost reflects competition for water delivered to refuges; hence, qualitatively access the likelihood of waster scarcity at refuges. Negative opportunity cost represents a net benefit to the system to deliver water to the refuge.

Negative opportunity cost indicates a net system-wide benefit as result of delivering more water to the refuge. The negative opportunity cost exists in all months except June through September, the peak irrigation months. Although tunnels (ERIF and HOIF scenarios) reduce that window of negative opportunity cost to just January, opportunity cost from March through May and October through February is marginal compared to the peak irrigation months. The opportunity cost is always negative in January under warm-dry hydrology because, as a result of shift in precipitation pattern, runoff under warm-dry hydrology exceeds runoff under historical hydrology during month of January (*Figure 3-11*). Monthly averaged opportunity cost plots for other refuges are included in *Appendix 10c*.

As water travels south into the Central Valley, opportunity cost of refuge deliveries increases to $235 - $250 per acre-foot in San Joaquin Valley and to $320 - $340 per acre-feet in Tulare Basin. This opportunity cost triples with the warm-dry hydrology and increases from $235 - $250 to $700 - $815 per acre-foot in San Joaquin Valley and from $320 - $340 to $925 - $940 per acre-foot in Tulare Basin. South of the Delta refuges are impacted by regulatory scenarios under both, historical and warm-dry hydrology, but the impacts are dampened with the warm-dry hydrology. Peripheral tunnels, under ERIF scenario and historical hydrology, lower opportunity costs by 35 to 45% compared to 8 to 20% under the warm-dry hydrology. Export curtailments, under HOEC scenario and historical hydrology, increase the opportunity cost by 45 to 60% compared to 10 to 15% under the warm-dry hydrology. Peripheral tunnels and high outflows (HOIF) combined lower opportunity costs by 20 to 25% with the historical hydrology and by 10% with the warm dry hydrology.

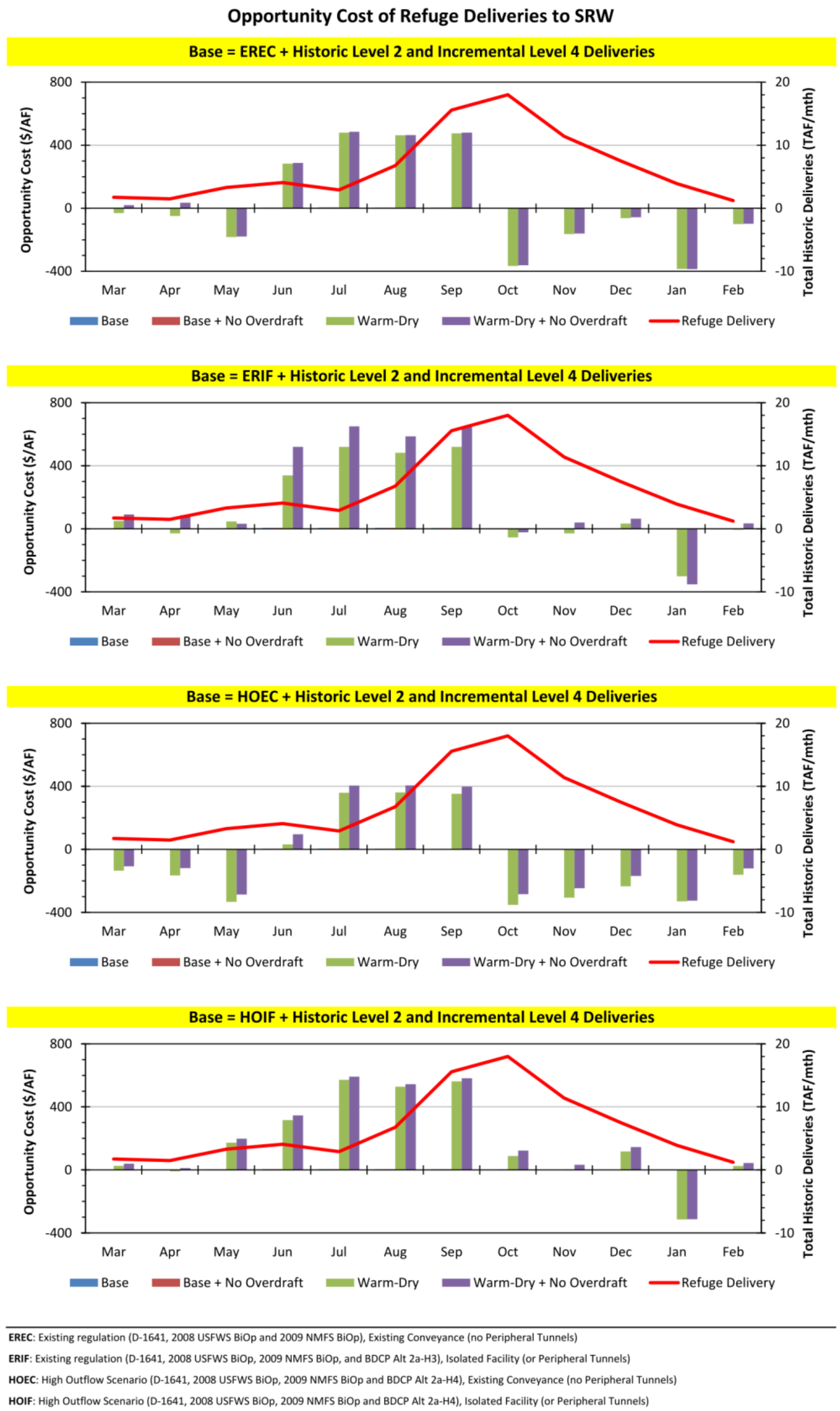


Figure 3-17. Monthly averaged opportunity cost of historic deliveries to refuges west of the Sacramento River

Figure 3-18. Refuge water supply portfolio assuming historic refuge deliveries and optimized system-wide management

Overall, Upper Sacramento Valley refuges have the least opportunity cost and Tulare Basin refuges the highest opportunity cost. With historical hydrology, peripheral tunnels increase the opportunity cost by about 20% north of the Delta and reduce it by about 40% south of the Delta. Increased export opportunities combined with economically more valuable agriculture south of the Delta with two to three times the Willingness to Pay (WTP) compared to the users in the north intensify competition for surface water north of the Delta and subsequently, increase opportunity cost of north of the Delta refuge deliveries (*Figure 3-8*). Export curtailments under the HOEC scenario widen the north-south disparity. On average, opportunity cost falls by 15% north of the Delta and increases by 50% increase south of the Delta. Peripheral tunnels and high Delta Outflow regulations combined curb negative and positive impacts on opportunity cost north and south of the Delta, respectively. Opportunity cost increases by 5% instead of 20% north of the Delta and lowers by 20% instead of 40% south of the Delta. Ending overdraft increases opportunity cost by 2 – 3% north of the Delta and 30 – 80% south of the Delta. The warm-dry climate increases competition for water throughout the Central Valley. On average, agricultural scarcity increases from 3 to 27% north of the Delta and from 11 to 44% south of the Delta (*Table 3-8*).

Adaptation strategies

Groundwater is used to meet only 3% of the refuge need under historical hydrology and expands to 4 – 5% under warm-dry hydrology (*Figure 3-18*). Currently, only Gray Lodge WA, Sutter NWR, Merced NWR, Pixley NWR, and some of the refuges west of the San Joaquin River pump groundwater. Recently, some members of the Congress have proposed to expand groundwater pumping at the refuges in lieu of surface water. However, several refuges south of the Delta which previously used groundwater had to shut all or some of their wells due to poor water quality, subsidence and/or drop in groundwater levels below their well screens (USBR, 2010a-b; USBR, 2011a-l). Refuge managers are reluctant to pursue this option. There are also proposals to expand surface water deliveries to Sutter NWR and Pixley NWR, both of which are CVPIA refuges, but lack access to reliable surface water supplies. Sutter NWR is considering expanding its surface water deliveries from Sutter Extension Water District (SEWD) and Pixley NWR from Friant-Kern Canal via Delano-Earlimart Irrigation District. Overall, historical deliveries are still short of Full Level 4. Only 89% of the Full Level 2 and 47% of the incremental Level 4 deliveries have been met between 2001 and 2014 (*Table 2-2*). Meanwhile, USBR and USFWS are working to find long-term and short-term water trading partners to realize Full Level 4 deliveries. This section tries to answer three key questions: (1) how to manage existing water supply sources to best respond to changing hydrologic and management conditions; (2) where to expand surface water and groundwater resources; (3) possible water trading partners and cost of realizing Full Level 4 deliveries? The results are restricted by the model's limitations. Water quality is not explicitly modeled in CALVIN. Although an operating cost is assigned to pumping operations to deter the model from over-relying on groundwater pumping when surface water supplies are available, cost does not vary with groundwater head nor does it account for water quality issues. Therefore, the optimal water supply portfolio may not be fully identified. The model does not account for many operational limitations of refuges. For example, lift pumps at Sutter NWR require a certain head before the water can be lifted from the bypass into the refuge. As far as the model is concerned, Sutter NWR can divert water from the bypass as long as there is water available in the bypass.

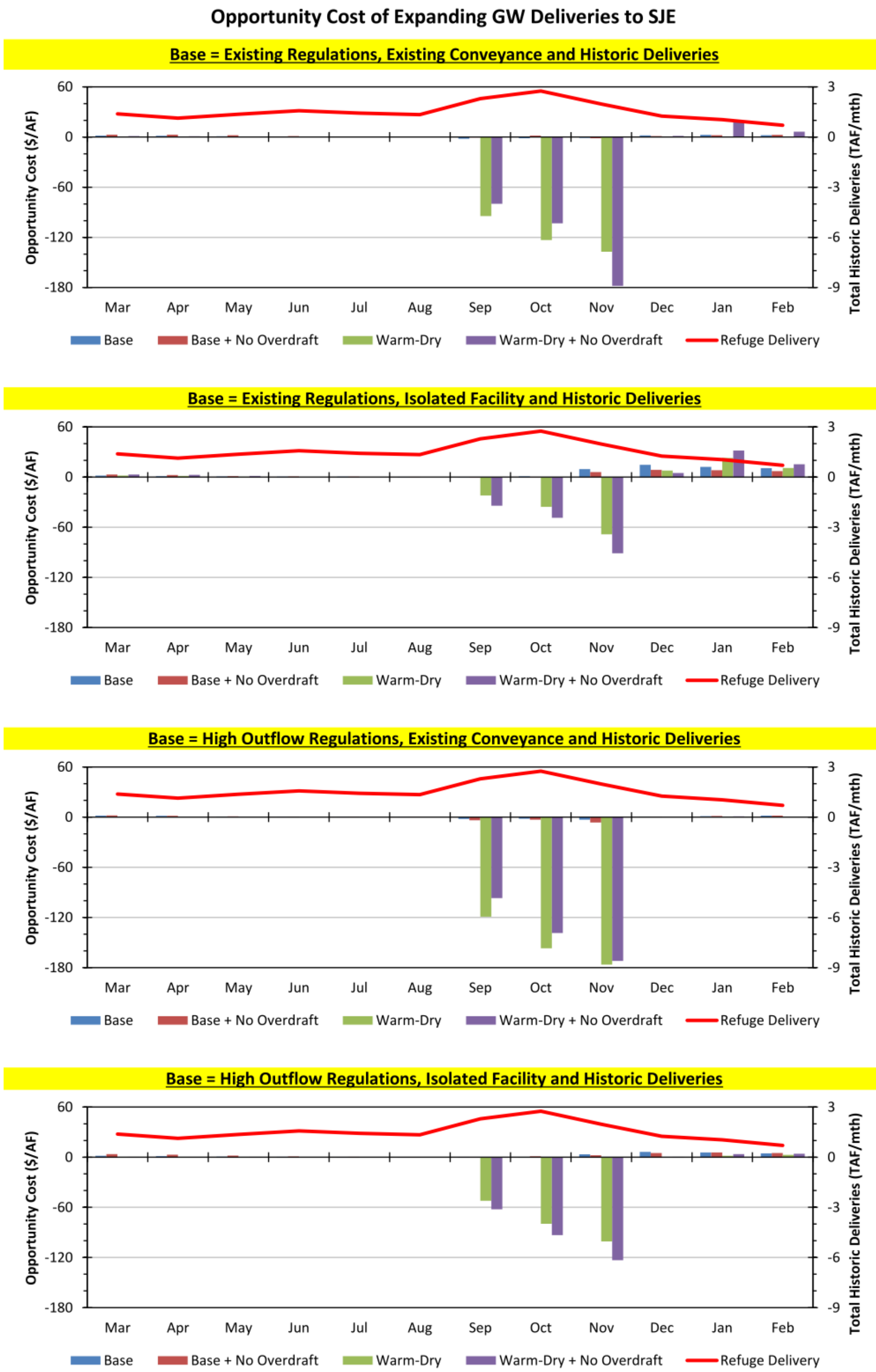
Refuge management

Water supply portfolio for different climatic and regulatory conditions is summarized in *Figure 3-18*. Due to current refuge water supply configuration, only four of the eight refuge areas have access to both surface water and groundwater. These include Gray Lodge WA (GLD), Sutter NWR (SUT), and refuges east and west of the San Joaquin River (SJE and SJW).

Existing groundwater capacity at Gray Lodge WA (GLD), as modelled in this study, can provide 20 – 90% of historic monthly refuge deliveries between June and December and 100% of the historic refuge deliveries in the remaining months. Similarly, exiting groundwater capacity at Sutter NWR (SUT) can provide up to 100% of historical refuge deliveries. However, long-term groundwater use is 3 – 6% for Gray Lodge WA (GLD) across all scenarios, at 2 – 3% for Sutter NWR (SUT) with historical hydrology, and 0% for Sutter NWR under warm-dry climate with the exception of peripheral tunnels and no overdraft scenario where groundwater use increases to 16% and 21% for GLD and SUT. Agricultural scarcity increases dramatically under warm-dry climate and ending overdraft scenario further restricts the use of groundwater. Since peripheral tunnels expand the opportunity to move surface water south of the Delta, north of the Delta water users switch to groundwater to forgo use of surface water which is delivered to users south of the Delta. Except for this one case, there is no apparent trend in groundwater management to adapt to the changing conditions. Moreover, since only a small portion of available groundwater capacity is used to meet refuge needs, it appears that groundwater does not play a significant role north of the Delta in adapting to changing hydrologic and management conditions.

Developed groundwater supplies at refuges west of the San Joaquin River are extremely limited. Existing groundwater capacity can only provide maximum of 1 – 6% of historic monthly deliveries. Even then, groundwater use is limited to 0.2 – 0.3%, and only maximizes to full capacity under HOEC scenario with warm-dry hydrology and groundwater overdraft when exports are curtailed 30% below the base scenario and San Joaquin Valley has lost more than 40% of its water supplies. Results echo a similar conclusion as north of the Delta refuges: since only a small portion of available groundwater capacity is used to meet refuge needs, it appears that groundwater does not play a significant role at refuges west of San Joaquin River in adapting to changing hydrologic and management conditions.

Among the four refuges, refuges east of San Joaquin River (SJE) have the most dynamic water use portfolio. Existing groundwater capacity, as modelled in this study, can provide up to 100% of historical refuge deliveries in all months except for September and October. Groundwater use corresponds with the availability of surface water supplies. In the base case, 60% of the demand is met with groundwater. Peripheral tunnels expand export opportunities and subsequently, groundwater use drops to 45 – 50% under ERIF and HOIF with historical hydrology. HOEC scenario curtails south of the Delta exports and as a result, groundwater use increases to 65 – 67%. Warm-dry hydrology reduces available water supplies by 40% in the San Joaquin Valley. Consequently, groundwater use expands to 93% in absence of tunnels, and 83 – 88% with peripheral tunnels. Ending long-term groundwater overdraft curbs groundwater use by 2 – 5% under both, historical and warm-dry hydrology with a few exceptions: (1) no impact under HOEC and warm-dry hydrology; (2) lowers by 22% under EREC and warm-dry hydrology; and (2) lowers by 12% under HOIF and historical hydrology.



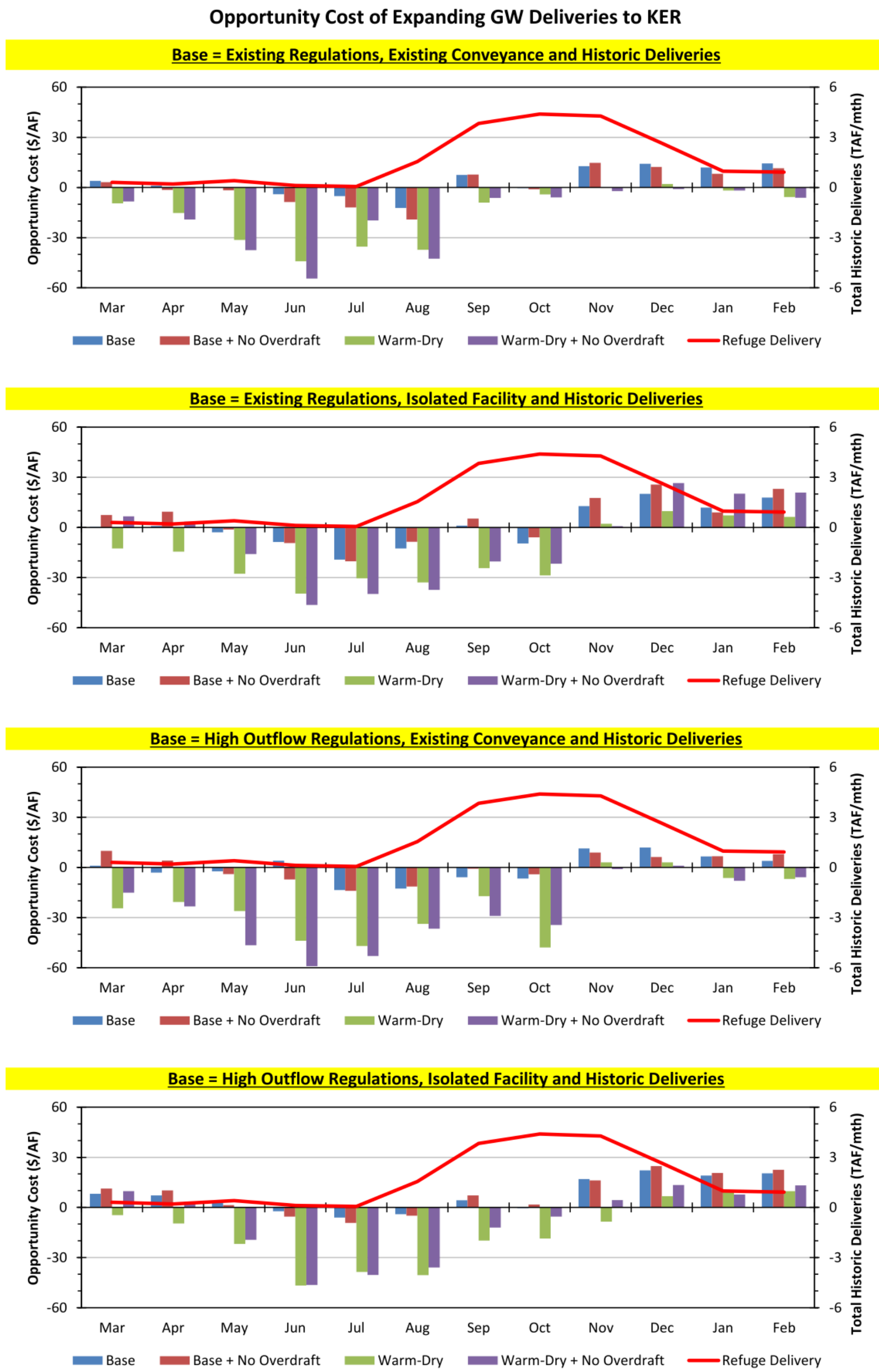
EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Figure 3-19. Monthly averaged opportunity cost of expanding groundwater pumping at refuges east of the San Joaquin River



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Figure 3-20. Monthly averaged opportunity cost of expanding groundwater pumping at Kern NWR

Finally, the results indicate a negative opportunity cost on refuge deliveries to refuges west of Sacramento River (SRW) outside of the peak irrigation months, June through September (*Figure 3-17*). Negative opportunity cost indicates a net system-wide benefit as result of delivering more water to the refuge. Although tunnels (ERIF and HOIF scenarios) reduce that window, opportunity cost from March through May and October through February is still marginal compared to the peak irrigation months. Timothy grass and watergrass (or smartweed) combined account for roughly 85% of the total managed wetlands at SRW refuges. Both land-use types are flooded approximately beginning late August – early September. Watergrass units are also irrigated mid-June prior to flood-up. Monthly averaged opportunity cost indicates that under warm-dry hydrology, competition for water can be reduced if irrigation could be moved earlier in the season, April – May, and most flood up could be delayed until October – November. Both strategies reduce the production time period, but show a promising way to tackle the effects of a warm-dry hydrology. Moving irrigation to earlier in the season also mean that wetlands cannot be sustained as late as May; they would need to be drained by late March – early April. Delaying flood-up till October will also keep these wetlands out of production for an additional month. Collectively, flood-up season will be reduced from late August – early May to late September – early April.

Table 3-12. Opportunity cost* of expanding surface water deliveries to CVPIA refuges ($/AF)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	0	0	28	27	0	0	33	45	0	0	23	27	0	0	38	42
Gray Lodge Wildlife Area (GLD)	0	0	25	25	0	0	27	25	0	0	18	20	0	0	32	32
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	0	0	33	23	0	0	10	5	0	0	80	43	0	0	27	11
West of San Joaquin River (SJE)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mendota Wildlife Area (MDT)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	-11	-8	84	291	-16	-13	16	169	-10	-1	190	437	-12	-10	13	154
Kern National Wildlife Refuge (KER)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
***** Opportunity cost (or Lagrange multiplier) reflects change in objective function if the capacity constraint is relaxed by one unit. Since objective function is a cost minimization function, opportunity cost represents system-wide cost of expanding conveyance capacity by one acre-foot. Negative opportunity cost represents a net benefit to the system from expanding conveyance capacity by one acre-foot.

Infrastructure development

Infrastructure development opportunities are explored by examining the opportunity cost of expanding existing or constructing new surface water and groundwater conveyance (*Tables 3-12* and *3-13*). Similar to the opportunity cost ($/AF) on refuge deliveries, opportunity cost represents system-wide economic output lost as a result of expanding the conveyance capacity. Negative opportunity cost indicates a net system-wide benefit from expanding the conveyance capacity. All CVPIA refuges have access to reliable surface water, except for Sutter NWR (SUT), which relies on the Sutter Bypass flows for most of its water supply, and Pixley NWR (PIX) which completely relies on groundwater. On the other end of the spectrum, refuges west of Sacramento River (SRW), Mendota Pool WA (MDT) and Kern NWR (KER) have no active groundwater wells available for refuge management.

Two potential surface water expansion projects are evaluated: expanding SEWD deliveries to Sutter NWR and connecting Pixley NWR to Friant-Kern Canal. Model results are indifferent to expanding SEWD deliveries under historical hydrology, but deter any expansion under warm-dry conditions, especially with peripheral tunnels due to increased opportunity for exporting surface water south of the Delta users where willingness to pay is three to four times higher compared to users in the north (Figure 3-8). Results indicate a net benefit in expanding surface water deliveries from Friant-Kern Canal to Pixley NWR under historical hydrology regardless of conveyance, Delta Outflow or groundwater overdraft scenario. However, all benefits are lost under a warm-dry hydrology and reliable surface water supplies from Friant-Kern Canal become increasing competitive to acquire.

Table 3-13. Opportunity cost* of expanding groundwater deliveries to CVPIA refuges ($/AF)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	1	2	320	323	1	2	328	205	1	1	259	275	2	2	352	400
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	3	4	291	292	4	4	283	261	3	3	241	262	4	4	268	271
Gray Lodge Wildlife Area (GLD)	2	2	205	161	2	2	262	225	2	2	142	75	3	3	182	135
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	1	1	-30	-28	4	3	-7	-10	0	0	-38	-34	2	2	-19	-22
West of San Joaquin River (SJE)	7	14	18	-13	4	6	6	10	8	10	-29	572	7	4	3	12
Mendota Wildlife Area (MDT)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kern National Wildlife Refuge (KER)	4	1	-16	-17	1	4	-15	-9	0	0	-22	-26	7	8	-15	-9

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
***** Opportunity cost (or Lagrange multiplier) reflects change in objective function if the capacity constraint is relaxed by one unit. Since objective function is a cost minimization function, opportunity cost represents system-wide cost of expanding conveyance capacity by one acre-foot. Negative opportunity cost represents a net benefit to the system from expanding conveyance capacity by one acre-foot.

Groundwater expansion is explored at all refuges. Water quality is not explicitly modeled in CALVIN, so results are limited to water quantity benefits realized from groundwater expansion. Even though model results might indicate some promising solutions, they may not be attainable without additional investment in water treatment or blending with surface water supplies. A low, positive opportunity cost is associated with groundwater expansion under historical hydrology throughout the Central Valley. A pattern begins to emerge with the warm-dry hydrology. Despite 28% reduction in water supplies under warm-dry hydrology and increased competition for surface water supplies due to peripheral canal, results indicate a net cost to the system for expanding groundwater supplies north of the Delta. On the other hand, a net benefit emerges from expanding groundwater supplies at refuges east of San Joaquin River (SJE) and at Kern NWR (KER) regardless of the regulatory scenario. *Figures 3-19* and *3-20* plot monthly averaged opportunity costs from expanding groundwater conveyance at SJE and KER, respectively. Results show a net benefit from expanding groundwater supplies during months of peak demand (September – November) and no net cost from expanding groundwater supplied in months leading up to peak demand (February – August) at SJE. Similarly, results indicate a net benefit from expanding groundwater supplies from March through October at Kern NWR. In summary, expanding groundwater supplies may not be an appropriate short-term solution, but it shows promise as a long-term solution to adapt to changing hydrologic and regulatory conditions. However, these benefits are limited to refuges south of the Delta only, including East Bear Creek unit, Merced NWR and Kern NWR.

Water trading

Results from model runs with historical and Full Level 4 refuge deliveries are compared to determine potential water trading partners and additional system-wide scarcity cost from providing Full Level 4 refuge deliveries. These results come with a barrage of caveats, and should be only used to assess general trends and approximations. Results represent additional scarcity cost in an optimized system with perfect foresight, and a competitive and unregulated market. In other words, system-wide operations are optimally restructured to minimize scarcity cost. Perfect foresight allows the operators to adjust reservoir releases, groundwater pumping, water conservation, recycling and groundwater recharge operations with perfect knowledge of the entire 82-years of hydrology simulated in the model runs. Moreover, an unregulated market ensures that the least economically productive user is the first reduce water use. In reality, neither the operators have perfect knowledge of future hydrologic events nor does a true competitive and unregulated market exist. Therefore, these results represent a lower bound estimate on cost of trading water at best and trading partners may be more localized than predicted by the model outcomes.

On average, 95 TAF of additional supplies are needed to realize Full Level 4 deliveries out of which 25 TAF are needed in Upper Sacramento Valley, 24 TAF in Lower Sacramento Valley, 36 TAF in San Joaquin Valley and remaining 10 TAF in Tulare Basin. Assuming that agricultural users will be the most likely trading partners, differences in agricultural scarcities resulting from additional refuge deliveries are determined at each agricultural demand node to identify potential trading partners (Table 3-14). Three key trends emerge with respect of water trading partners: (1) refuges west of the Sacramento River (SRW), Mendota WA (MDT) and Kern NWR (KER) will have to reach out to users outside of local agricultural users; (2) agricultural water users in the San Joaquin Valley will become aggressive trading partners under the no groundwater overdraft scenario since Tulare Basin users will be prevented from pumping groundwater to substitute for lost6 surface water deliveries; and (3) agricultural water users north of the Delta will become increasingly important water trading partners under a warm-dry hydrology.

Table 3-14. Water scarcity incurred by agricultural water users to provide additional refuge water supplies to reach Full Level 4 delivery target (TAF/yr)

Region			EREC				ERIF				HOEC				HOIF				
			Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		
			With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	
Upper Sacramento Valley (Δ = 25 TAF)	101	CVPM01	0	0	1	0.6	0	0	0.5	0.1	0	0	0	0.5	0	0	1.4	0.2	
	102	CVPM02	0.1	0.1	0.1	0.2	0	0	0.0	0.0	0.8	0	0.1	0.4	0.1	0.3	6.3	0.8	
	103A	CVPM03A	0	0	1.8	1.5	0	0	3.3	13.4	0	0	4	10.1	0	0	3	2.3	<-- R-SAC (Δ = 25 TAF)
	103B	CVPM03B	0	0	0.3	0.3	0	0	3.2	0.4	0	0	0.9	2.4	0	0	0.3	0.1	
	104	CVPM04	0	0	34.1	31.9	0	0.1	0	0.1	0	0	9.3	10.4	0	0	0.1	0	
Lower Sacramento Valley and Delta (Δ = 24 TAF)	202	CVPM05	0	0.1	3.3	3.4	0.1	0.3	35.8	40.2	0.1	0.3	0.6	1.5	0	-0.1	26.7	41.5	<-- R-SUT (Δ = 10 TAF) & R-GLD (Δ = 14 TAF)
	203	CVPM06	0	0	0.7	1.1	0	0	8.2	3.6	0	0	17.2	2.2	0	0	2.5	1.7	
	204	CVPM07	0	0	5	8.3	0	0	3.1	0.6	0	0	7.8	4	0	0	3.7	0.5	
	206	CVPM08	0	1.1	0	4.1	0	9.1	2.8	0.1	0.3	0.1	0	0	0.1	0	1.1	0.1	
	207	CVPM09	0.1	0.6	0.9	0.4	0.3	1.2	1.2	0.5	0.1	0.1	1.8	9.4	0.6	0.1	3.9	5	
San Joaquin and South Bay (Δ = 36 TAF)	302	CVPM10	0	0.3	2.9	18.7	1.5	1.3	4.8	4.1	24.8	3.8	0.3	0	0	0.2	2.3	32.5	<-- R-SJW (Δ = 10 TAF)
	303	CVPM11	0	6.9	1.6	0.2	0	0	3.3	4.3	0.8	0.1	0.4	19.9	0.1	0	0.3	1.1	<-- R-MDT (Δ = 24 TAF)
	305	CVPM12	0	0.2	3.5	0	17.3	0	1.3	8.8	0.3	0	0.2	15.8	28.5	0	0.3	1.3	
	306	CVPM13	0.5	0.2	0	17.3	0	0.4	0.1	0.2	0.2	0	0	0	1.2	0	0.0	0	<-- R_SJE (Δ = 2 TAF)
Tulare Basin (Δ = 10 TAF)	401	CVPM14A	0.1	0	1.1	3.1	0	0.1	2.6	3.3	0	1.3	0	0	1.4	0	0.5	7.8	
	402A	CVPM14B	1.9	0	0.8	0.1	0	0	0.5	0.5	0	0	0.1	0	0.1	0	1.5	0	
	402B	CVPM15A	2.9	5.2	3.1	0	6.3	2.4	1	7.9	0.1	39.9	0	0	4.7	0.7	6.5	0	
	403	CVPM15B	0	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0	0.5	
	404A	CVPM16	0.1	0	0	0	0	3.3	0	0	0	0	0	0	3.6	0	0	0	
	404B	CVPM17	0	0	21.6	0	12.4	0	0	0.1	0	0	0	0	1.7	0	0	0	
	405	CVPM18	37	6.2	7.2	7.2	0	2	31.5	7.2	27.9	2	7.2	7.2	2.3	0.5	31.5	7.2	<-- R-PIX (Δ = 5 TAF)
	407	CVPM19A	0	0	0	0	0	0	0	0.1	0	0	0	0	0.5	0	0	0.1	
	408A	CVPM19B	0.1	2.2	1.3	0	4.8	0	0.8	6.2	0.1	0.7	0	0	0	0.1	0.2	0.1	
	408B	CVPM20	0	0.1	0.7	0	0	0.9	0	0.5	0	0	0	0.1	0	0.2	0.1	0.1	<-- R-KER (Δ = 5 TAF)
	409A	CVPM21A	0	0.8	8	0	1.2	4.8	5.1	3.1	0	2.6	0	0	0.1	0.7	9.1	0.2	
	409B	CVPM21B	0	0.1	0	0	0.5	0	0.1	0	0.2	0	0	0.1	0	0.1	0	0	
	409C	CVPM21C	0.1	0	0.1	0	0	0	0	0.2	0	0	0	0.1	0	0	0	0	
Southern California	501	Ventura	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	502	Antelope Valley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	507	Coachella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	508	Palo Verde	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	509	East and West MWD	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	
	510	Imperial	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	511	San Diego	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	512	Bard WD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

[6] Current representation of refuge deliveries as fixed deliveries forces the model to meet refuge deliveries before allocating water to urban and agricultural users. Hence, the use of word *lost* to describe additional agricultural and urban scarcity resulting from increases refuge deliveries.

Table 3-15. Cost of trading water* to secure additional refuge water supplies to reach Full Level 4 delivery target ($/AF)

			Urban			Ag			TOTAL
			Scarcity (TAF/yr)	Scarcity Cost ($k/yr)	Tradiing Cost ($/AF)	Scarcity (TAF/yr)	Scarcity Cost ($k/yr)	Tradiing Cost ($/AF)	Tradiing Cost ($/AF)
EREC	Historic	Overdraft	6	7,045	74	43	11,249	118	192
EREC	Historic	No Overdraft	1	1,351	▼ 14	24	9,058	▼ 95	▼ 109
EREC	Warm-Dry	Overdraft	1	836	▼ 9	99	55,305	▲ 582	▲ 591
EREC	Warm-Dry	No Overdraft	1	462	▼ 5	98	57,235	▲ 602	▲ 607
ERIF	Historic	Overdraft	4	3,251	▼ 34	44	6,810	▼ 72	▼ 106
ERIF	Historic	No Overdraft	15	17,306	▲ 182	26	6,950	▼ 73	▲ 255
ERIF	Warm-Dry	Overdraft	1	1,836	▼ 19	109	56,644	▲ 596	▲ 615
ERIF	Warm-Dry	No Overdraft	5	5,758	▼ 61	106	57,056	▲ 601	▲ 662
HOEC	Historic	Overdraft	1	1,056	▼ 11	56	19,788	▲ 208	▲ 219
HOEC	Historic	No Overdraft	4	4,873	▼ 51	51	23,938	▲ 252	▲ 303
HOEC	Warm-Dry	Overdraft	1	791	▼ 8	50	17,633	▲ 186	▲ 194
HOEC	Warm-Dry	No Overdraft	5	6,525	▼ 69	84	56,087	▲ 590	▲ 659
HOIF	Historic	Overdraft	2	1,562	▼ 16	45	8,701	▼ 92	▼ 108
HOIF	Historic	No Overdraft	3	3,080	▼ 32	3	835	▼ 9	▼ 41
HOIF	Warm-Dry	Overdraft	4	3,394	▼ 36	101	54,439	▲ 573	▲ 609
HOIF	Warm-Dry	No Overdraft	2	1,260	▼ 13	103	56,812	▲ 598	▲ 611

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Trading cost calculated by dividing the average annual state-wide urban and agricultural scarcity cost ($k/yr) by average annual amount of additional refuge water supplies needed to reach Full Level 4 (TAF/yr).

Implicit valuation is used to estimate the costs of acquiring additional water by comparing system-wide scarcity costs resulting from historical and Full Level 4 refuge deliveries (Table 3-15). Due to optimized operations and perfect foresight, additional urban and agricultural scarcity does not always equal 95 TAF/yr. Despite some anomalies, general trends include: cost of trading is $200 per acre-foot for the historical hydrology and Existing Regulations, Existing Conveyance (HEREC) scenario; peripheral tunnels reduce cost of trading by 50% and ending overdraft increases cost of trading by 25 – 50% compared to the HEREC scenario; under the warm-dry case, trading cost increases to $600 per acre-foot and is largely unaffected by regulatory conditions. Although these might be competitive trading prices north of the Delta, Central Valley agricultural users south of the Delta are willing to pay $300 - $350 per acre-foot with the historical hydrology and $1,050 - $1,300 per acre-foot with the warm-dry hydrology (Table 3-8). Peripheral tunnels lower the willingness to pay, but not to a level where it becomes economical to compete directly with the agricultural users south of the Delta. Therefore, securing additional water supplies becomes three times more expensive under a warm-dry climate and agricultural water users will continue to have the competitive advantage over refuges, making it increasingly harder to acquire additional surface water supplies. The next chapter discusses localized refuge management strategies to optimize the use of water historically available to refuges.

Conclusion

Agricultural water users represent nearly 65% (23.1 MAF/yr) of the total statewide demand (*Table 3-5*). More than 90% of the demand is concentrated in the Central Valley with 40% in Tulare Basin, 20% in Lower Sacramento and San Joaquin Valley, and 10% in Upper Sacramento Valley. CVPIA refuge deliveries, on the other hand, constitute less than 2% (0.5 MAF/yr) of the total demand. Even then, only 89% of the Level 2 deliveries and 47 % of incremental Level 4 have been met between 2001 and 2014 (*Table 2-2*).

Sixteen scenarios are analyzed using CALVIN, a hydro-economic model of State of California, to capture and quantify the hydrologic and economic implications of evolving climatic and management conditions on refuge water deliveries including (1) climate vulnerability: historical and warm-dry climates; (2) Delta regulations: high and existing Delta Outflows; (3) infrastructure: with and without isolated facility or peripheral tunnels; and (4) groundwater management: with and without long-term overdraft (*Table 1-1*).

Hydrologic impacts are determined by comparing flows at or just upstream of key diversion points (*Table 3-10*). North of the Delta, the impacts are largely driven by warm-dry hydrology. In-stream flows lower by 20% across all regulatory scenarios under warm-dry hydrology. Export curtailments under high outflow/ low export (HOEC) scenario trap previously exported water north of the Delta. As a result, excess flows are routed through the bypass system, and inflows into Sutter Bypass increase by 15% under historical hydrology and 9% under warm-dry hydrology.

Limited groundwater access under no overdraft case, lack of local surface water supplies under warm-dry hydrology and export curtailments under high outflow/ low export (HOEC) scenario intensify competition for surface water supplies south of the Delta. However, the economic value of agricultural output drives the hydrologic conditions in the San Joaquin Valley and Tulare Basin. Long-term groundwater use, as represented in CALVIN, results in 1.03 MAF of overdraft per year with more than 70% (700 TAF/yr) of average annual overdraft occurring in the Tulare Basin. As a result, ending long-term groundwater overdraft has the largest impact in Tulare Basin and any surface water supplies previously available to users in San Joaquin Valley are left in Delta-Mendota Canal or California Aqueduct to be diverted by Tulare Basin water users. Warm-dry hydrology results in 30% decrease in available water supplies statewide (*Figure 3-11; Appendix 8*). San Joaquin Valley experiences the largest volumetric change south of the Delta. Subsequently, more surface water supplies are delivered into Mendota Pool via Delta-Mendota Canal and inflows increase by 200 – 300% across all cases under the warm-dry hydrology. Increased inflows, however, do not reduce competition for water in San Joaquin Valley. Agricultural scarcity increases by more than 300% in San Joaquin Valley and increased inflows are diverted by local farmers to offset losses from reduced local inflows (*Table 3-8*).

Results also indicate increased competition for water in the lower Merced River watershed regardless of the hydrologic and regulatory conditions. Securing long-term surface water deliveries from irrigation districts located in the upper Merced River watershed could ensure a more reliable water supply to refuges east of the San Joaquin River.

Economic impacts are indirectly evaluated from the opportunity costs of delivering water to refuges (*Table 3-11*). Overall, Upper Sacramento Valley refuges have the least opportunity cost ($1 – 4 per acre-feet) and Tulare Basin refuges the highest opportunity cost ($340 per acre-feet) under historical hydrology. Peripheral tunnels increase the opportunity cost by about 20% north of the Delta and reduce it by about 40% south of the Delta. Increased export opportunities combined with economically more valuable agriculture south of the Delta intensify competition for surface water north of the Delta and subsequently, increase opportunity cost of north of the Delta refuge deliveries. Export curtailments under the high outflow/ low exports (HOEC) scenario widen the north-south disparity. On average, opportunity cost falls by 15% north of the Delta and increases by 50% south of the Delta. Peripheral tunnels and high Delta Outflow regulations combined curb negative and positive impacts on opportunity cost north and south of the Delta, respectively. Opportunity cost increases by 5% instead of 20% north of the Delta and lowers by 20% instead of 40% south of the Delta. Ending overdraft increases opportunity cost by 2 – 3% north of the Delta and 30 – 80% south of the Delta. The warm-dry climate increases competition for water throughout the Central Valley. On average, agricultural scarcity increases from 3 to 27% north of the Delta and from 11 to 44% south of the Delta (*Table 3-8*). Subsequently, opportunity costs increase to $30 per acre-foot in Upper Sacramento Valley, $290 per acre-foot in Lower Sacramento Valley, $800 per acre-foot in San Joaquin Valley and $925 per acre-foot in Tulare Basin. However, the trends observed under historical hydrology are still retained under warm-dry hydrology.

Several adaptation strategies are also explored including: (1) optimal management of existing resources (*Figure 3-18*), (2) opportunities for expanding existing or constructing new water supply sources (*Table 3-12* and *3-13*), and (3) identifying potential partners and cost of acquiring additional water supplies to reach Full Level 4 deliveries targets (*Table 3-14* and *3-15*).

Only four of the eight refuge areas have access to both surface water and groundwater including Gray Lodge WA (GLD), Sutter NWR (SUT), and refuges east and west of the San Joaquin River (SJE and SJW). Among the four refuges, refuges east of the San Joaquin River (SJE) have the most dynamic water use portfolio. Existing groundwater capacity, as modelled in this study, can provide up to 100% of historical refuge deliveries in all months except for September and October. Groundwater use corresponds with the availability of surface water supplies. In the base case, 60% of the demand is met with groundwater. Peripheral tunnels expand export opportunities and subsequently, groundwater use drops to 45 – 50%. High outflow/ low export (HOEC) scenario curtails south of the Delta exports and as a result, groundwater use increases to 65 – 67%. Warm-dry hydrology reduces available water supplies by 40% in the San Joaquin Valley. Consequently, groundwater use expands to 93% in absence of tunnels, and 83 – 88% with the peripheral tunnels. Although expanding groundwater supplies may not be an appropriate short-term solution, it appears to be a promising long-term solution at East Bear Creek unit, Merced NWR and Kern NWR. Results show a net benefit from expanding groundwater supplies during months of peak demand (September – November) and little to no net cost from expanding groundwater supplies in months leading up to peak demand (February – August) at SJE refuges and Kern NWR (*Figure 3-19* and *3-20*).

As for expanding surface water supplies, there is little to no short-term benefit from connecting Pixley NWR with Friant-Kern Canal or expanding Sutter Extension Water District (SEWD) deliveries to Sutter NWR, but it may not prove to be a reliable source of supply in the long-term as competition for surface water supplies increases in the Central Valley. The results also indicate a negative opportunity cost on increasing surface deliveries to refuges located west of the Sacramento River (SRW) outside of the peak irrigation season (*Figure 3-17*). Negative opportunity cost indicates a net system-wide benefit as result of delivering more water to the refuge. Timothy grass and watergrass (or smartweed) combined account for roughly 85% of the total managed wetlands at SRW refuges. Both land-use types are flooded approximately beginning late August – early September. Watergrass units are also irrigated mid-June prior to flood-up. Monthly averaged opportunity cost indicates that under warm-dry hydrology, competition for water can be reduced if irrigation could be moved earlier in the season, April – May, and if flood-up could be delayed until October – November. Moving irrigation to earlier in the season also mean that wetlands cannot be sustained as late as May; they would need to be drained by late March – early April. Delaying flood-up till October will also keep these wetlands out of production for an additional month. Collectively, the production season for 85% of the refuge habitat will be reduced from late August – early May to late September – early April, but these management changes show a promising way to tackle the effects of a warm-dry hydrology.

Finally, the results from model runs with historical and Full Level 4 refuge deliveries are compared to determine potential water trading partners and additional system-wide scarcity cost from providing Full Level 4 refuge deliveries. Agricultural water users in the San Joaquin Valley will become aggressive trading partners under no groundwater overdraft scenario. Under warm-dry hydrology, agricultural water users north of the Delta will become increasingly important water trading partners. Cost of trading is expected to increase three times as a result of climate change; from $200 per acre-foot under historical hydrology to $600 per acre-foot under warm-dry hydrology. Peripheral tunnels reduce cost of trading by 50% and no overdraft scenario increases cost of trading by 25 – 50% under historical hydrology; however, the cost is largely unaffected by the regulatory scenarios under warm-dry scenario. Although these might be competitive trading prices north of the Delta, results indicate, agricultural users in San Joaquin Valley and Tulare Basin are willing to pay $300 - $350 per acre-foot (two times more) under historical hydrology and $1,050 - $1,300 per acre-foot (three times more) under warm-dry hydrology (*Table 3-9*). Therefore, as the warming trend continues, securing additional water supplies will become more expensive and agricultural users south of the Delta will continue to have competitive advantage over refuges, making it increasingly harder to acquire additional surface water supplies regardless of the hydrologic or management scenario.

Limitations are inherent of any model which must be factored in when interpreting results for insights into refuge management. Although these limitations have a significant effect on results of an individual model run, their impact is often muted in comparative analysis since all runs equally represent these limitations.

Hydro-economic models, such as CALVIN, assume rational response to economic incentives. As water scarcity grows, the system re-operates to accommodate economically superior uses. Therefore, the results are purely economics-driven; however, in reality water rights and other institutional constraints also factor into the decision-making process.

Mathematical structure of the network flow models limits CALVIN's ability to represent complex physical and operational constraints that play a critical role in determining required Delta Outflow and allowable Delta Exports. To mitigate for this limitation, CALVIN directly employs minimum in-stream flow requirements, required Delta Outflow and Delta export timeseries from CalSim II. Four CalSim II runs completed as part of the 2013 BDCP EIR/EIS report are used to represent two infrastructure scenarios – with and without the peripheral tunnels – and two Delta regulatory scenarios, high outflow/ low export, and existing regulations. Since hydrology is perturbed differently in CALVIN, only CalSim II runs assuming historical hydrology are used in the analysis. Moreover, groundwater overdraft scenarios were not explored during the EIR/EIS analysis. As a result, minimum in-stream flows, required Delta outflow, and south of the Delta exports vary only by the Delta export and outflow scenario and are independent of the hydrologic or groundwater overdraft scenario. Therefore, the model runs, under current set-up, represent an optimistic exports scenario for a warm-dry hydrology. Warming is projected to increase required Delta outflow demands during non-winter months to maintain suitable fish habitat and water quality within the Delta which will reduce the amount of water available for export (Cayan et al., 2008; Hayhoe et al., 2004). Sustaining the same level of Delta exports as under historical hydrology overestimates the amount of water available to meet urban, agricultural and refuge needs south of the Delta.

Lastly, water quality considerations are not explicit modeled in CALVIN. An operating cost is assigned to groundwater pumping to deter the model from over-relying on groundwater to meet refuge water needs. However, the cost does not vary with groundwater head nor does it include water treatment costs.

References

Bartolomeo, E. S. (2011). *Economic responses to water scarcity in southern California* (Master's Thesis). University of California, Davis, CA.

Bay Delta Conservation Plan (BDCP). (2013). *Draft Environmental Impact Report/ Environmental Impact Statement*.

Cayan, D. R., Maurer, E. P., Dettinger, M. D., Tyree, M. & Hayhoe, K. (2008). Climate change scenarios for the California region. *Climatic Change, 87*(1), 21-42.

Chou, H. (2012). *Groundwater overdraft in California's Central Valley: updated CALVIN modeling using recent CVHM and C2VSIM representations* (Master's Thesis). University of California, Davis, CA.

Connell, C. R. (2009). *Bring the heat, but hope for rain adapting to climate warming for California* (Master's Thesis). University of California, Davis, CA.

Central Valley Habitat Joint Venture (CVHJV). (1990). *Central Valley Habitat Joint Venture implementation plan: A component of the North American Waterfowl Management Plan*.

Central Valley Joint Venture (CVJV). (2006). *Central Valley Joint Venture implementation plan: Conserving bird habitat*. Sacrament, CA: U.S. Fish and Wildlife Service.

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., … Zhang, R. (2006). GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and simulation characteristics. *Journal of Climate, 19*(5), 643-674.

Dogan, M. S. (2015). *Integrated water operations in California: Hydropower, overdraft and climate change* (Master's Thesis). University of California, Davis, California.

Draper, A. J. (2001). *Implicit stochastic optimization with limited foresight for reservoir systems* (PhD Dissertation). University of California, Davis, California.

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., and Howitt, R. E. (2003). Economic-engineering optimization for California water management. *Journal of Water Resources Planning and Management, 129*(3), 155-164.

Department of Water Resources, California (DWR). (2003). *CalSim II simulation of historic SWP-CVP operations: Technical memorandum report*. Sacramento, CA: Bay Delta Office, California Department of Water Resources.

Department of Water Resources, California (DWR). (2014). *California Water Plan Update 2013 Bulletin 160-13: Investing in innovation and infrastructure* (Vol. 1). Sacramento, CA.

Hayhoe K., Cayan, D., Field, C. B., Frumhoffe, P. C., Maurer, E. P., Miller, N. L., … Cleland, E.E. (2004). Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Science, 101*(34), 12422–12427.

Harou, J. J., & Lund, J. R. (2008). Ending groundwater overdraft in hydrologic-economic systems. *Hydrogeology Journal, 16*(6), 1039-1055.

Harou, J. J., Pulido-Velazquez, M. A., Rosenberg, D. E., Medellin-Azuara, J., Lund, J. R. & Howitt, R. E. (2009). Hydro-economic modeling: Concepts, design, applications and future prospects. *Journal of Hydrology, 375*(3-4), 627-643.

Jenkins, M. W., Draper, A. J., Lund, J. R., Howitt, R. E., Tanaka, S. K., Ritzema, R., … Ward, K. B. (2001). *Improving California water management: Optimizing value and flexibility* (Report). University of California, Davis, California.

Jenkins, M. W., Lund, J. R., Howitt, R. E., Draper, A. J., Msangi, S. M., Tanaka, S. K., … Marques, G. F. (2004). Optimization of California's water supply system: Results and insights. *Journal of Water Resources Planning and Management, 130*(4), 271-280.

Loucks, D. P., Stedinger, J. R. & Haith, D. A. (1981). *Water resources systems planning and analysis*. Englewood Cliffs, New Jersey: Prentice-Hall.

Lund, J.R., Howitt, R. E., Jenkins, M. W., Zhu, T., Tanaka, S. K., Pulido-Velazquez, M. A. … Ferreira, I. (2003). *Climate warming and California's water future* (Report). Sacramento, CA: California Energy Commission.

Lund, J.R., Howitt, R. E., Medellin-Azuara, J., & Jenkins, M.W. (2009). Water management lessons for California from statewide hydro-economic modeling: A Report for the California Department of Water Resources. In *California Water Plan Update 2009* (Vol. 4).

Medellin-Azuara, J., Harou, J. J., Olivares, M. A., Madani, K., Lund, J. R., Howitt, R. E., … Jenkins, M. W. (2008). Adaptability and adaptations of California's water supply system to dry climate warming, *Climatic Change, 87*(1), 75-90.

Medellin-Azuara, J., Connell, C. R., Madani, K., Lund, J. R. & Howitt, R.E. (2009). Water management adaptation with climate change (Report). Sacramento, CA: California Energy Commission.

Null, S. E. & Lund, J. R. (2006). Reassembling Hetch Hetchy: Water supply without O'Shaughnessy Dam. *Journal of the American Water Resources Association, 42*(2), 395-408.

Pulido-Velazquez, M., Jenkins, M. W. & Lund, J. R. (2004). Economic values for conjunctive use and water banking in southern California. *Water Resources Research, 40*(3), W03401.

Tanaka, S. K., Zhu, T., Lund, J. R., Howitt, R. E., Jenkins, M. W., Pulido-Velazquez, M., … Ferreira, I. (2006). Climate warming and water management adaptation for California. *Climatic Change, 76*(3-4), 361-387.

Tanaka, S. K., Connell, C. R., Madani, K., Lund, J. R., Hanak, E. & Medellin-Azuara, J. (2011). Economic costs and adaptations for alternative Delta regulations. *San Francisco Estuary and Watershed Science, 9*(2).

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010a). *Merced National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010b). *San Luis National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011a). *Colusa National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011b). *Delevan National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011c). *Grasslands Resource Conservation District Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011d). *Gray Lodge Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011e). *Kern National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011f). *Los Banos Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011g). *Mendota Pool Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011h). *North Grasslands Wildlife Area China Island Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011i). *North Grasslands Wildlife Area Salt Slough Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011j). *Pixley National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011k). *Sacramento National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011l). *Volta Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2012). *Statewide Agricultural Production*

(SWAP) Model Update and Application to Federal Feasibility Analysis (Report).

Zikalala, P. G. (2013). *Representing groundwater management in California's Central Valley: CALVIN and C2VSIM* (Master's Thesis). University of California, Davis, CA.

Chapter 4: Refuge operations' analysis and results using Spreadsheet Tool

On average, only 89% of Full Level 2 and 47% of incremental Level 4 refuge deliveries have been met since 2001 (*Table 2-2*). Refuge managers cite budgetary constraints and rising cost of water as the major impediment in realizing its goals of delivering Full Level 4 deliveries (CVJV, 2006). Some estimates indicate that, on average, the cost of acquiring water for wetlands increased by 400 percent since 1990s (2006). Findings from chapter 3 indicate that securing additional water supplies for Full Level 4 deliveries will become more expensive under a warm-dry climate; cost of trading could increase from $200 per acre-foot under a historical hydrology to $600 per acre-foot under warm-dry hydrology. Although these might be competitive trading prices north of the Delta, results indicate Central Valley agricultural users south of the Delta are willing to pay $300 - $350 per acre-foot under historical hydrology and $1,050 - $1,300 per acre-foot under a warm-dry hydrology. Therefore, agricultural water users in the San Joaquin Valley and Tulare Basin will continue to have competitive advantage over refuges, making it harder to acquire additional surface water supplies within an already limited budget. This begs a question how refuge managers can maximize their returns on available water supplies. Two specific management alternatives are explored in this chapter: (1) inter-refuge trading to reallocate of available water supplies; and (2) improved refuge land-use management practices. Under current CALVIN configuration, refuge demands are represented as pre-processed, fixed delivery timeseries (refer to *Limitation* sub-section under *CALVIN Overview* in Chapter 3 for details). Therefore, refuge deliveries and land-use operations are not dynamically represented in CALVIN. Moreover, the management objectives behind refuge management and statewide water resource management are very different. Minimizing scarcity cost is a reliable metric for managing statewide water resources if the focus is on agricultural or urban uses. However, assigning economic value to environmental uses is a still an on-going field of research. Although public hunting at managed wetlands generates revenue, this revenue does not provide a holistic evaluation of economic benefits from managed wetlands. As a result, a separate Spreadsheet Tool is developed to explore the benefits and implications of the evaluated alternatives. This tool bypasses quantifying economic benefits from managed wetlands and uses an alternative management objective: maximizing statewide managed wetland acreage. Although the Spreadsheet Tool currently focuses only on USFWS managed refuges, it can be easily adapted to remaining CVPIA refuges. This chapter has two main sections. First section outlines the conceptual set-up of the Spreadsheet Tool including a discussion on model inputs and limitations. Second section includes a detailed discussion of results obtained using the Spreadsheet Tool.

Conceptual set-up and data flow

The Spreadsheet Tool is a network flow optimization model of USFWS managed Central Valley refuges. These include Sacramento (SAC), Delevan (DEL) and Colusa (COL) NWRs east of the Sacramento River; Sutter NWR (SUT) in the Feather River watershed; San Luis NWR Complex and Merced NWR (MER) in San Joaquin Valley; and Pixley (PIX) and Kern NWR (KER) in Tulare Basin (*Table 1-2*). San Luis NWR Complex is comprised of five contiguous units including Freitas, Kesterson, San Luis, West Bear Creek and East Bear Creek. For data reporting purposes, Freitas and Kesterson are combined into West of Highway 165 refuges (W165), San Luis and West Bear Creek are combined into East of Highway 165 refuges (E165), and East Bear Creek (EBR) is represented individually.

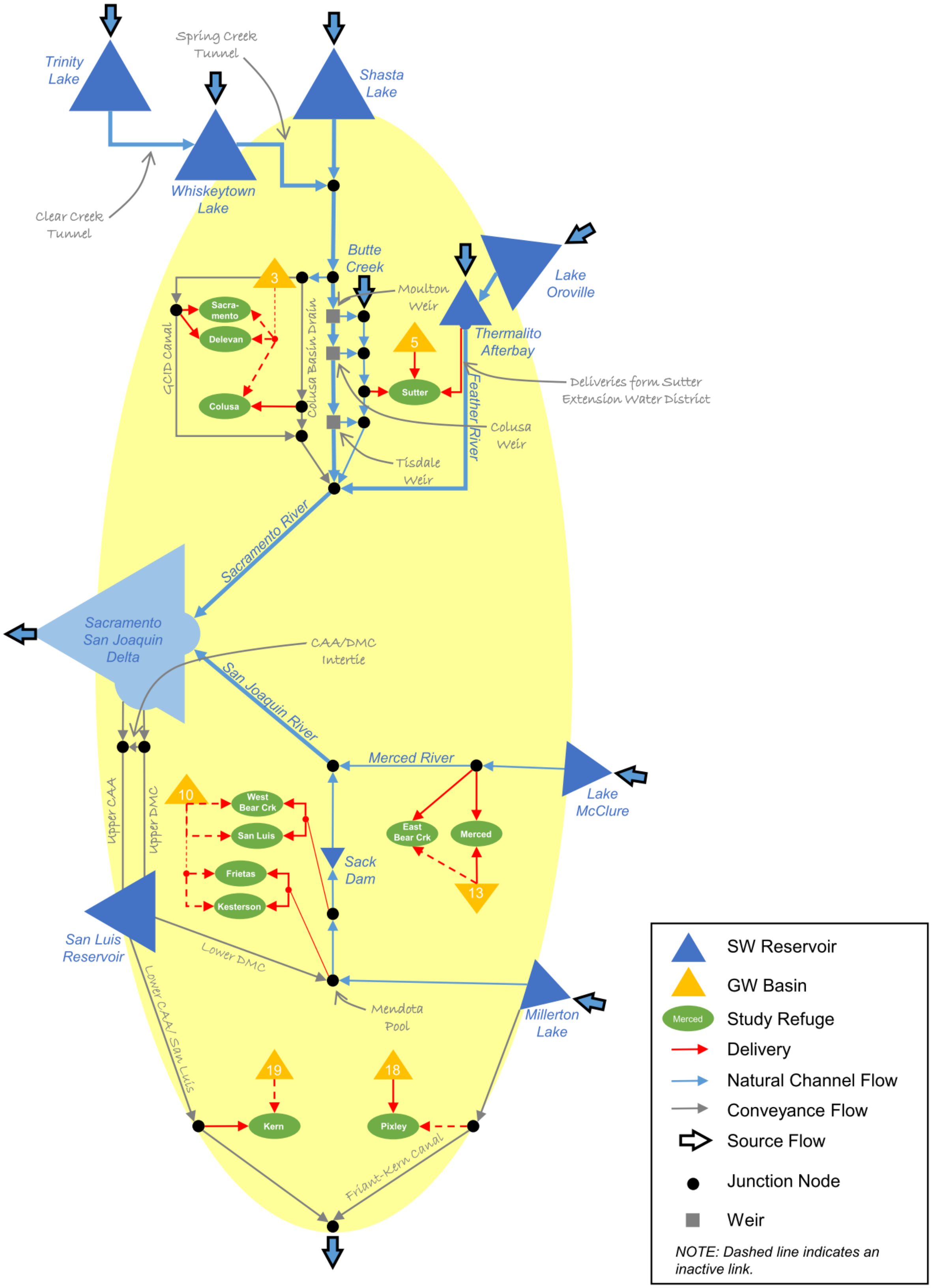


Figure 4-1. Simplified on-the-ground water conveyance schematic of USFWS refuges

Network flow

A schematic of on-the-ground refuge water supply conveyance and the corresponding network used in the Spreadsheet Tool appear in *Figures 4-1* and *4-2*, respectively. Although a highly simplified network flow model, all the nodes and links have a physical counterpart where C01 – C05 represent the major rivers in the system including Sacramento River, Feather River, Merced River, and San Joaquin River. Conveyance links C06 and C07 represent the two major north-south conveyances systems, California Aqueduct (CAA) and Delta-Mendota Canal (DMC). Conveyance losses are applied on the conveyance links C06 and C07 to represent seepage and evaporation losses on the canals, 1% on CAA and 2% on DMC.

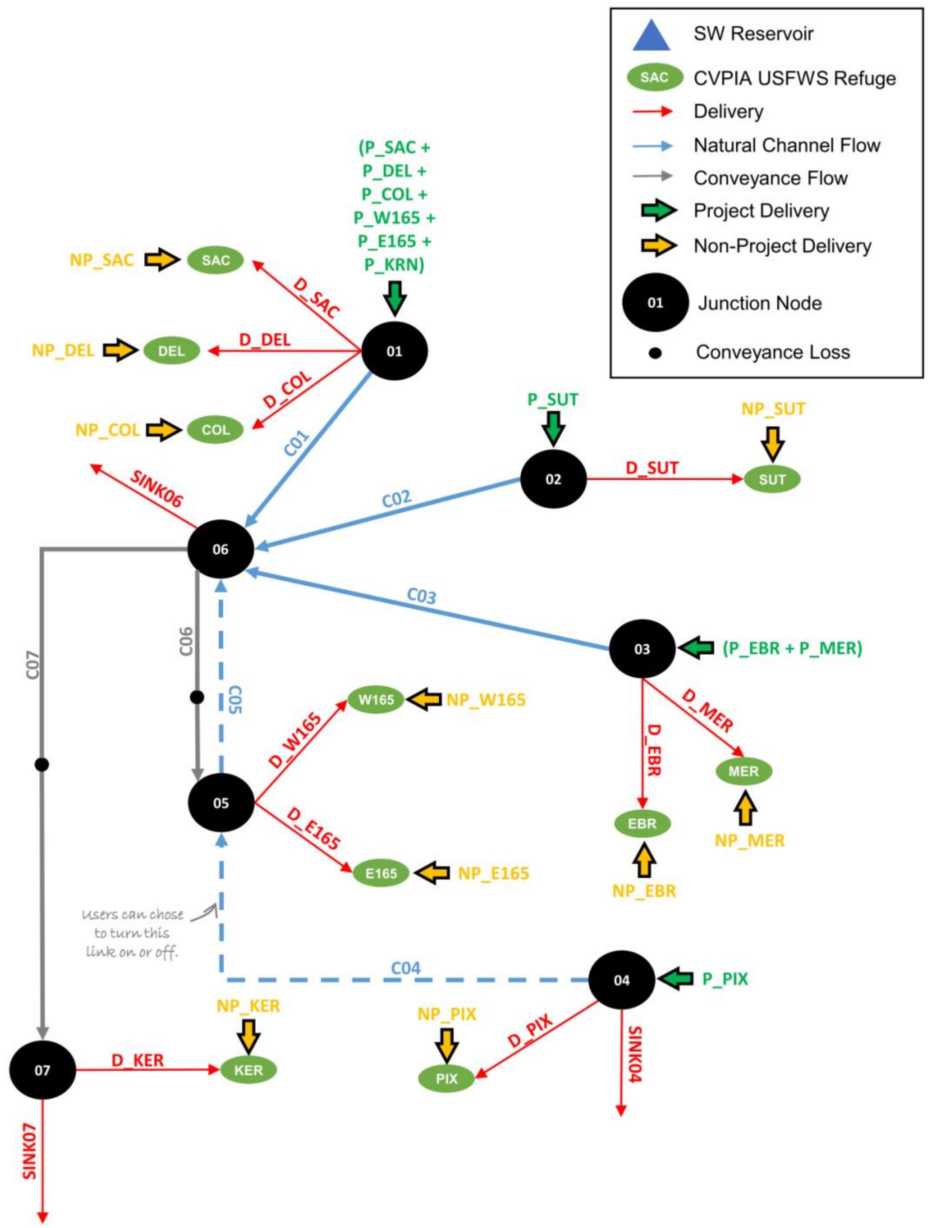


Figure 4-2. Network flow schematic used in the Spreadsheet Tool

Conveyance links C04 and C05, combined, represent the San Joaquin River, and could be turned on or off. Historically, San Joaquin River downstream of Friant Dam up to its Confluence with Merced River has not flowed year around since the construction of Friant Dam. San Joaquin River Restoration Act (SJRRA) was passed in 2009 to maintain year around flows in the river to create a reliable fish passage. However, the act is not yet fully implemented. Model runs included in this analysis assume no year-round flows on C04 and C05. As a result, Pixley NWR does not participate in inter-refuge trading.

Mathematical representation

The Spreadsheet Tool uses linear programming (LP) to optimize refuge operations. The tool is structured into two separate optimization modules: inter-refuge optimization and intra-refuge optimization. Both optimization routines share a common objective function – maximize total managed wetland acreage – and are bounded by available land. Both optimization routines use an annual time-step. Refuge water demands depend on the flood-up and drawdown operations which can fluctuate with the management objectives, hydrologic conditions and water delivery schedule. An annual time-step bypasses this variability and focuses on the two management alternatives – inter-refuge trading and optimized refuge operations – which are the original intent of developing the Spreadsheet Tool. Despite these similarities, each optimization routine focuses on different decision variables which distinguish the two optimization routines.

Inter-refuge operations focus on allocating water supply among the managed refuges. Therefore, decisions include refuge deliveries and inputs include project and non-project water supplies available at individual refuges. In absence of inter-refuge trading, each refuge is delivered its allocated water. The primary use of this optimization routine is to explore benefits and management implications of inter-refuge trading. *Equations 3-1 through 3-18* represent the mathematical formulation of inter-refuge LP optimization and *Table 4-1* outlines the sources of corresponding input variables.

Objective Function:

$$\max\left\{\sum_k \sum_j \mathrm{HabAcr}_{jk}\right\} \tag{3-01}$$

Subject to:

$$\mathrm{WaterDemand}_{jk} = \mathrm{WaterSupply}_{jk} \tag{3-02}$$

$$\sum X_{mn} = \sum(1 - \mathrm{Loss}_{lm}) * X_{lm} + b_m \tag{3-03}$$

$$X_{lm} \leq u_{lm} \tag{3-04}$$

$$\mathrm{HabAcr}_{jk} \geq \mathrm{MinHabAcr}_j \tag{3-05}$$

$$\mathrm{HabAcr}_{jk} \leq \mathrm{MaxHabAcr}_j \tag{3-06}$$

$$\mathrm{Prj}_{jk} \leq \mathrm{AllocatedWater}_{jk} \tag{3-07}$$

$$\mathrm{HabAcr}_{jk} \geq 0 \tag{3-08}$$

$$\mathrm{Prj}_{jk} \geq 0 \tag{3-09}$$

$$X_{lm} \geq 0 \tag{3-10}$$

Where:

$$\mathrm{WaterDemand}_{jk} = \mathrm{HabAcr}_{jk} * \mathrm{AvgNetHabDem}_j \tag{3-11}$$

$$\text{AvgNetHabDem}_{\text{j}} = \frac{\sum_{\text{i}} \text{HistHabAcr}_{\text{ij}} * \text{NetHabDem}_{\text{ij}}}{\sum_{\text{i}} \text{HistHabAcr}_{\text{ij}}} \quad (3\text{-}12)$$

$$\text{NetHabDem}_{\text{ij}} = \left[\left(1 + \text{CCHabDem}_{\text{ij}}\right) * \text{HabDem}_{\text{ij}}\right] - \text{EffPrecip}_{\text{ijk}} \quad (3\text{-}13)$$

$$\text{EffPrecip}_{\text{ijk}} = \min\left\{\text{MaxEffPrecip}_{\text{ij}}, \left[\left(1 - \text{CCPrecip}_{\text{j}}\right) * \text{Precip}_{\text{jk}} * \text{Weight}_{\text{ij}}\right]\right\} \quad (3\text{-}14)$$

$$\text{Weight}_{\text{ij}} = \frac{\text{HabDem}_{\text{ij}}}{\sum_{i} \text{HabDem}_{\text{ij}}} \quad (3\text{-}15)$$

$$\text{WaterSupply}_{\text{jk}} = \left(1 + \text{Reuse}_{\text{jk}}\right) * \left(\text{Prj}_{\text{jk}} + \text{NPrj}_{\text{jk}}\right) \quad (3\text{-}16)$$

$$\text{AllocatedWater}_{\text{jk}} = \text{L2Loss}_{\text{jk}} * \text{L2}_{\text{jk}} + \text{L4Loss}_{\text{jk}} * \text{L4}_{\text{jk}} \quad (3\text{-}17)$$

$$\text{NPrj}_{\text{jk}} = \text{SW1Loss}_{\text{jk}} * \text{SW1}_{\text{jk}} + \text{SW2Loss}_{\text{jk}} * \text{SW2}_{\text{jk}} + \text{GW}_{\text{jk}} + \text{RF}_{\text{jk}} \quad (3\text{-}18)$$

Indices	Description
j	Study refuges; = {SAC, DEL, COL, SUT, W165, E165, EBR, MER, PIX, KER}
k	Time-step in Water Years (WY)
l, m, n	Nodes in the network flow model; = {01,...,07}

Variable	Type	Description	Units
$\mathbf{AllocatedWater_{jk}}$	Calculated	Total project water, Level 2 and Level 4 water, allocated to study refuge, j, during time-step, k.	*Acre-Foot/ WY*
$\mathbf{AvgNetHabDem_{j}}$	Calculated	Combined weighted average evapotranspiration (ET) demand of all land-use types at study refuge, j	*Acre-Foot/ Acre/ WY*
$\mathbf{b_{m}}$	Model Input	Inflows into node, m	*Acre-Foot/ WY*
$\mathbf{CCHabDem_{ij}}$	Model Input	Percent change in evapotranspiration demand of land-use type, i, at study refuge, j, due to warm-dry climate change scenario	*Percent/ WY*
$\mathbf{CCPrecip_{j}}$	Model Input	Percent change in precipitation at study refuge, j, due to warm-dry climate change scenario	*Percent/ WY*
$\mathbf{EffPrecip_{ijk}}$	Calculated	Effective precipitation; amount of precipitation that is used to satisfy all or portion of the evapotranspiration demand of land-use type, i, at study refuge, j, for time-step, k	*Acre-Foot/ Acre/ WY*
$\mathbf{GW_{jk}}$	Model Input	Amount of groundwater pumped to meet the water demand of study refuge, j, for time-step, k	*Acre-Foot/ WY*
$\mathbf{HabAcr_{jk}}$	Decision Variable	Size of total managed area at study refuge, j, for time-step, k	*Acre/ WY*
$\mathbf{HabDem_{ij}}$	Model Input	Evapotranspiration demand of land-use type, i, at study refuge, j	*Acre-Foot/ Acre/ WY*
$\mathbf{HistHabAcr_{ij}}$	Model Input	Historically supported acreage of a land-use type, i, at study refuge, j	*Acre/ WY*
$\mathbf{L2_{jk}}$	Model Input	Amount of Level 2 water allocated to study refuge, j, for time-step, k.	*Acre-Foot/ WY*
$\mathbf{L4_{jk}}$	Model Input	Amount of Level 4 water allocated to study	*Acre-Foot/ WY*

		refuge, j, for time-step, k.	
$L2Loss_{jk}$	Model Input	Conveyance loss associated with Level 2 deliveries to study refuge, j, for time-step, k	*Percent/ WY*
$L4Loss_{jk}$	Model Input	Conveyance loss associated with Level 4 deliveries to study refuge, j, for time-step, k	*Percent/ WY*
$Loss_{lm}$	Model Input	Loss incurred on flow arc, lm	*Percent/ WY*
$MaxEffPrecip_{ij}$	Model Input	Maximum effective precipitation; maximum amount of precipitation that can be used to satisfy evapotranspiration demand of land-use type, i, at study refuge, j	*Acre-Foot/ Acre/ WY*
$MinHabAcr_{j}$	Model Input	Lower bound on total managed acreage that must be supported at study refuge, j	*Acre/ WY*
$MaxHabAcr_{j}$	Model Input	Upper bound on total managed acreage that can be supported at study refuge, j	*Acre/ WY*
$NetHabDem_{ij}$	Calculated	Evapotranspiration demand minus demand satisfied by precipitation. Determine for each land-use type, i, at study refuge, j.	*Acre-Foot/ Acre/ WY*
$NPrj_{jk}$	Calculated	Non-project water supplies to study refuge, j, for time-step, k. Supplies include surface water from local streams, groundwater, and return flows from surrounding agricultural lands.	*Acre-Foot/ WY*
$Precip_{jk}$	Model Input	Precipitation that falls within the boundary of study refuge, j, for time step, k	*Acre-Foot/ WY*
Prj_{jk}	Decision Variable	Project water supplies to study refuge, j, for time-step, k. Supplies include Level 2 and Level 4 deliveries after conveyance loss.	*Acre-Foot/ WY*
$Weight_{ij}$	Calculated	Weighting factor to determine how much of the annual precipitation can be used to meet evapotranspiration demand of land-use type, i, at study refuge, j	-
$Reuse_{jk}$	Model Input	On-site reuse of project and non-project water supplies at study refuge, j, for time-step,k	*Percent/ WY*
RF_{jk}	Model Input	Return flow from surrounding agricultural fields that is captured and used as a source of water supply at study refuge, j, for time-step, k	*Acre-Foot/ WY*
$SW1_{jk}$	Model Input	Surface water deliveries from a local surface water source #1 to study refuge, j, for time-step, k	*Acre-Foot/ WY*
$SW2_{jk}$	Model Input	Surface water deliveries from a local surface water source #2 to study refuge, j, for time-step, k	*Acre-Foot/ WY*
$SW1Loss_{jk}$	Model Input	Conveyance loss associated with SW1 deliveries to study refuge, j, for time-step, k	*Percent/ WY*
$SW2Loss_{jk}$	Model Input	Conveyance loss associated with SW2 deliveries to study refuge, j, for time-step, k	*Percent/ WY*
u_{lm}	Model Input	Upper bound on flow arc, lm	*Acre-Foot/ WY*
$WaterDemand_{jk}$	Calculated	Total evapotranspiration demand of all land-use types at study refuge, j, for time-step, k	*Acre-Foot/ WY*
$WaterSupply_{jk}$	Calculated	Total water supplies delivered to study refuge, j, for time-step, k to meet their evapotranspiration demands	*Acre-Foot/ WY*

X_{lm}	Decision Variable	Flow from node l to node m.	*Acre-Foot/ WY*

Table 4-1. Source of inputs to the inter-refuge operations optimization module

Variable	Source
b_m	Historic and Full Level 2 and Level 4 water deliveries to study refuges.
$CCHabDem_{ij}$	Calculated separately using historic temperature data from PRISM and temperature change associated with warm-dry climate. See *Scenarios* section of this chapter for details.
$CCPrecip_j$	Calculated separately using precipitation change associated with warm-dry climate. See *Scenarios* section of this chapter for details.
GW_{jk}	Not included. Analysis only focused on project deliveries.
$HabDem_{ij}$	2011 – 2015 Water Management Plan Section A-5, Section B-2 or Table 3, *Managed Lands Water Needs*, of the WMP Appendix.
$HistHabAcr_{ij}$	2011 – 2015 Water Management Plan Section A-5
$L2_{jk}$, $L4_{jk}$	Historic Level 2 and Level 4 deliveries data from WY 2001 – 2014 was provided by USFWS. Full Level 2 and Level 4 deliveries either provided by USFWS or determined from Section A-3 of 2011 – 2015 Water Management Plan.
$L2Loss_{jk}$, $L4Loss_{jk}$	Zero since the water supply data used in the analysis represent deliveries, not allocations.
$Loss_{lm}$	Delta-Mendota Canal and California Aqueduct conveyance loss determined from the 2009 Delivery Capability Report CalSim II study
$MaxEffPrecip_{ij}$	2011 – 2015 Water Management Plan Table 3, *Managed Lands Water Needs*, of the WMP Appendix
$MinHabAcr_j$	Assumed zero.
$MaxHabAcr_j$	Maximum historic total managed wetland acreage at study refuge, j, rounded to the nearest ten.
$Precip_{jk}$	Not included. Analysis only focused on project deliveries.
$Reuse_{jk}$	Not included. Analysis only focused on project deliveries.
RF_{jk}	Not included. Analysis only focused on project deliveries.
$SW1_{jk}$	Not included. Analysis only focused on project deliveries.
$SW2_{jk}$	Not included. Analysis only focused on project deliveries.
$SW1Loss_{jk}$	Not included. Analysis only focused on project deliveries.
$SW2Loss_{jk}$	Not included. Analysis only focused on project deliveries.
u_{lm}	Zero upper bound on C04 and C05 to represent dry stretches in the San Joaquin River downstream of Millerton Lake to its confluence with Merced River.

Intra-refuge optimization focuses on optimizing the land-use operations at individual refuge nodes. The model determines land-use acreages at all refuges given a fixed refuge water delivery timeseries. This optimization routine is used to explore differences between optimized and historic refuge land-use operations. In the model runs, water delivery timeseries are transferred from inter-refuge optimization runs. *Equations 3-19 through 3-24* represent the mathematical formulation of intra-refuge LP optimization and *Table 4-2* lists the sources of input variables. Combined, both routines are used to explore the two management alternatives: inter-refuge trading and optimized refuge management.

Objective Function: $\max\{\sum_k \sum_j \sum_i \text{HabAcr}_{ijk}\}$ (3-19)

Subject to: $\text{WaterDemand}_{jk} = \text{WaterSupply}_{jk}$ (3-20)

$\text{HabAcr}_{ijk} \geq \text{MinHabAcr}_{ij}$ (3-21)

$\text{HabAcr}_{ijk} \leq \text{MaxHabAcr}_{ij}$ (3-22)

$\text{HabAcr}_{ijk} \geq 0$ (3-23)

Where: $\text{WaterDemand}_{jk} = \sum_i \text{NetHabDem}_{ij} * \text{HabAcr}_{ijk}$ (3-24)

NetHabDem_{ij} calculated same as the Inter-Refuge Optimization Model. See equations 3-13 through 3-15.

Indices	Description
i	Refuge land-use type; = {HAB01,…, HAB11}
j	Study refuges; = {SAC, DEL, COL, SUT, W165, E165, EBR, MER, PIX, KER}
k	Annual time-step
l, m, n	Nodes in the network flow model; = {01,…,07}

Variable	Type	Description	Units
$\mathbf{HabAcr_{ijk}}$	Decision Variable	Size of total managed area of land-use type, i, at study refuge, j, for time-step, k	*Acre / WY*
$\mathbf{MinHabAcr_{ij}}$	Model Input	Lower bound on total managed acreage of land-use type, i, that must be supported at study refuge, j	*Acre-Foot/ WY*
$\mathbf{MaxHabAcr_{ij}}$	Model Input	Upper bound on total managed acreage of land-use type, i, that can be supported at study refuge, j	*Acre-Foot/ WY*
$\mathbf{NetHabDem_{ij}}$	Calculated	Evapotranspiration demand minus demand satisfied by precipitation. Determine for each land-use type, i, at study refuge, j.	*Acre-Foot/ Acre/ WY*
$\mathbf{WaterDemand_{jk}}$	Calculated	Total evapotranspiration demand of all land-use types at study refuge, j, for time-step, k	*Acre-Foot / WY*
$\mathbf{WaterSupply_{jk}}$	Model Input	Total water supplies delivered to study refuge, j, for time-step, k to meet their evapotranspiration demands	*Acre-Foot/ WY*

Table 4-2. Source of inputs to the intra-refuge operations optimization module

Variable	Source
$\mathbf{MinHabAcr_{ij}}$	Not included in the analysis. The lower bound was redefined as total statewide managed wetland acreage of a particular land-use type, i, under optimized refuge operations must be equal to or greater than total statewide managed wetland acreage of a particular land-use type, i, under historic refuge operations.
$\mathbf{MaxHabAcr_{ij}}$	Maximum historic total managed wetland acreage at study refuge, j, rounded to the nearest ten.
$\mathbf{WaterSupply_{jk}}$	Refuge deliveries determined using the Inter-Refuge Optimization Model

Scenarios

Eight scenarios are explored using the Spreadsheet Tool including: with and without inter-refuge trading; historical and warm-dry hydrology; and historical and Full Level 4 refuge deliveries (*Table 4-3*). As explained later, representation of the warm-dry scenario is highly simplified and is included for exploration purposes only. For each scenario, refuge operations are optimized using an annual time-step over a 14 year time period, Water Year 2001 through Water Year 2014[7]. The 14 year simulation is chosen because historical refuge delivery data was only available for these Water Years.

These scenarios reflect only a limited use of the Spreadsheet Tool. The model can be also set-up to examine inter-refuge trading among selective refuges, for example, refuges north of the Delta only or refuges south of the Delta only as opposed to inter-refuge trading among all the USFWS managed refuges. Only project deliveries, water allocated and delivered to the refuges under CVPIA, are included in the analysis. However, the model has provisions to include non-project deliveries as well. On-site reuse is assumed inactive in the model runs to be consistent with the CALVIN runs, but the tool contains provision to include on-site reuse.

Table 4-3. Summary of scenarios analyzed using Spreadsheet Tool

#	Delivery	Hydrology	Trading
1	Historic	Historic	No Trading
2	Historic	Warm-Dry	No Trading
3	Historic	Historic	Trading
4	Historic	Warm-Dry	Trading
5	Full Level 4	Historic	No Trading
6	Full Level 4	Warm-Dry	No Trading
7	Full Level 4	Historic	Trading
8	Full Level 4	Warm-Dry	Trading

[7] Water Year is defined as USFWS's definition: March of current calendar year to February of following calendar year.

Table 4-4. Historical Level 2 and incremental Level 4 deliveries to USFWS refuges between 2001 and 2014 (Acre-feet/ Yr) [a]

Water Year [b] -->		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SAC	L2	33,948	38,909	36,811	40,507	35,872	36,845	40,004	37,153	34,773	34,932	37,390	35,736	40,498	22,340
	L4	3,213	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	37,161	38,909	36,811	40,507	35,872	36,845	40,004	37,153	34,773	34,932	37,390	35,736	40,498	22,340
DEL	L2	19,570	19,621	16,858	16,898	17,053	17,625	17,507	18,265	18,594	17,988	19,447	17,425	21,377	16,344
	L4	0	1,500	5,355	5,308	5,355	7,905	5,355	3,750	3,315	3,315	3,250	3,250	2,550	0
	Tot	19,570	21,121	22,213	22,206	22,408	25,530	22,862	22,015	21,909	21,303	22,697	20,675	23,927	16,344
COL	L2	17,039	17,807	18,708	20,171	21,305	19,562	20,140	20,500	16,552	17,751	19,856	16,410	17,421	14,680
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	17,039	17,807	18,708	20,171	21,305	19,562	20,140	20,500	16,552	17,751	19,856	16,410	17,421	14,680
SUT	L2	14,338	14,201	17,906	20,012	12,733	13,267	18,398	23,606	13,690	17,746	15,151	12,569	13,570	7,200
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	14,338	14,201	17,906	20,012	12,733	13,267	18,398	23,606	13,690	17,746	15,151	12,569	13,570	7,200
W165	L2	15,225	14,758	15,390	14,157	15,364	14,898	15,053	14,582	15,069	15,511	14,428	15,024	15,973	10,261
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	15,225	14,758	15,390	14,157	15,364	14,898	15,053	14,582	15,069	15,511	14,428	15,024	15,973	10,261
E165	L2	23,727	25,397	27,257	26,686	25,396	25,926	25,526	26,207	25,809	26,605	26,207	26,067	26,031	15,412
	L4	3,656	3,082	0	0	0	0	0	0	0	0	3,603	0	0	0
	Tot	27,383	28,479	27,257	26,686	25,396	25,926	25,526	26,207	25,809	26,605	29,810	26,067	26,031	15,412
EBR	L2	3,008	7,400	8,552	2,568	0	0	0	3,528	4,084	4,273	4,919	3,888	3,902	245
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	3,008	7,400	8,552	2,568	0	0	0	3,528	4,084	4,273	4,919	3,888	3,902	245
MER [c]	L2	21,226	21,226	21,226	21,226	21,226	13,500	13,500	13,500	27,000	27,000	25,000	27,000	26,984	17,550
	L4	1,778	1,778	1,778	1,778	1,778	1,500	1,500	1,500	1,500	2,500	2,500	2,500	2,500	0
	Tot	23,004	23,004	23,004	23,004	23,004	15,000	15,000	15,000	28,500	29,500	27,500	29,500	29,484	17,550
PIX	L2	821	771	776	686	632	990	585	681	592	551	1,265	858	1,382	1,280
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	67
	Tot	821	771	776	686	632	990	585	681	592	551	1,265	858	1,382	1,347
KER	L2	9,950	9,004	8,933	10,705	9,950	9,950	9,950	9,950	10,133	9,413	9,982	9,950	9,950	6,788
	L4	8,000	10,713	12,919	8,270	11,514	11,305	7,538	9,000	8,105	9,406	15,050	6,710	5,567	1,682
	Tot	17,950	19,717	21,852	18,975	21,464	21,255	17,488	18,950	18,238	18,819	25,032	16,660	15,517	8,470

[a] Source: Rachel Esralew, USFWS Hydrologist
[b] Water Year is defined as March of current calendar year to February of the following calendar year
[c] Historic delivery data was only available beginning WY 2006. Deliveries prior to WY 2006 were calculated by averaging historic deliveries from WY 2006 to 2014.

Inputs

Inputs include refuge deliveries, upper and lower bound constraints on managed wetland acreage, and habitat water demand. A detailed description of each input along with assessment of effects of climate change on refuge demand is presented below.

Refuge deliveries

Two types of refuge delivery time series are used in the analysis: historical deliveries and Full Level 4 deliveries. Historical deliveries include historical project deliveries between March 2001 and February 2015 (*Table 4-4*). Historical delivery data for Merced was only available beginning WY 2006. Average deliveries between WY 2006 and 2014 are used to represent refuge deliveries during WY 2001 – 2005. Full Level 4 deliveries are determined similarly as in the CALVIN model runs. Full Level 2 plus 100% incremental Level 4 deliveries during all years except in critical years – determined using Shasta Lake Index – Full Level 2 deliveries are reduced to 75% (*Table 4-5*).

Table 4-5. Full Level 4 refuge deliveries between 2001 and 2014 (Acre-feet/ Yr) [a,b]

Water Year [c] -->		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SAC	L2	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	46,400	34,800
	L4	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
	Tot	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	38,400
DEL	L2	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	21,950	16,463
	L4	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050	8,050
	Tot	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	24,513
COL	L2	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	18,750
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	18,750
SUT	L2	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	17,625
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	17,625
W165	L2	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	11,468
	L4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tot	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	15,290	11,468
E165	L2	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	26,107	19,580
	L4	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603	3,603
	Tot	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	29,710	23,183
EBR	L2	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	8,863	6,647
	L4	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432	4,432
	Tot	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	13,295	11,079
MER	L2	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	10,125
	L4	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
	Tot	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	12,625
PIX	L2	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	1,280	960
	L4	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720	4,720
	Tot	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	5,680
KER	L2	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	9,950	7,463
	L4	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050	15,050
	Tot	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	22,513

[a] Source: Rachel Esralew, USFWS Hydrologist. See *Appendix 4* for details.
[b] Level 2 deliveries are reduced by 25% during critical years at Shasta.
[c] Water Year is defined as March of current calendar year to February of the following calendar year

Table 4-6. Historical managed wetland acreage at USFWS refuges by land-use type (acres) [a]

#	Land-Use Description	SAC			DEL			COL			SUT [c]			W165			E165			EBR			MER			PIX			KER		
		1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010	1992	1997	2010
HAB01	Timothy Grass	6,257	6,258	5,929	3,768	3,768	3,284	2,851	2,851	2,700	1,435	1,435	1,435	1,140	1,140	1,120	300	1,526	2,241	-	-	715	725	985	1,136	-	309	309	1,736	3,876	5,891
HAB02	Smartweed	-	-	-	-	-	-	-	-	173	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	138	136	-
HAB03	Watergrass	486	510	608	531	531	803	247	247	224	247	247	247	65	65	109	300	1,018	751	-	-	-	-	304	304	-	-	-	-	-	50
HAB04	Permanent Wetland	295	61	376	286	286	30	150	150	71	80	80	80	32	32	47	40	136	227	-	-	-	21	41	41	-	-	-	-	-	-
HAB05	Semi-Permanent Wetland/ Brood Pond	414	623	539	139	139	607	101	101	449	117	117	117	242	276	276	40	697	459	-	-	-	-	88	88	-	-	-	-	-	-
HAB06	Irrigated Pasture	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	354	391	391	-	-	-	-	-	-
HAB07	Cropland (Corn)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HAB08	Cropland (Small Grain)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	446	453	453	-	-	-	-	-	-
HAB09	Riparian (Irrigated)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HAB10	Upland (irrigated)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HAB11	Habitat type 11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Σ		7,452	7,452	7,452	4,724	4,724	4,724	3,349	3,349	3,617	1,880	1,880	1,880	1,479	1,513	1,552	680	3,377	3,678	0	0	715	1,546	2,262	2,413	0	309	309	1,874	4,012	5,941
Total Managed Wetland Acreage used in the model		7,460			4,730			3,620			1,880			1,560			3,680			720			2,420			310			5,950		

[a] *Section A-5* of Water Management Plan (USBR 2010a-b; USBR 2011a-l)
[b] No WMP available for Sutter NWR. Assumed same land-use proportions as Delevan NWR.

Managed wetland acreage

Managed wetland acreage represents the part of total refuge acreage actively managed by applying supplied water deliveries. It is calculated using historic land use acreage data included in the refuge Water Management Plan (WMP). Historic land-use data is only available for WY 1992, 1997 and 2010 and is tabulated in *Table 4-6*. Maximum historical acreage is used as an upper bound on managed wetland acreage at the refuge nodes. Not all land-use types are supported at the individual refuges. East Bear Creek and Pixley NWR only grow timothy grass. Kern NWR only manages all types of seasonal wetlands, including timothy grass, smartweed and watergrass. Merced NWR is the only refuge that uses project deliveries to irrigate pasture and small grain crops. Roughly 32,000 acres of wetlands are managed by USFWS in the Central Valley. About 55% of these wetlands are located north of the Delta. Of the remaining 45%, nearly half are in Tulare Basin, 35% west of the San Joaquin River and 20% east of the San Joaquin River in the Merced River watershed.

Water demand

Annual unit water demand represents acre-feet of water needed to grow an acre of a crop. This information is also included in the Water Management Plans (WMPs). It varies by land-use and by refuge (*Table 4-7*). Permanent wetlands have the highest water demand followed by semi-permanent wetlands across all refuges. However, permanent wetland unit demand is significantly higher north of the Delta than south of the Delta. On the other hand, water demand of timothy grass and watergrass is higher south of the Delta compared to north of the Delta.

Table 4-7. Land-use water demand at USFWS refuges assuming historical hydrology (Acre-feet/ Acre) [a]

#	Land-Use Description	SAC	DEL	COL	SUT	W165	E165	EBR	MER	PIX	KER
HAB01	Timothy Grass	5.00	5.00	5.00	5.00	8.00	8.00	8.00	8.00	5.00	6.00
HAB02	Smartweed	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	-	5.00
HAB03	Watergrass	7.50	7.50	7.50	7.50	8.00	8.00	8.00	8.00	-	8.00
HAB04	Permanent Wetland	13.25	13.25	13.25	13.25	10.00	10.00	10.00	10.00	-	-
HAB05	Semi-Permanent Wetland/ Brood Pond	9.00	9.00	9.00	9.00	8.75	8.75	8.75	8.75	-	-
HAB06	Riparian (Irrigated)	-	-	-	-	4.00	4.00	4.00	4.00	-	-
HAB07	Pasture (Irrigated)	-	-	-	-	4.50	4.50	4.50	4.50	-	-
HAB08	Upland (Irrigated)	-	-	-	-	1.75	1.75	1.75	2.00	-	-
HAB09	Grain Crops	-	-	-	-	-	-	-	-	-	-
HAB10	Upland (irrigated)	-	-	-	-	-	-	-	-	-	-
HAB11	Habitat type 11	-	-	-	-	-	-	-	-	-	-
Average Habitat Demand [b]		**5.73**	**5.93**	**5.72**	**5.93**	**8.18**	**8.20**	**8.00**	**5.95**	**5.00**	**5.97**

[a] *Section A-5* or *Appendix Table 3* of Water Management Plan (USBR 2010a-b; USBR 2011a-l)
[b] Weighted by historic land-use acreage (*Table 4-6* of this chapter)

Weighted unit water demand is used in the inter-refuge optimization routine which is the average water demand of all land-use managed at a refuge weighted multiplied by the amount of land-use acreage historically managed at that refuge. In other words, outputs from the inter-refuge model assume historical refuge operations. The intra-refuge optimization routine optimizes land-use operations to maximize the benefits from the water supplies delivered to the refuge. Comparing the two highlights differences between historic and optimized refuge operations, and provides management insights into maximizing water use efficiency for a refuge. Refuges in the San Joaquin Valley have the highest weighted unit water demand with the exception of Merced NWR. Refuges in Sacramento Valley and Tulare Basin have the same weighted unit water demand. Inter-refuge trading will reallocate water deliveries away from water intensive refuges toward water efficient refuges. Since it is more effective to grow timothy grass in the north or south in Tulare Basin and permanent wetlands in the south, optimizing land-use operations is expected to reallocate more managed wetland acreage to timothy grass north of the Delta and to permanent wetlands south of the Delta.

Effects of climate change

Effects of a warm-dry hydrology on refuge water demand or evapotranspiration demands are also considered in this analysis. However, this is just included as an added feature. Some obviously wrong assumptions are made in quantifying the impacts of a warm-dry scenario and further improvement is definitely needed to refine these impacts. The Hagreaves-Samani equation is used to determine percent change in evapotranspiration demands of land-use types managed at the refuges. Hagreaves-Samani is an empirical equation that uses solar radiation and temperature to estimate reference evapotranspiration rate (*Equation 3-25*). Together, solar radiation and temperature capture roughly 80% of the parameters that affect evapotranspiration, but fail to include the effects of latitude, elevation, topography, storm pattern, etc. (Samani, 2000). However, limitations are less since the emphasis is on relative change in evapotranspiration.

$$ET_o = 0.0135\ (KT)\ (R_a)\ (TD)^{0.5}\ (TC + 17.8) \qquad (3\text{-}25)$$

Where

ET_o	Reference evapotranspiration
KT	Empirical coefficient (0.162 for interior regions and 0.19 for coastal region is recommended)
R_a	Extraterrestrial radiation (*mm/day*)
TD	Difference between daily maximum and minimum temperature (*degree Celsius*)
TC	Average daily temperature (*degree Celsius*)

$$\Delta ET_c = \frac{(TC - TC')}{(TC' + 17.8)} \qquad (3\text{-}26)$$

Where

ΔET_c	Percent change in crop evapotranspiration demand
TC	Average daily temperature under warm-dry hydrology (*degree Celsius*)
TC'	Average daily temperature under historic hydrology (*degree Celsius*)

The Hagreaves-Samani equation is simplified to *Equation 3-26* after a series of assumptions and simplifications (see *Appendix 11* for details). These assumptions are limitations imposed by either resolution of or lack of available data. At the end, the two inputs include average daily temperature under a warm-dry hydrology and historical hydrology. Historical temperature data from the PRISM database is used. However, the data are only available at monthly time-step. So, a uniform distribution of temperature across entire month is assumed. To calculate average daily temperature under a warm-dry climate, percent change in temperature data used to a create warm-dry case in CALVIN is used here as well for consistency. Since percent change in temperature data is only available for the major reservoirs, refuges are mapped to the nearest reservoir as outlined in *Table 4-8*. There is not much variability in percent change in temperature; difference between north and south is less than 1% on average. Perturbed unit water demand is tabulated in *Table 4-9*. Even though unit water demand increases overall, results are roughly same as unit water demand under the historical hydrology.

Table 4-8. Effects of warm-dry hydrology

Abb.	Description	Mapped to...	ΔETc (%)	ΔPrecip (%)
SAC	Sacramento NWR	Black Butte Lake	0.12	-0.32
DEL	Delevan NWR	Black Butte Lake	0.12	-0.32
COL	Colusa NWR	Black Butte Lake	0.12	-0.32
SUT	Sutter NWR	Lake Oroville	0.13	-0.33
W145	Kesterson and Frietas Unit (San Luis NWR)	San Luis Reservoir	0.11	-0.26
E145	San Luis and West Bear Creek Unit (San Luis NWR)	San Luis Reservoir	0.11	-0.26
EBR	East Bear Creek Unit (San Luis NWR)	Lake McClure	0.12	-0.22
MER	Merced NWR	Lake McClure	0.12	-0.22
PIX	Pixley NWR	Lake Success	0.12	-0.26
KER	Kern NWR	Lake Success	0.12	-0.26

Table 4-9. Land-use water demand at USFWS refuges assuming warm-dry hydrology (Acre-feet/ Acre) [a]

#	Land-Use Description	SAC	DEL	COL	SUT	W165	E165	EBR	MER	PIX	KER
HAB01	Timothy Grass	5.59	5.58	5.58	5.63	8.86	8.86	8.94	8.97	5.62	6.74
HAB02	Smartweed	5.59	5.58	5.58	5.63	5.54	5.54	5.59	5.61	-	5.62
HAB03	Watergrass	8.38	8.38	8.38	8.44	8.86	8.86	8.94	8.97	-	8.99
HAB04	Permanent Wetland	14.80	14.80	14.80	14.91	11.07	11.07	11.17	11.21	-	-
HAB05	Semi-Permanent Wetland/ Brood Pond	10.05	10.05	10.05	10.13	9.69	9.69	9.77	9.81	-	-
HAB06	Riparian (Irrigated)	-	-	-	-	4.43	4.43	4.47	4.48	-	-
HAB07	Pasture (Irrigated)	-	-	-	-	4.98	4.98	5.03	5.04	-	-
HAB08	Upland (Irrigated)	-	-	-	-	1.94	1.94	1.95	2.24	-	-
HAB09	Grain Crops	-	-	-	-	-	-	-	-	-	-
HAB10	Upland (irrigated)	-	-	-	-	-	-	-	-	-	-
HAB11	Habitat type 11	-	-	-	-	-	-	-	-	-	-
Average Habitat Demand [b]		**6.40**	**6.62**	**6.39**	**6.67**	**9.06**	**9.09**	**8.94**	**6.67**	**5.62**	**6.71**

[a] Land-use water demand from *Table 4-7* multiplied by percent ΔETc from *Table 4-8*
[b] Weighted by historic land-use acreage (*Table 4-6*)

Limitations

Carriage water cost is not considered in the analysis. It is the additional amount of water that is released to the ocean to maintain the salinity barrier in the Delta anytime exports compared to the inflows in southern Delta exceed a threshold. Pumps generate reverse flows in Old and Middle River which create a predominant north-south flow in the Delta opposed to the natural east-west tidal flow. As a result, saline ocean water is drawn into the Delta and a portion of Delta exports is set aside to maintain the salinity barrier. The portion varies with the hydrologic conditions within Delta, and could be as high as 40% of the amount transferred south of the Delta[8]. This certainly impacts the results from the inter-refuge trading management alternative.

[8] Personal communication with Rachel Esralew, hydrologist, USFWS.

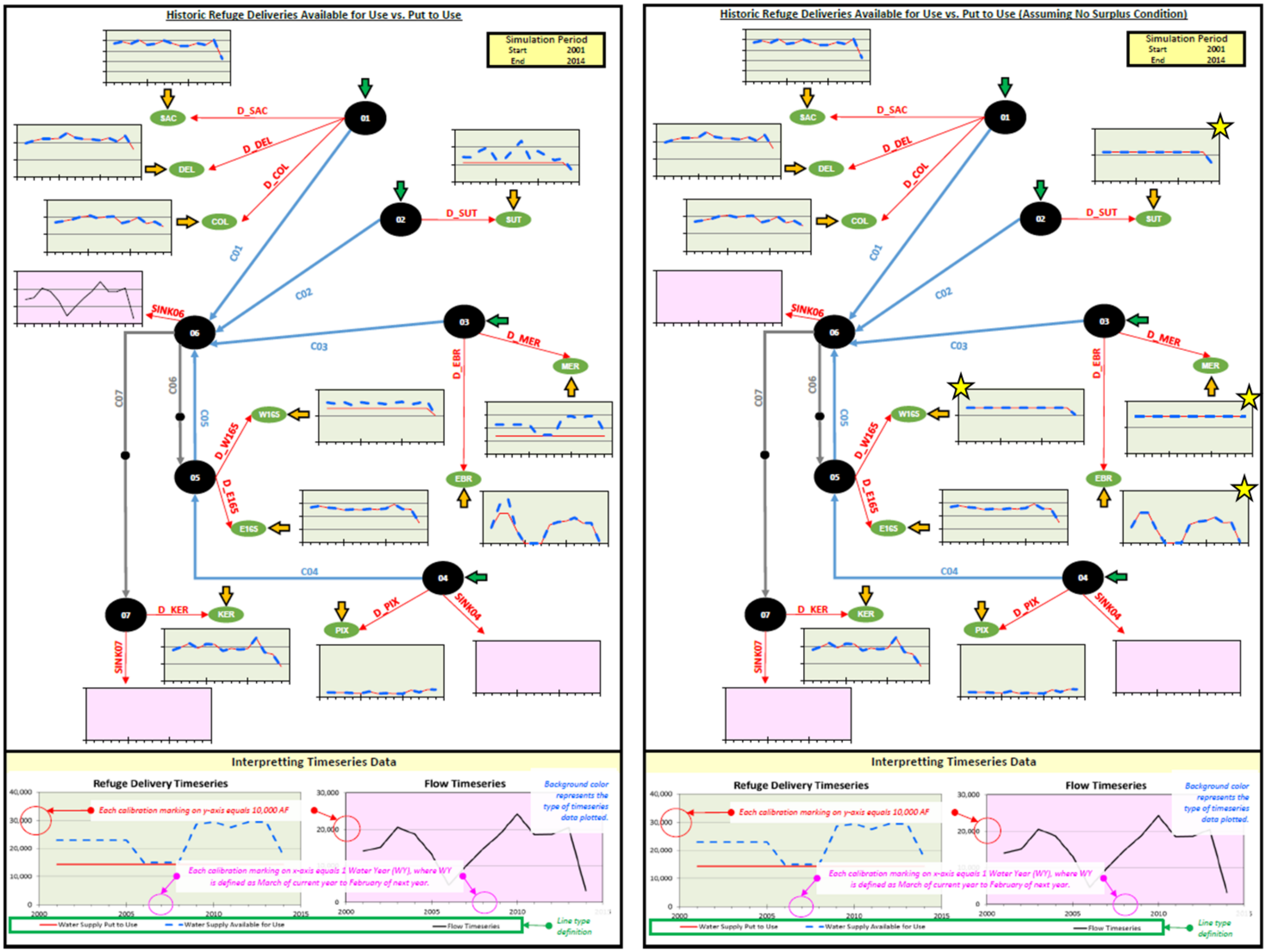


Figure 4-3. Comparison of *surplus* and no *surplus* conditions assuming historical refuge deliveries, historical hydrology and no inter-refuge trading

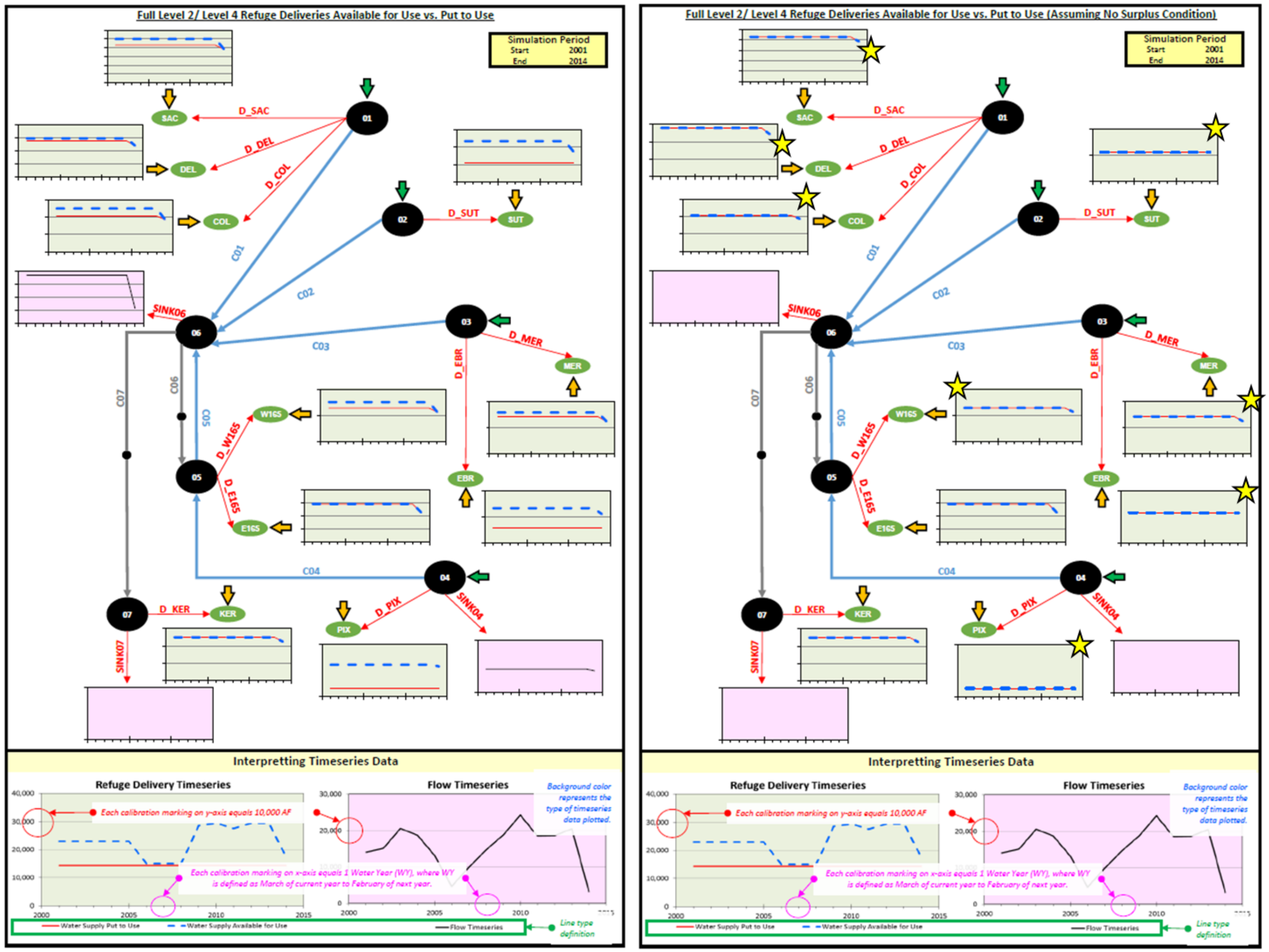


Figure 4-4. Comparison of *surplus* and no *surplus* conditions assuming Full Level 4 refuge deliveries, historical hydrology and no inter-refuge trading

Water supply is limited to project deliveries. However, refuges also rely on non-project sources and precipitation to meet some evapotranspiration demands. Therefore, managed wetland acreage could be more than the acreage indicated by model for an individual case, but the comparative trends between the scenarios remain reliable.

The last limitation stems from quality of input data obtained from WMPs. Historical land-use data is only available for three years. Water demand data has limited spatial variability and sometimes there is even conflicting water demand information presented in different sections of the WMP which raises concerns about reliability of refuge water demand data. Even though WMPs are not the most reliable source of information, they are the most comprehensive source of information available at the moment.

Results

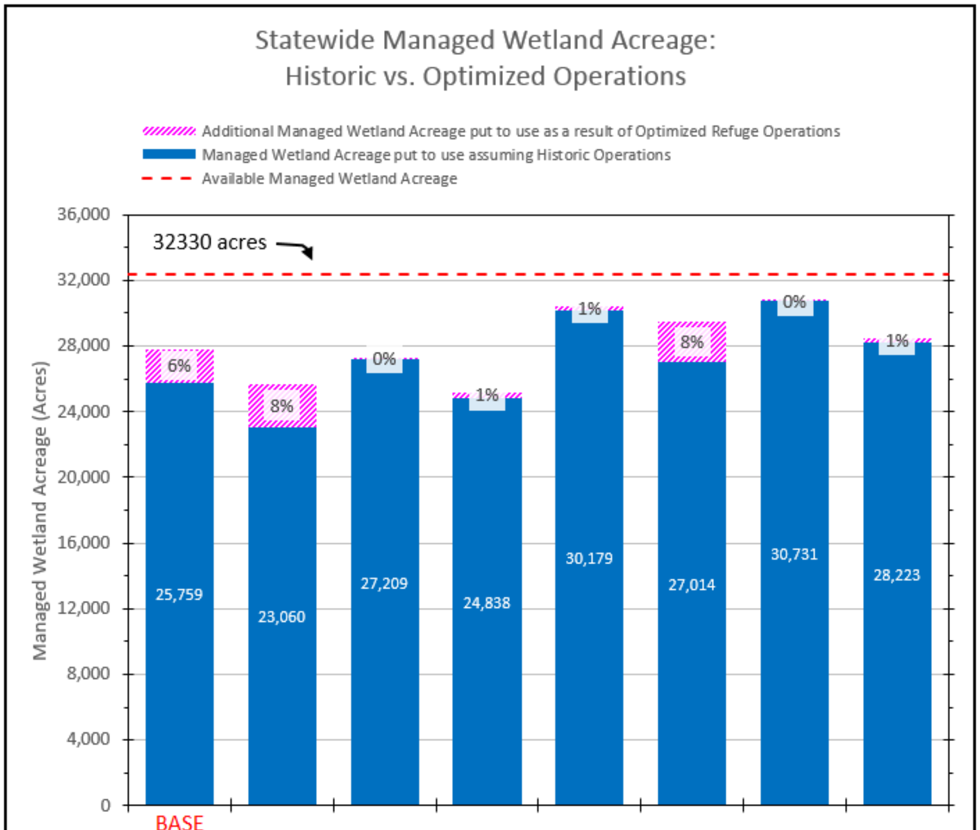
The base case assumes historical hydrology and no inter-refuge trading. Other scenarios are compared against the base case to assess the benefits and management implications of inter-refuge trading and optimized land-use operations. Results include the impact of eight hydrologic and management scenarios on refuge deliveries, total managed wetland acreage, and differences between optimized and historical land-use operations. At the end, Lagrange multipliers on available water supply and land use acreage are compared to assess effects of inter-refuge trading and optimized land-use operations on addressing water scarcity.

No surplus conditions

There are instances of surplus water supply in the system which could be a byproduct of input data quality – underestimated water demand or maximum amount of land available for use – or simply a limitation of the model assumption that no project water is used to irrigate uplands or riparian habitat, which is true in theory, but may not be entirely consistent with on-the-ground operations. In either case, to create a perfect competition for water, no surplus conditions are assumed in all model runs. Any historical or Full Level 4 deliveries that are not put to use under the base case, are subtracted from the refuge water delivery timeseries. Figures 4-3 and 4-4 highlight the differences between surplus and no surplus runs for historical and Full Level 4 refuge deliveries, respectively, for the base case. Refuges impacted by the no surplus conditions are marked with a star (★).

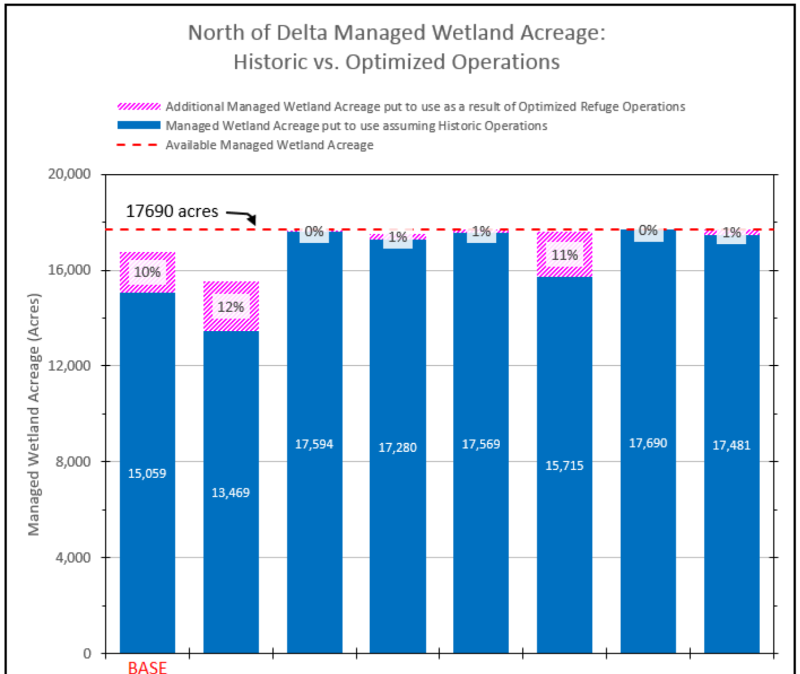
Managed wetland acreage

Effects of hydrologic and management scenario on statewide managed wetland acreage are included in *Figure 4-5*. Under the base case, historical refuge deliveries result in 20% unmanaged acreage statewide. Full Level 4 deliveries reduce unmanaged acreage by roughly 15%. Warm-dry hydrology increases unmanaged wetland acreage by 10%. Percent reduction in unmanaged wetland acreage from inter-refuge trading is higher with reallocation of historical deliveries compared to Full Level 4 deliveries; unmanaged acreage decreases by 4 – 6% with reallocation of historical deliveries compared to 2-3% with reallocation of Full Level 4 deliveries. However, overall unmanaged wetland acreage is still 10 – 15% lower with Full Level 4 deliveries. Optimized land-use management reduces unmanaged acreage by 6 – 8% in absence of inter-refuge trading, but has a marginal effect when combined with inter-refuge trading. Results indicate that optimizing land-use operations is at least as beneficial as reallocating available water supplies among refuges and can significantly curb the effects of a warm-dry hydrology on managed wetland acreage. Since USFWS is responsible for setting management objectives, from a regulatory standpoint, optimizing land-use operations is easier and often cheaper than working with USBR and local irrigation districts to reallocate refuge water supplies.



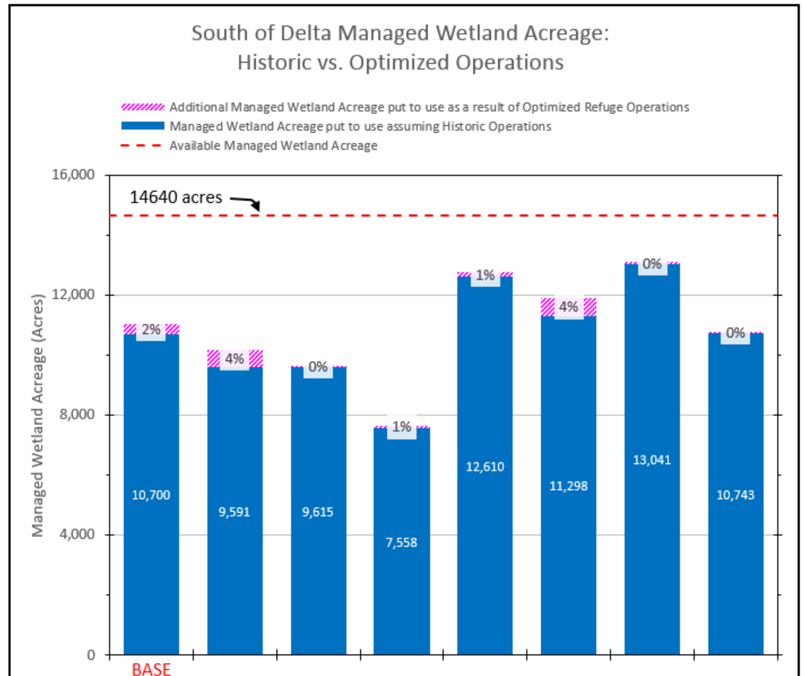
Refuge Deliveries	Historic	Historic	Historic	Historic	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4
Climate Change	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry
Inter-refuge Trading			✓	✓			✓	✓
% Unmanaged (Historic Operations)	20%	29%	16%	23%	7%	16%	5%	13%
% Unmanaged (Optimized Operations)	14%	21%	16%	22%	6%	9%	5%	12%

Figure 4-5. Statewide managed wetland acreage



Refuge Deliveries	Historic	Historic	Historic	Historic	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4
Climate Change	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry
Inter-refuge Trading			✓	✓			✓	✓
% Unmanaged (Historic Operations)	15%	24%	1%	2%	1%	11%	0%	1%
% Unmanaged (Optimized Operations)	5%	12%	0%	1%	0%	0%	0%	0%

Figure 4-6. North of the Delta managed wetland acreage



Refuge Deliveries	Historic	Historic	Historic	Historic	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4
Climate Change	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry
Inter-refuge Trading			✓	✓			✓	✓
% Unmanaged (Historic Operations)	27%	34%	34%	48%	14%	23%	11%	27%
% Unmanaged (Optimized Operations)	25%	30%	34%	48%	13%	19%	11%	27%

Figure 4-7. South of the Delta managed wetland acreage

Despite statewide gains in managed wetland acreage from inter-refuge trading and optimized land-use operations, there are significant differences in regional effects of the two management scenarios. Managed wetland acreage under different hydrologic and management cases is summarized in *Figures 4-6* and *4-7* for north of the Delta and south of the Delta refuges, respectively. Inter-refuge trading reallocates refuge deliveries with preference for refuges north of the Delta. As a result, unmanaged wetland acreage increases south of the Delta due to inter-refuge trading. Under historical hydrology, unmanaged wetland acreage falls from 15% to 1% with reallocation of historical deliveries and from 11% to 1% with reallocation of Full Level 4 deliveries in the north. For the same conditions, unmanaged wetland acreage increases from 27% to 34% with historical deliveries and from 23% to 27% with Full Level 4 deliveries in the south. Gains from optimized land-use operations are also significantly higher north of the Delta. In absence of inter-refuge trading, unmanaged wetland acreage reduces by 10 – 12% in the north compared to 1 – 4% in the south. However, combining inter-refuge trading and optimized land-use operations diminishes the difference in the effect of optimized land-use operations north and south of the Delta.

Optimized land-use operations

Table 4-10 summarizes the effects of hydrologic and management cases on habitat acreage for each land-use type managed at the refuges assuming historical land-use operations. *Table 4-11* summarizes the effects for optimized land-use operations. The base case assumes historical deliveries in addition to historical hydrology and no inter-refuge trading.

Table 4-10. Pecent change in managed wetland acreage assuming historic refuge management practices

		Timothy Grass	Smartweed	Watergrass	Permanent Wetland	Semi-Permanent	Irrigated Pasture	Small Grain Crops	**All Land-use Types**
Base Scenario Acreage	NOD	12,052	54	1,403	557	994	0	0	**15,059**
	SOD	7,444	72	1,160	239	817	442	526	**10,700**
	CA	**19,496**	**126**	**2,563**	**796**	**1,811**	**442**	**526**	**25,759**
Full Level 4 Deliveries	NOD	10%	5%	9%	12%	9%	0%	0%	**10%**
	SOD	9%	19%	4%	3%	3%	-1%	-1%	**7%**
	CA	**19%**	**24%**	**14%**	**14%**	**13%**	**-1%**	**-1%**	**17%**
Warm-dry Hydrology	NOD	-4%	-2%	-4%	-4%	-3%	0%	0%	**-4%**
	SOD	-5%	-5%	-8%	-5%	-10%	-6%	-6%	**-6%**
	CA	**-9%**	**-7%**	**-12%**	**-10%**	**-13%**	**-6%**	**-6%**	**-9%**
Inter-refuge Trading	NOD	9%	6%	8%	10%	8%	0%	0%	**8%**
	SOD	2%	39%	-27%	-18%	-26%	6%	6%	**-3%**
	CA	**10%**	**44%**	**-19%**	**-8%**	**-19%**	**6%**	**6%**	**5%**

Full Level 4 deliveries increase managed acreage of all land-use types except for a marginal 1% decrease in irrigated pasture and small grain crops. Smartweed and timothy grass acreages increases the most as a result of Full Level 4 deliveries; 24% and 19%, respectively. Gains in timothy grass acreage are equally distributed north and south of the Delta. Rest of the land-use increase two – three times more north of the Delta except for Smartweed which increases four times more south of the Delta.

The warm-dry hydrology decreases managed wetland acreage by 9%, on average. Watergrass and semi-permanent wetland acreages fall the most under the warm-dry hydrology; 12 – 13% compared to 7 – 10% for other land-use types. Timothy grass and permanent wetland acreage reduces equally north and south of the Delta whereas other land-use types experience two – three times more reduction south of the Delta.

Table 4-11. Pecent change in managed wetland acreage assuming optimized refuge management practices

		Timothy Grass	Smartweed	Watergrass	Permanent Wetland	Semi-Permanent	Irrigated Pasture	Small Grain Crops	All Land-use Types
Base Scenario Acreage	NOD	12,052	54	1,403	557	994	0	0	15,059
	SOD	7,444	72	1,160	239	817	442	526	10,700
	CA	19,496	126	2,563	796	1,811	442	526	25,759
No Inter-Refuge Trading	NOD	29%	-100%	-100%	-63%	-25%	-	-	10%
	SOD	-47%	2067%	125%	150%	30%	0%	86%	4%
	CA	0%	1166%	0%	0%	0%	0%	86%	7%
Inter-Refuge Trading	NOD	4%	-50%	-31%	-2%	15%	-	-	1%
	SOD	-7%	74%	130%	30%	-42%	9%	9%	1%
	CA	0%	34%	0%	2%	1%	9%	9%	1%
Historic Hydrology	NOD	12%	-72%	-68%	-12%	15%	-	-	3%
	SOD	-18%	719%	117%	27%	-37%	2%	20%	1%
	CA	0%	389%	0%	0%	0%	2%	20%	2%
Warm-Dry Hydrology	NOD	21%	-78%	-63%	-53%	-25%	-	-	7%
	SOD	-35%	1422%	138%	152%	25%	7%	75%	3%
	CA	0%	811%	0%	2%	1%	7%	75%	6%

Inter-refuge trading increases statewide managed wetland acreage by 5%, but has opposite effects on refuges north and south of the Delta. In the north, managed wetland acreage increases by 8%, on average, with highest gains in permanent wetland (10% increase) and timothy grass acreage (9% increase). In the south, managed wetland acreage reduces by 3%, on average. However, not all land-use types are reduced. Timothy grass, smartweed and cropland acreages increase while watergrass, permanent wetland and semi-permanent wetland acreages reduce. In a nutshell, under historical operations, results indicate an investment in timothy grass and smartweed, and divestment in watergrass, permanent wetlands, and semi-permanent wetlands as a result of inter-refuge trading.

Table 4-11 summarizes the effects of optimized land-use operations under various hydrologic and management cases. Results are driven by land-use water demand. Since it is more effective to grow timothy grass in the north and permanent wetlands in the south, optimized land-use operations reallocate more of managed wetland acreage to timothy grass north of the Delta and to permanent wetlands south of the Delta. Irrigated pasture and small grain crops are grown south of the Delta only; therefore, any gains from optimized land-use operations are only seen in the south. Other land-use types are distributed across the Central Valley and have approximately same water demand. Optimized land-use operations result increased acreage of smartweed and watergrass south of the Delta. Semi-permanent wetlands have a mixed response: inter-refuge trading reduces habitat acreage south of the Delta by 40% whereas a warm-dry hydrology increases acreage by 25%.

From a statewide perspective, optimized land-use operations result in a net gain in smartweed and small grain crop acreage. Other land-use types see little to no gain despite significant north-south fluctuations in land-use acreage. Under warm-dry hydrology, optimizing land-use operations will result in three times more gains on average which reduces unmanaged wetland acreage from 9% to 3%. Across different hydrologic and management scenarios, optimizing land-use operations results in 1 – 7% gain in managed wetland acreage with two – three times more gain north of the Delta compared to south of the Delta. Even though gains from optimized land-use operations reduce significantly when combined with inter-refuge trading, combining the two helps retain land-use diversity across the Central Valley. Optimized land-use operations result in drastic reallocations of land-use types such as complete divestment from smartweed and watergrass land-use types in the north. Inter-refuge trading introduces additional flexibility and allows refuges to retain land-use diversity at individual refuges.

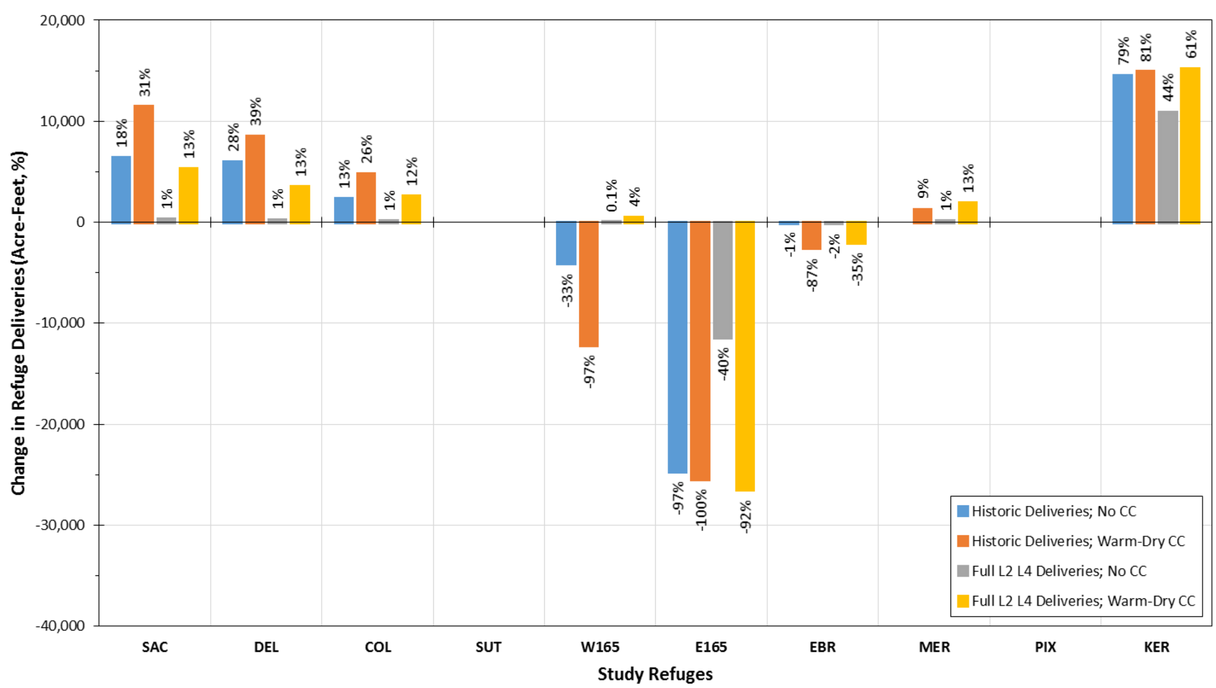


Figure 4-8. Impact of inter-refuge trading on refuge deliveries

Inter-refuge trading

The effects of inter-refuge trading on refuge deliveries are summarized in *Figure 4-8*. Weighted habitat demand is the driving factor in reallocating refuge deliveries. Refuges located in the San Joaquin Valley have the highest weighted unit water demand with the exception of Merced NWR. Refuges in Sacramento Valley and Tulare Basin have the same weighted unit water demand. As a result, water supplies are reallocated from San Luis NWR Complex to Sacramento, Delevan and Colusa NWRs in the north, and Merced and Kern NWR in the south. Percent change in refuge deliveries intensify with warm-dry hydrology; however, the trends are still retained. Water supplies to Sacramento, Delevan, Colusa and Kern NWR increase across all scenarios and water supplies to refuges east of Highway 165, San Luis unit and West Bear Creek unit of San Luis NWR Complex, reduce across all scenarios. Water supplies to refuges west of Highway 165 are only reduced under historical refuge deliveries. Finally, East Bear Creek unit and Merced NWR participate in local water trading where supplies from East Bear Creek unit are reallocated to Merced NWR under a warm-dry hydrology.

Water versus land scarcity

Similar to the opportunity cost of refuge deliveries, Lagrange multipliers on refuge deliveries and managed wetland acreage available for use can be used to estimate whether water supplies or available land-use acreage are a limiting factor. Since the objective is to maximize total managed wetland acreage, change in objective function represents change in total managed wetland acreage. Lagrange multiplier or shadow price on refuge deliveries indicates change in total managed wetland acreage resulting from additional unit of water delivered to the refuge (acre/acre-foot). Similarly, the shadow price on available land-use acreage represents change in total managed wetland acreage resulting from one additional unit of land available for use at the refuge (acre/acre). Results are tabulated in *Table 4-12* for both historic and optimized land-use operations and qualitatively summarized in *Figure 4-9*.

The shadow price on refuge deliveries and available land-use acreage is compared at each refuge to determine whether water scarcity is a limiting factor. Results indicate that under base case – historical deliveries, historical hydrology and no inter-refuge trading – available water supply is the limiting factor at all refuges. With a few exceptions, water scarcity remains a limiting constraint even if refuge deliveries increase to Full Level 4. As a result of warm-dry hydrology, water scarcity becomes increasingly limiting regardless of the refuge delivery scenario. Optimizing land-use operations without any inter-refuge trading significantly reduces and even eliminates water scarcity at all refuges north of the Delta, and refuges west of Highway 165 and Merced NWR in the San Joaquin Valley. Inter-refuge trading with historical land-use operations lowers water scarcity at refuges north of the Delta, Merced NWR and Kern NWR, but does not completely eliminate water scarcity. Combining inter-refuge trading with optimized land-use operations, completely eliminates water scarcity from these refuges. Finally, regardless of the management alternatives or hydrologic conditions, water scarcity remains a limiting factor at San Luis, West Bear Creek and East Bear Creek units of the San Luis NWR Complex.

Table 4-12. Shadow price* of expanding managed wetland acreage vs. available water supply

Marginal Benefit of Expanding Managed Wetland Acreage (Acre/ Acre) vs. Available Water Supply assuming Historic Operations (Acre/ AF)

	Hist Del (Base)		Hist Del + CC		Hist Del + Trade		Hist Del + CC + Trade		Full L2 L4		Full L2 L4 + CC		Full L2 L4 + Trade		Full L2 L4 + CC + Trade	
	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply
CVPIA Refuges																
SAC	-	0.17	-	0.16	0.29	0.12	0.1	0.14	0.93	0.01	-	0.16	0.31	0.12	0.29	0.11
DEL	-	0.17	-	0.15	0.27	0.12	0.07	0.14	-	0.17	-	0.15	0.29	0.12	0.26	0.11
COL	0.07	0.16	-	0.16	0.29	0.12	0.1	0.14	0.93	0.01	-	0.16	0.31	0.12	0.29	0.11
SUT	-	0.17	-	0.15	-	0.17	-	0.15	-	0.17	-	0.15	-	0.17	-	0.15
W165	-	0.12	-	0.11	-	0.12	-	0.11	-	0.12	-	0.11	-	0.12	-	0.11
E165	-	0.12	-	0.11	-	0.12	-	0.11	-	0.12	-	0.11	-	0.12	-	0.11
EBR	-	0.13	-	0.11	-	0.13	-	0.11	-	0.13	-	0.11	-	0.13	-	0.11
MER	-	0.17	-	0.15	0.18	0.14	0.06	0.14	-	0.17	-	0.15	0.26	0.13	0.24	0.11
PIX	-	0.2	-	0.18	-	0.2	-	0.18	-	0.2	-	0.18	-	0.2	-	0.18
KER	-	0.17	-	0.15	0.26	0.12	0.05	0.14	-	0.17	-	0.15	0.28	0.12	0.25	0.11
Scenario Description																
Refuge Deliveries	Historic		Historic		Historic		Historic		Full Level 2 Level 4		Full Level 2 Level 4		Full Level 2 Level 4		Full Level 2 Level 4	
Climate Change	-n/a-		Warm-Dry		-n/a-		Warm-Dry		-n/a-		Warm-Dry		-n/a-		Warm-Dry	
Inter-refuge Trading	×		×		✓		✓		×		×		✓		✓	

Marginal Benefit of Expanding Managed Wetland Acreage (Acre/ Acre) vs. Available Water Supply assuming Optimized Operations (Acre/ AF)

	Hist Del (Base)		Hist Del + CC		Hist Del + Trade		Hist Del + CC + Trade		Full L2 L4		Full L2 L4 + CC		Full L2 L4 + Trade		Full L2 L4 + CC + Trade	
	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply	Managed Wetland Acreage	Available Water Supply
CVPIA Refuges																
SAC	0.4	0.16	-	0.21	1.43	-	1.13	-	1.16	0.01	0.98	0.04	1	-	1.01	-
DEL	0.16	0.2	-	0.21	1.43	-	1.06	0.01	1.16	0.01	0.98	0.04	1	-	1.01	-
COL	0.55	0.13	0.15	0.19	1.43	-	1.13	-	1.16	0.01	0.98	0.04	1	-	1.01	-
SUT	1.01	0.04	0.98	0.04	1.36	0.01	1.06	0.01	1.16	0.01	1.04	0.03	1	-	1.01	-
W165	0.21	0.12	-	0.13	0.43	0.13	-	0.13	0.87	0.04	-	0.14	0.93	0.01	0.93	0.01
E165	-	0.15	-	0.13	-	0.18	-	0.13	-	0.15	-	0.14	-	0.13	-	0.11
EBR	-	0.13	-	0.13	-	0.18	-	0.13	-	-	-	0.13	-	0.13	-	0.11
MER	0.92	0.04	0.91	0.04	0.86	0.07	0.96	0.02	0.93	0.03	0.9	0.04	1	-	1	-
PIX	-	0.24	-	0.21	-	0.29	-	0.2	-	-	-	0.21	-	-	-	0.18
KER	-	0.2	-	0.18	1.36	0.01	0.29	0.13	-	0.2	-	0.18	1	-	0.93	0.01
Scenario Description																
Refuge Deliveries	Historic		Historic		Historic		Historic		Full Level 2 Level 4		Full Level 2 Level 4		Full Level 2 Level 4		Full Level 2 Level 4	
Climate Change	-n/a-		Warm-Dry		-n/a-		Warm-Dry		-n/a-		Warm-Dry		-n/a-		Warm-Dry	
Inter-refuge Trading	×		×		✓		✓		×		×		✓		✓	

*Shadow price on refuge deliveries indicates change in total managed wetland acreage resulting from additional unit of water delivered to the refuge (acre/acre-foot). Similarly, the shadow price on available land-use acreage represents change in total managed wetland acreage resulting from one additional unit of land available for use at the refuge (acre/acre). The shadow prices on refuge deliveries and available land-use acreage are compared at each refuge to determine whether water scarcity is a limiting factor.

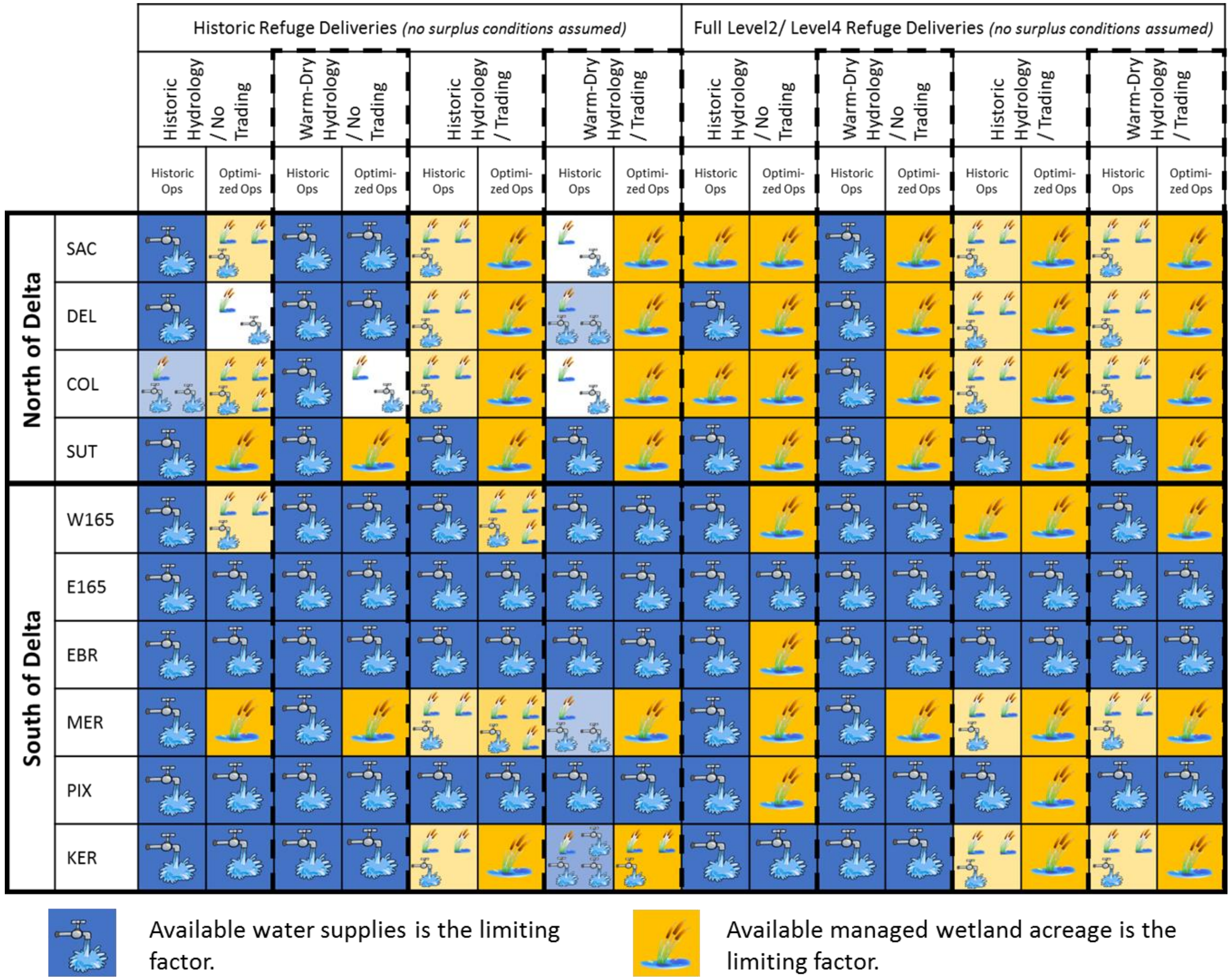


Figure 4-9. Qualitative comparison of shadow price on refuge delivery and managed wetland acreage
(See *Table 4-12* for details)

Conclusion

Eight scenarios are explored using the Spreadsheet Tool – a network flow model of USFWS managed refuges in Central Valley – including: with and without inter-refuge trading; historical and warm-dry hydrology; and historical and Full Level 4 deliveries (*Table 4-3*). For each scenario, refuge operations are optimized using annual time-step over a 14 year period, from Water Year 2001 to Water Year 2014. The tool is structured into two separate optimization modules: inter-refuge optimization and intra-refuge optimization. Both optimization modules share a common objective function – maximize total managed wetland acreage – and are bounded by the amount of land and water available. Inter-refuge optimization module optimizes refuge deliveries given refuge water supply allocations. The intra-refuge optimization module optimizes land-use operations at individual refuges given water supply timeseries. Combined, both optimization modules are used to explore benefits and implications of inter-refuge trading and optimal refuge land-use operations.

A major limitation is the absence of carriage water cost, a portion of Delta exports set aside to maintain salinity barrier in the west Delta. The portion varies depending on hydrologic conditions within Delta. Since there is no fixed estimate available, salinity cost is not considered in the analysis even though it could considerably alter the results for inter-refuge trading management alternative.

Results indicate that optimizing land-use operations is at least as beneficial as reallocating available water supplies and can significantly curb the effects of a warm-dry hydrology (*Figure 4-5*). Since USFWS is responsible for setting management objectives, from a regulatory standpoint, optimizing land-use operations is easier and probably cheaper than working with USBR and local irrigation districts to reallocate refuge water supplies. Despite statewide gains in managed wetland acreage from inter-refuge trading and optimized land-use operations, there are significant differences in regional effects for the two management cases (*Figures 4-6 – 4-8*). Both, inter-refuge trading and optimized land-use operations prefer reallocating water or expanding managed wetland acreage among refuges north of the Delta more than the refuges south of the Delta.

Under historical operations, inter-refuge trading results in increased timothy grass and smartweed acreage, and reduction in watergrass, permanent wetland, and semi-permanent wetland acreage (*Table 4-10*). Optimized land-use operations result in net gain in smartweed and small grain crop acreage and little to no net gain in the other land-use types (*Table 4-11*). Results, however, exhibit significant fluctuations north and south of the Delta. Since it is more effective to grow timothy grass in the north and permanent wetlands in the south, optimized land-use operations reallocate more of managed wetland acreage to timothy grass north of the Delta and to permanent wetlands south of the Delta. As a result of inter-refuge trading, water supplies are reallocated from San Luis NWR Complex to Sacramento, Delevan and Colusa NWRs in the north, and Merced and Kern NWR in the south. Percent change in refuge deliveries intensify with warm-dry hydrology; however, the trends are still retained.

Finally, shadow prices on refuge deliveries and available land-use acreage are compared at each refuge to assess the limiting factors and identify refuges impacted by water scarcity (*Figure 4-9 and Table 4-12*). Results indicate that under present conditions – historical deliveries, historical hydrology and no inter-refuge trading – available water supply is the limiting factor at all refuges. Full Level 4 deliveries only alleviate water scarcity at Sacramento and Colusa NWR. Optimizing land-use operations and/or inter-refuge trading, alleviates water scarcity concerns at Sacramento, Delevan, Colusa and Merced NWRs. Results show a tradeoff between Kern NWR and refuges West of Highway 165. West of Highway 165 refuges benefit from optimizing land-use operations in absence of inter-refuge trading, whereas Kern NWR benefits from inter-refuge trading with and without optimized land-use operations. Regardless of inter-refuge trading or optimized land-use operations, water scarcity remains a limiting factor at San Luis, West Bear Creek and East Bear Creek units.

References

Central Valley Joint Venture (CVJV). (2006). *Central Valley Joint Venture implementation plan: Conserving bird habitat*. Sacrament, CA: U.S. Fish and Wildlife Service.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010a). *Merced National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2010b). *San Luis National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011a). *Colusa National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011b). *Delevan National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011c). *Grasslands Resource Conservation District Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011d). *Gray Lodge Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011e). *Kern National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011f). *Los Banos Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011g). *Mendota Pool Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011h). *North Grasslands Wildlife Area China Island Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011i). *North Grasslands Wildlife Area Salt Slough Unit Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011j). *Pixley National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011k). *Sacramento National Wildlife Refuge Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

U.S. Bureau of Reclamation Mid-Pacific Region (USBR). (2011l). *Volta Wildlife Area Water Management Plan*. Retrieved from https://www.usbr.gov/mp/watershare/wcplans/.

This page is left blank intentionally.

Chapter 5: Summary and future work

Agricultural water users represent nearly 65% (23.1 MAF/yr) of the total statewide demand (*Table 3-5*). More than 90% of the demand is concentrated in the Central Valley with 40% in Tulare Basin, 20% in Lower Sacramento and San Joaquin Valley, and 10% in Upper Sacramento Valley. CVPIA refuge deliveries, on the other hand, constitute less than 2% (0.5 MAF/yr) of the total demand. Even then, only 89% of the Level 2 deliveries and 47 % of the incremental Level 4 have been met between 2001 and 2014 (*Table 2-2*). Refuge managers cite budgetary constraints and rising cost of water as the major impediment in realizing its goals of delivering Full Level 4 deliveries. Some estimates indicate that, on average, the cost of acquiring water for wetlands has increased 400% since 1990s. Global warming and regional hydro-climatic alterations are likely to further limit state's ability to manage water, reduce total volume of available water and intensify competition for surface water. Historically, reduction in surface water supplies is substituted with groundwater pumping. Long-term overdraft and Sustainable Groundwater Management Act (SGMA) provisions will, however, limit future pumping opportunities. This research examines impacts from a warm-dry climate, peripheral tunnels, groundwater overdraft regulations, and competing environmental flow demands on water deliveries to CVPIA refuges. The study is conducted within a statewide framework using CALVIN – a hydro-economic optimization model of State of California – to capture the physical, environmental and policy constraints in the existing water management system. A separate Spreadsheet Tool is also developed to evaluate localized refuge management adaptation strategies.

Key Findings

Central Valley refuges are managed as part of the integrated water management system; therefore, compete against other environmental, urban and agricultural water users for water supply. An integrated water resource model is required to obtain a holistic understanding of the effects of changing climatic and management conditions on refuge management. Sixteen scenarios are analyzed using CALVIN, a hydro-economic model of State of California, to capture and quantify the hydrologic and economic implications of evolving climatic and management conditions on refuge water deliveries including (1) climate vulnerability: historical and warm-dry climates; (2) Delta regulations: high and existing Delta Outflows; (3) infrastructure: with and without isolated facility or peripheral tunnels; and (4) groundwater management: with and without long-term overdraft (*Table 1-1*).

Hydrologic impacts are determined by comparing flows at or just upstream of key diversion points (*Table 3-10*). North of the Delta, the impacts are largely driven by warm-dry hydrology. In-stream flows lower by 20% across all regulatory scenarios under warm-dry hydrology. Export curtailments under high outflow/ low export (HOEC) scenario trap previously exported water north of the Delta. As a result, excess flows are routed through the bypass system, and inflows into Sutter Bypass increase by 15% under historical hydrology and 9% under warm-dry hydrology. Limited groundwater access under no overdraft case, lack of local surface water supplies under warm-dry hydrology and export curtailments under high outflow/ low export (HOEC) scenario intensify competition for surface water supplies south of the Delta. Results also indicate increased competition for water in the lower Merced River watershed regardless of the hydrologic and regulatory conditions. Securing long-term surface water deliveries from irrigation districts located in the upper Merced River watershed could ensure a more reliable water supply to refuges east of the San Joaquin River.

Economic impacts are indirectly evaluated from the opportunity costs of delivering water to refuges (*Table 3-11*). Overall, Upper Sacramento Valley refuges have the least opportunity cost ($1 – 4 per acre-feet) and Tulare Basin refuges the highest opportunity cost ($340 per acre-feet) under historical hydrology. Under warm-dry hydrology, agricultural scarcity increases from 3 to 27% north of the Delta and from 11 to 44% south of the Delta (*Table 3-8*). Subsequently, the opportunity cost also increases throughout the Central Valley: from $1 – 4 to $30 per acre-foot in Upper Sacramento Valley and $290 per acre-foot in Lower Sacramento Valley; from $250 to $800 per acre-foot in San Joaquin Valley; and from $330 to $925 per acre-foot in Tulare Basin. Impact from infrastructure and regulatory scenarios dampens under warm-dry hydrology; however, the trends are still retained. Peripheral tunnels increase south of Delta export opportunities which lower the water competition in the south, but intensify the competition north of the Delta and subsequently, increases opportunity cost of deliveries to refuges north of the Delta. Export curtailments under high outflow/ low exports (HOEC) scenario trap previously exported water north of the Delta which creates surplus conditions in the north and deficit conditions in the south. As a result, opportunity cost on refuge deliveries lowers north of the Delta and increases south of the Delta. Ending overdraft diminishes any gains from peripheral tunnels and doubles the impact when combined with high outflow/ low export (HOEC) scenario.

Several adaptation strategies are also explored including: (1) optimal management of existing resources (*Figure 3-18*), (2) opportunities for expanding existing or constructing new water supply sources (*Table 3-12* and *3-13*), and (3) identifying potential partners and cost of acquiring additional water supplies to reach Full Level 4 deliveries targets (*Table 3-14* and *3-15*).

Only four of the eight refuge areas have access to both surface water and groundwater including Gray Lodge WA (GLD), Sutter NWR (SUT), and refuges east and west of the San Joaquin River (SJE and SJW). Among the four refuges, refuges east of the San Joaquin River (SJE) have the most dynamic water use portfolio. Groundwater is used to meet 45 – 90% of the refuge needs depending on the availability of surface water supplies. Although expanding groundwater supplies may not be an appropriate short-term solution, it appears to be a promising long-term solution at East Bear Creek unit, Merced NWR and Kern NWR (*Figure 3-19* and *3-20*).

As for expanding surface water supplies, there is little to no short-term benefit from connecting Pixley NWR with Friant-Kern Canal or expanding Sutter Extension Water District (SEWD) deliveries to Sutter NWR, but it may not prove to be a reliable source of supply in the long-term. The results also indicate a negative opportunity cost on increasing surface deliveries to refuges located west of the Sacramento River (SRW) outside of the peak irrigation season (*Figure 3-17*). Negative opportunity cost indicates a net system-wide benefit as result of delivering more water to the refuge. Competition for water under warm-dry hydrology can be reduced if irrigation could be moved earlier in the season, April – May, and if flood-up could be delayed until October – November. Even though the production period will reduce from late August – early May to late September – early April, these management changes show a promising way to tackle the effects of a warm-dry hydrology.

The results from model runs with historical and Full Level 4 refuge deliveries are compared to determine potential water trading partners and additional system-wide scarcity cost from providing Full Level 4 refuge deliveries. Results show that (1) agricultural water users in the San Joaquin Valley will become aggressive trading partners under no groundwater overdraft scenario; (2) agricultural water users north of the Delta will become increasingly important water trading partners under warm-dry hydrology; and (3) as the warming trend continues, securing additional water supplies will become more expensive and agricultural users south of the Delta will continue to have competitive advantage over refuges, making it increasingly harder to acquire additional surface water supplies regardless of the hydrologic or management scenario.

Under current CALVIN configuration, refuge demands are represented as pre-processed, fixed delivery timeseries; therefore, refuge deliveries and land-use operations are not dynamically represented. A separate Spreadsheet Tool –network flow model of USFWS managed refuges in Central Valley – is developed to explore the benefits and implications of inter-refuge trading and optimizing refuge land-use management practices. Results indicate that optimizing land-use operations within refuges is at least as beneficial as reallocating available water supplies and can significantly curb the effects of a warm-dry hydrology (*Figure 4-5*). Since USFWS is responsible for setting management objectives, from a regulatory standpoint, optimizing land-use operations is easier and probably cheaper than working with USBR and local irrigation districts to reallocate refuge water supplies. Both, inter-refuge trading and optimized land-use operations, prefer reallocating water or expanding managed wetland acreage at refuges in the Sacramento Valley and Tulare Basin because of lower land-use water demand relative to the San Joaquin Valley refuges (*Figures 4-6 – 4-8*). Finally, the shadow price on refuge deliveries and available land-use acreage is compared at each refuge to determine whether water scarcity is a limiting factor (*Figure 4-9* and *Table 4-12*). Results show that under present conditions, available water supply is the limiting factor at all refuges. Full Level 4 deliveries only alleviate water scarcity at Sacramento and Colusa NWR. Optimizing land-use operations and/or inter-refuge trading alleviate water scarcity concerns at Sacramento, Delevan, Colusa and Merced NWRs, but water scarcity remains a limiting factor at San Luis, West Bear Creek and East Bear Creek units of the San Luis NWR Complex under all scenarios.

Limitations

Limitations are inherent of any model which must be factored in when interpreting results for insights into refuge management. Although these limitations have a significant effect on results of an individual model run, their impact is often muted in comparative analysis since all runs equally represent these limitations. Both, CALVIN and the Spreadsheet Tool, are planning models. Neither includes the complexity of detailed on-the-ground refuge operations. The purpose of these models is not simulate refuge operations, but to assess trends across hydrologic and management scenarios. Moreover, hydro-economic models, such as CALVIN, assume rational response to economic incentives. As water scarcity grows, the system re-operates to accommodate economically superior uses. Therefore, the results are purely economics-driven; however, in reality water rights and other institutional constraints also factor into the decision-making process.

Mathematical structure of the network flow models limits CALVIN's ability to represent complex physical and operational constraints that play a critical role in determining required Delta Outflow and allowable Delta Exports. To mitigate for this limitation, CALVIN directly employs minimum in-stream flow requirements, required Delta Outflow and Delta export timeseries from CalSim II. Four CalSim II runs completed as part of the 2013 BDCP EIR/EIS report are used to represent two infrastructure scenarios – with and without the peripheral tunnels – and two Delta regulatory scenarios, high outflow/

low export, and existing regulations. Since hydrology is perturbed differently in CALVIN, only CalSim II runs assuming historical hydrology are used in the analysis. Moreover, groundwater overdraft scenarios were not explored during the EIR/EIS analysis. As a result, minimum in-stream flows, required Delta outflow, and south of the Delta exports vary only by the Delta export and outflow scenario and are independent of the hydrologic or groundwater overdraft scenario. Therefore, the model runs, under current set-up, represent an optimistic exports scenario for a warm-dry hydrology. Warming is projected to increase required Delta outflow demands during non-winter months to maintain suitable fish habitat and water quality within the Delta which will reduce the amount of water available for export (Cayan et al., 2008; Hayhoe et al., 2004). Sustaining the same level of Delta exports as under historical hydrology overestimates the amount of water available to meet urban, agricultural and refuge needs south of the Delta.

Lastly, water quality considerations are not explicit modeled in CALVIN. An operating cost is assigned to groundwater pumping to deter the model from over-relying on groundwater to meet refuge water needs. However, the cost does not vary with groundwater head nor does it include water treatment costs.

A major limitation of the Spreadsheet Tool is the absence of carriage water cost, a portion of Delta exports set aside to maintain salinity barrier in the west Delta. The portion varies depending on hydrologic conditions within Delta. Since there is no fixed estimate available, salinity cost is not considered in the analysis even though it could considerably alter the results for inter-refuge trading management alternative.

Future Work

There is a considerable room to improve the Spreadsheet Tool. Most input data with the exception of refuge deliveries and precipitation data is obtained from Water Management Plans (WMPs). WMPs are not always reliable sources of information, but they are the most comprehensive information now available. Historical land-use data used to calculate historical water demand and upper and lower bound targets on land-use acreage is only available for three years at most: 1992, 1997 and 2010 which correspond with years when Central Valley Project Improvement Act was passed, one of the wettest years on record and year when WMPs were prepared. Moreover, there is very limited variability in water demand data and sometimes there is conflicting water demand information presented in different sections of the WMP which raises concerns about the reliability of refuge water demand data. Refuge specific data would improve resolution and reliability of the outputs. Lastly, the tool is limited to USFWS managed refuges which are only 15% of all managed wetlands in the Central Valley. CVPIA covers slightly more than 50% of the Central Valley refuges and there is information available to expand the tool to cover all CVPIA refuges.

CALVIN results can be significantly improved by updating the network flow representation. Due to lack of information, CALVIN model runs assume no contribution from on-site reuse or agricultural return flows to meet refuge demands. However, both these sources constitute a significant portion of refuge deliveries. Almost all the refuges south of the Delta have an operation loss recovery system to capture and re-use refuge return flows (*Table 3-2*). Most of these refuges are located at the tail end of service district’s delivery system and their water supplies are diluted with agricultural return flows.

Including these two water supply sources will curb the need to divert surface water to refuge demands which will further improve the reliability of the results.

Finally, the scope of this study is limited to refuge water supply. However, wetlands alone cannot provide enough food and cover for the migratory birds. Waterfowl also rely on adjacent grain fields and upland habitats for food and breeding opportunities. Impact of warm-dry hydrology, peripheral tunnels, Delta regulations and SGMA on agricultural land-use and more specifically on rice fields should also be taken into account to better understand vulnerability of Central Valley refuges to changing hydrologic and management conditions.

This page is left blank intentionally.

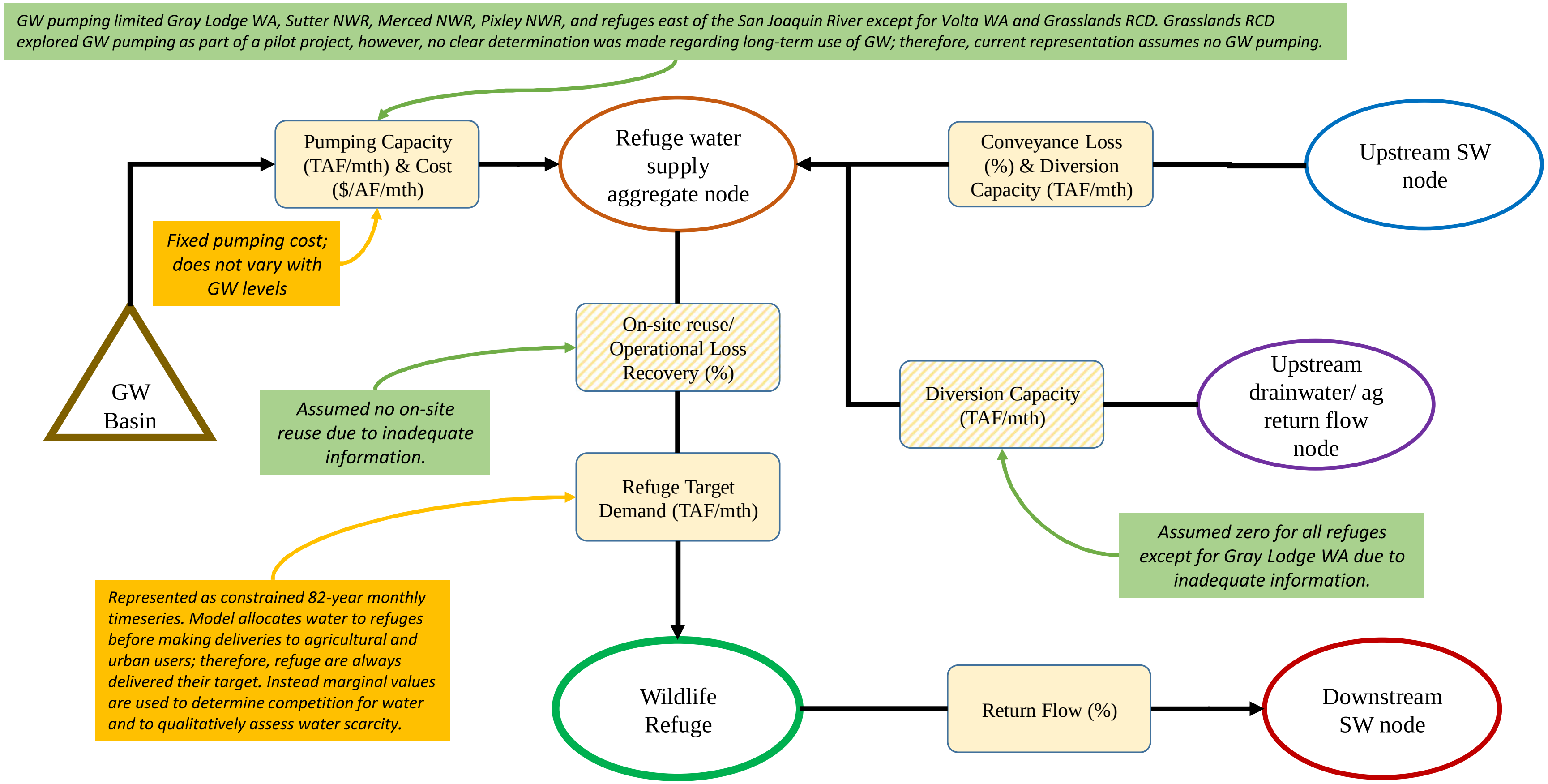
APPENDIX 1

Description of hydrologic and management scenarios

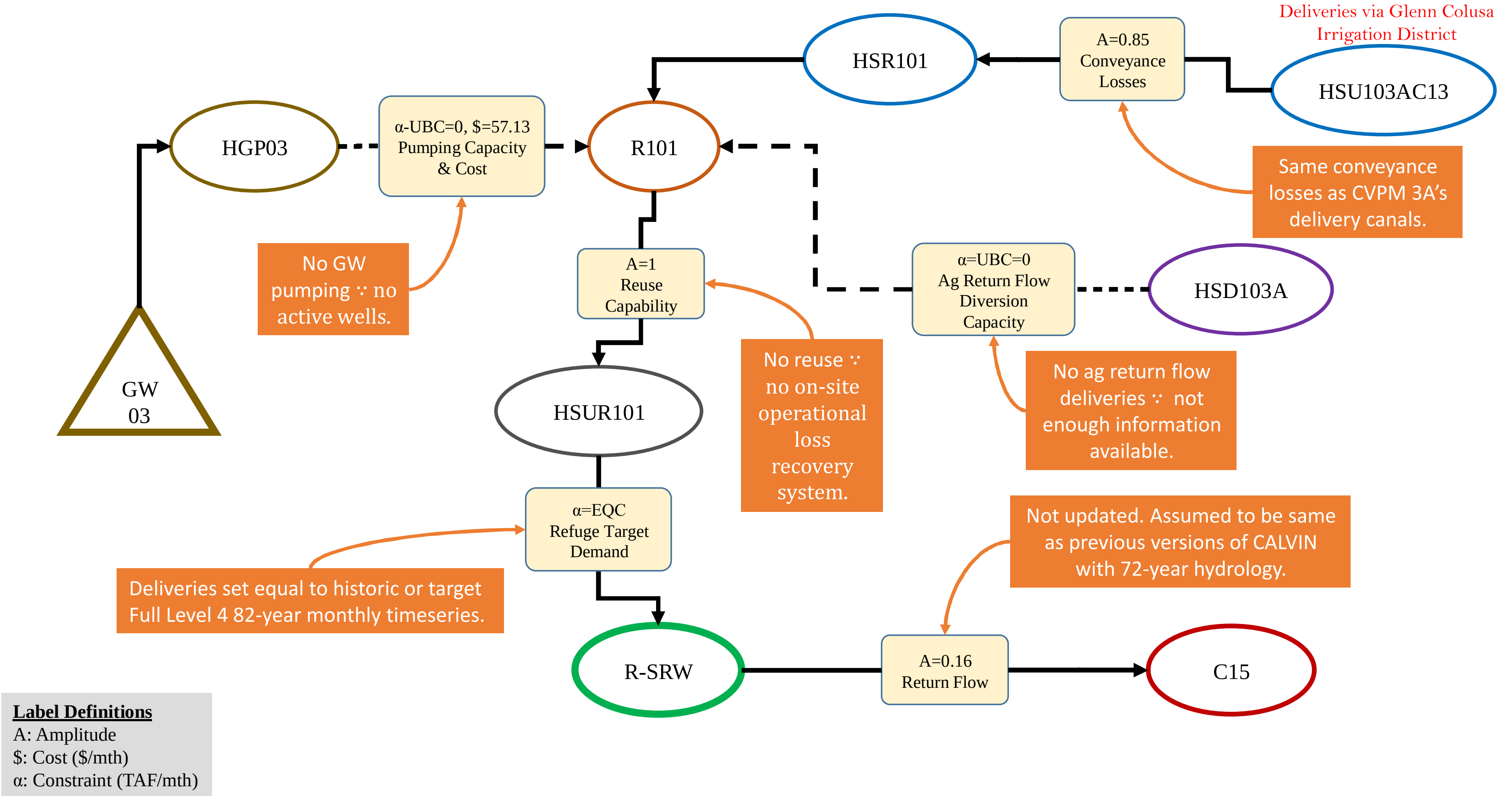
#	Scenario	Hydrology	Regulations	Conveyance	GW Overdraft	Refuge Delivery
1	**HEREC_Hist**	Historical	Existing	No Isolated Facility	Yes	Historic
2	**HERIF_Hist**	Historical	Existing	Isolated Facility	Yes	Historic
3	**HHOEC_Hist**	Historical	High Outflow	No Isolated Facility	Yes	Historic
4	**HHOIF_Hist**	Historical	High Outflow	Isolated Facility	Yes	Historic
5	**CEREC_Hist**	Warm-Dry	Existing	No Isolated Facility	Yes	Historic
6	**CERIF_Hist**	Warm-Dry	Existing	Isolated Facility	Yes	Historic
7	**CHOEC_Hist**	Warm-Dry	High Outflow	No Isolated Facility	Yes	Historic
8	**CHOIF_Hist**	Warm-Dry	High Outflow	Isolated Facility	Yes	Historic
9	**HERECG_Hist**	Historical	Existing	No Isolated Facility	No	Historic
10	**HERIFG_Hist**	Historical	Existing	Isolated Facility	No	Historic
11	**HHOECG_Hist**	Historical	High Outflow	No Isolated Facility	No	Historic
12	**HHOIFG_Hist**	Historical	High Outflow	Isolated Facility	No	Historic
13	**CERECG_Hist**	Warm-Dry	Existing	No Isolated Facility	No	Historic
14	**CERIFG_Hist**	Warm-Dry	Existing	Isolated Facility	No	Historic
15	**CHOECG_Hist**	Warm-Dry	High Outflow	No Isolated Facility	No	Historic
16	**CHOIFG_Hist**	Warm-Dry	High Outflow	Isolated Facility	No	Historic
17	**HEREC_Full**	Historical	Existing	No Isolated Facility	Yes	Full Level 2 and Level 4
18	**HERIF_Full**	Historical	Existing	Isolated Facility	Yes	Full Level 2 and Level 4
19	**HHOEC_Full**	Historical	High Outflow	No Isolated Facility	Yes	Full Level 2 and Level 4
20	**HHOIF_Full**	Historical	High Outflow	Isolated Facility	Yes	Full Level 2 and Level 4
21	**CEREC_Full**	Warm-Dry	Existing	No Isolated Facility	Yes	Full Level 2 and Level 4
22	**CERIF_Full**	Warm-Dry	Existing	Isolated Facility	Yes	Full Level 2 and Level 4
23	**CHOEC_Full**	Warm-Dry	High Outflow	No Isolated Facility	Yes	Full Level 2 and Level 4
24	**CHOIF_Full**	Warm-Dry	High Outflow	Isolated Facility	Yes	Full Level 2 and Level 4
25	**HERECG_Full**	Historical	Existing	No Isolated Facility	No	Full Level 2 and Level 4
26	**HERIFG_Full**	Historical	Existing	Isolated Facility	No	Full Level 2 and Level 4
27	**HHOECG_Full**	Historical	High Outflow	No Isolated Facility	No	Full Level 2 and Level 4
28	**HHOIFG_Full**	Historical	High Outflow	Isolated Facility	No	Full Level 2 and Level 4
29	**CERECG_Full**	Warm-Dry	Existing	No Isolated Facility	No	Full Level 2 and Level 4
30	**CERIFG_Full**	Warm-Dry	Existing	Isolated Facility	No	Full Level 2 and Level 4
31	**CHOECG_Full**	Warm-Dry	High Outflow	No Isolated Facility	No	Full Level 2 and Level 4
32	**CHOIFG_Full**	Warm-Dry	High Outflow	Isolated Facility	No	Full Level 2 and Level 4

APPENDIX 2

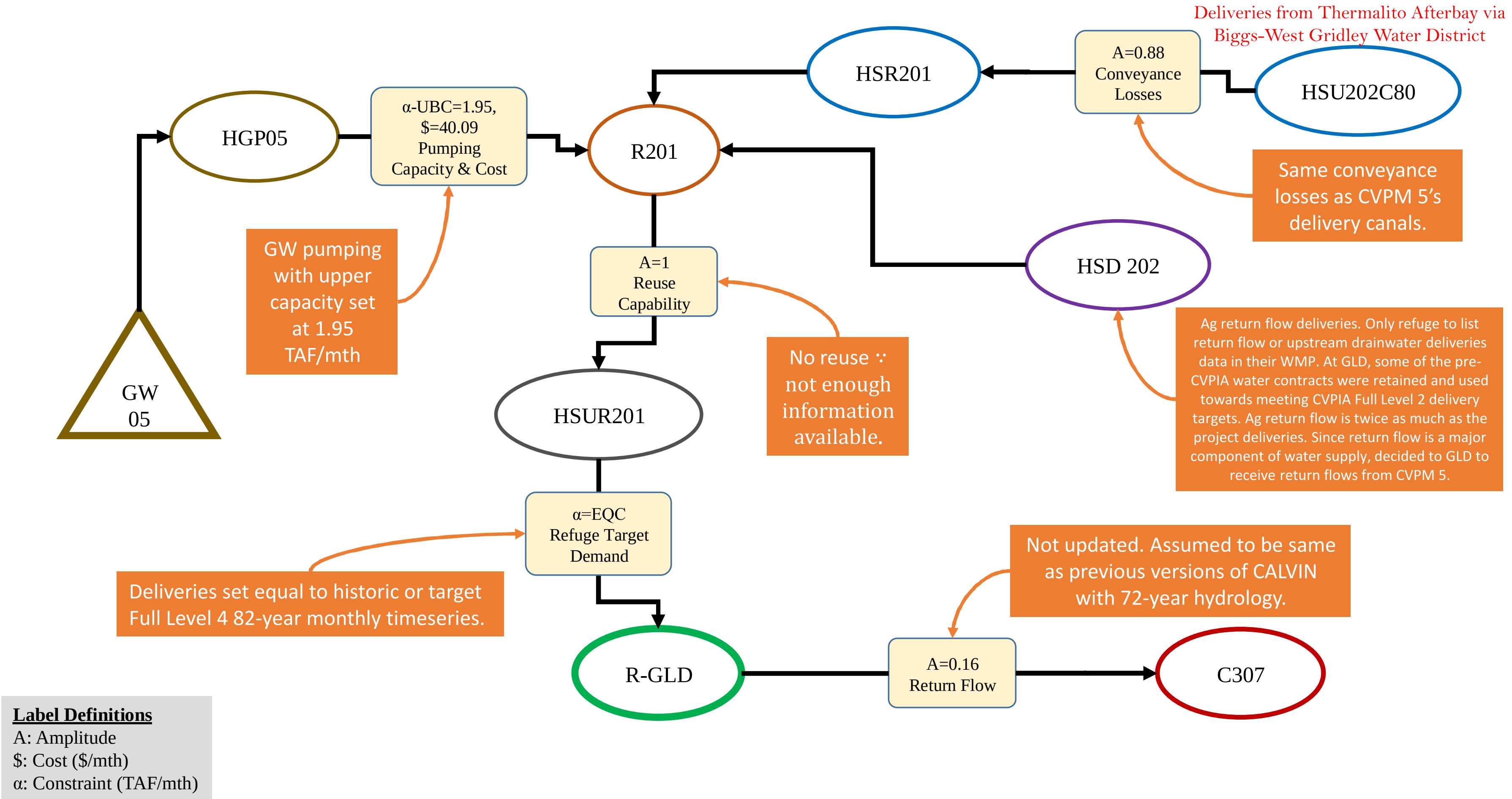
Network flow schematic of CALVIN refuge node


GW pumping limited Gray Lodge WA, Sutter NWR, Merced NWR, Pixley NWR, and refuges east of the San Joaquin River except for Volta WA and Grasslands RCD. Grasslands RCD explored GW pumping as part of a pilot project, however, no clear determination was made regarding long-term use of GW; therefore, current representation assumes no GW pumping.
Pumping Capacity (TAF/mth) & Cost ($/AF/mth)
Refuge water supply aggregate node
Conveyance Loss (%) & Diversion Capacity (TAF/mth)
Upstream SW node
Fixed pumping cost; does not vary with GW levels
GW Basin
On-site reuse/ Operational Loss Recovery (%)
Assumed no on-site reuse due to inadequate information.
Diversion Capacity (TAF/mth)
Upstream drainwater/ ag return flow node
Refuge Target Demand (TAF/mth)
Assumed zero for all refuges except for Gray Lodge WA due to inadequate information.
Represented as constrained 82-year monthly timeseries. Model allocates water to refuges before making deliveries to agricultural and urban users; therefore, refuge are always delivered their target. Instead marginal values are used to determine competition for water and to qualitatively assess water scarcity.
Wildlife Refuge
Return Flow (%)
Downstream SW node

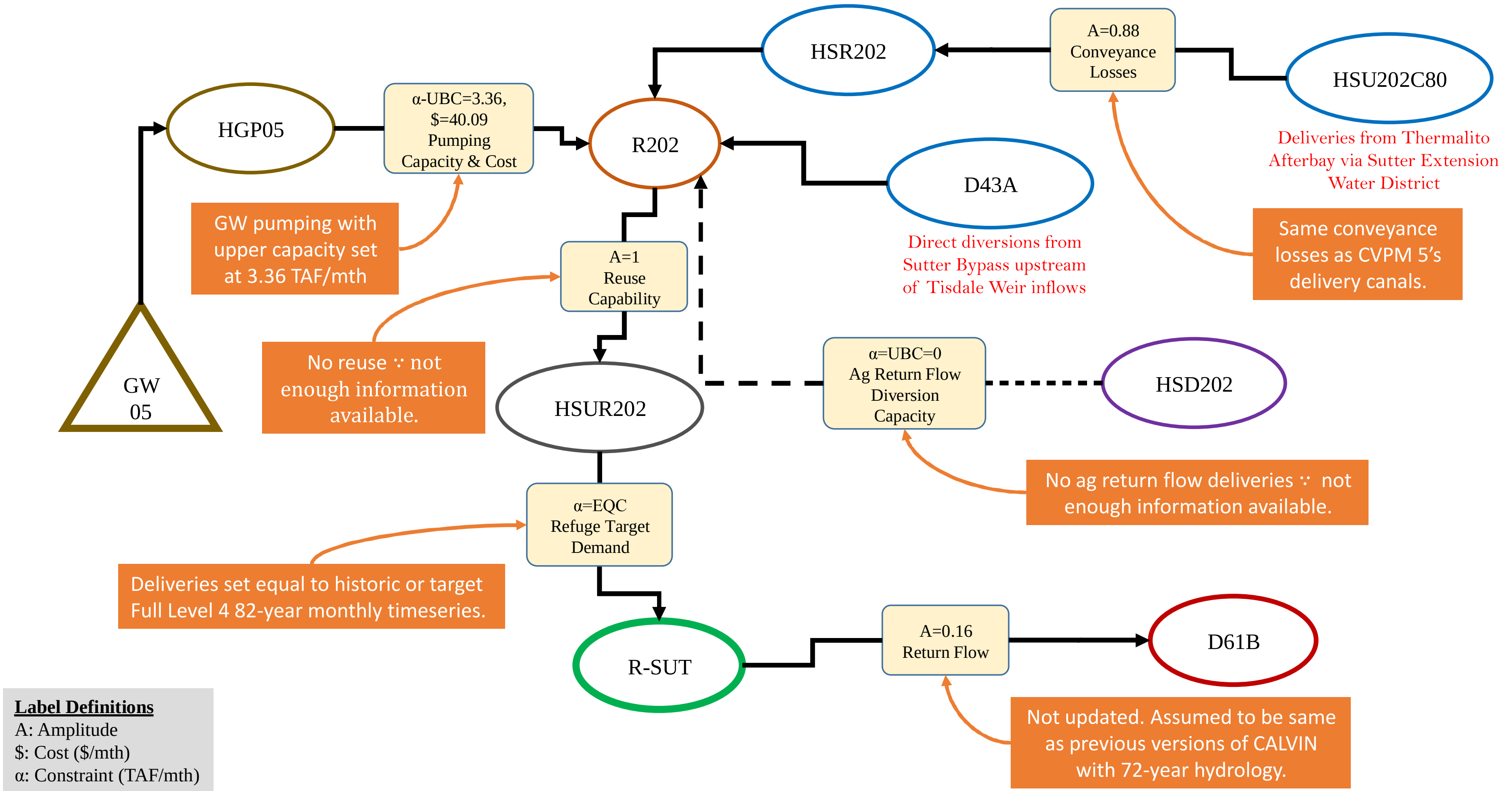
SRW: West of Sacramento River Refuges (CALVIN Region 1/ Upper Sacramento Valley)



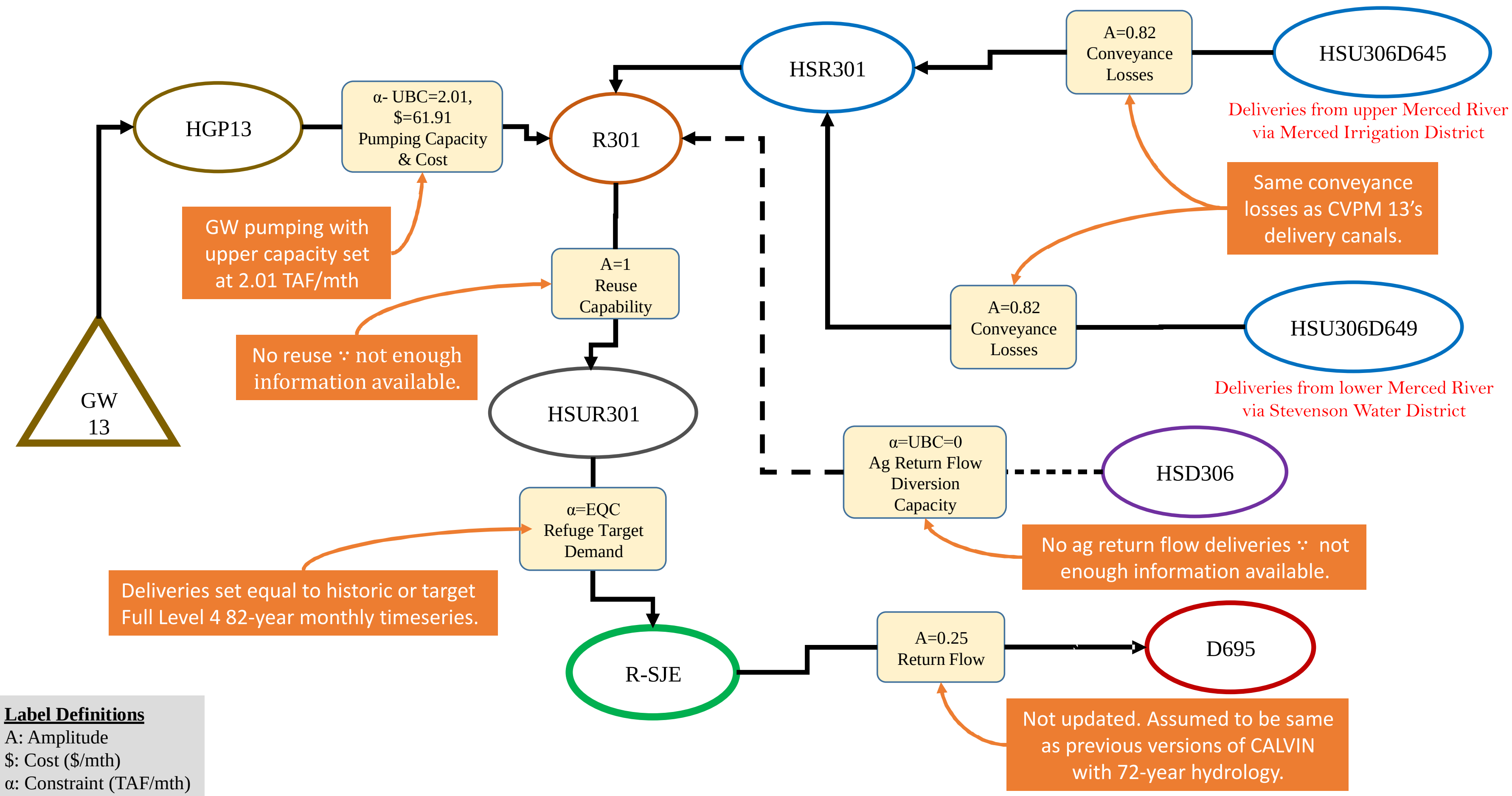
GLD: Gray Lodge Wildlife Area (CALVIN Region 2/ Lower Sacramento Valley)



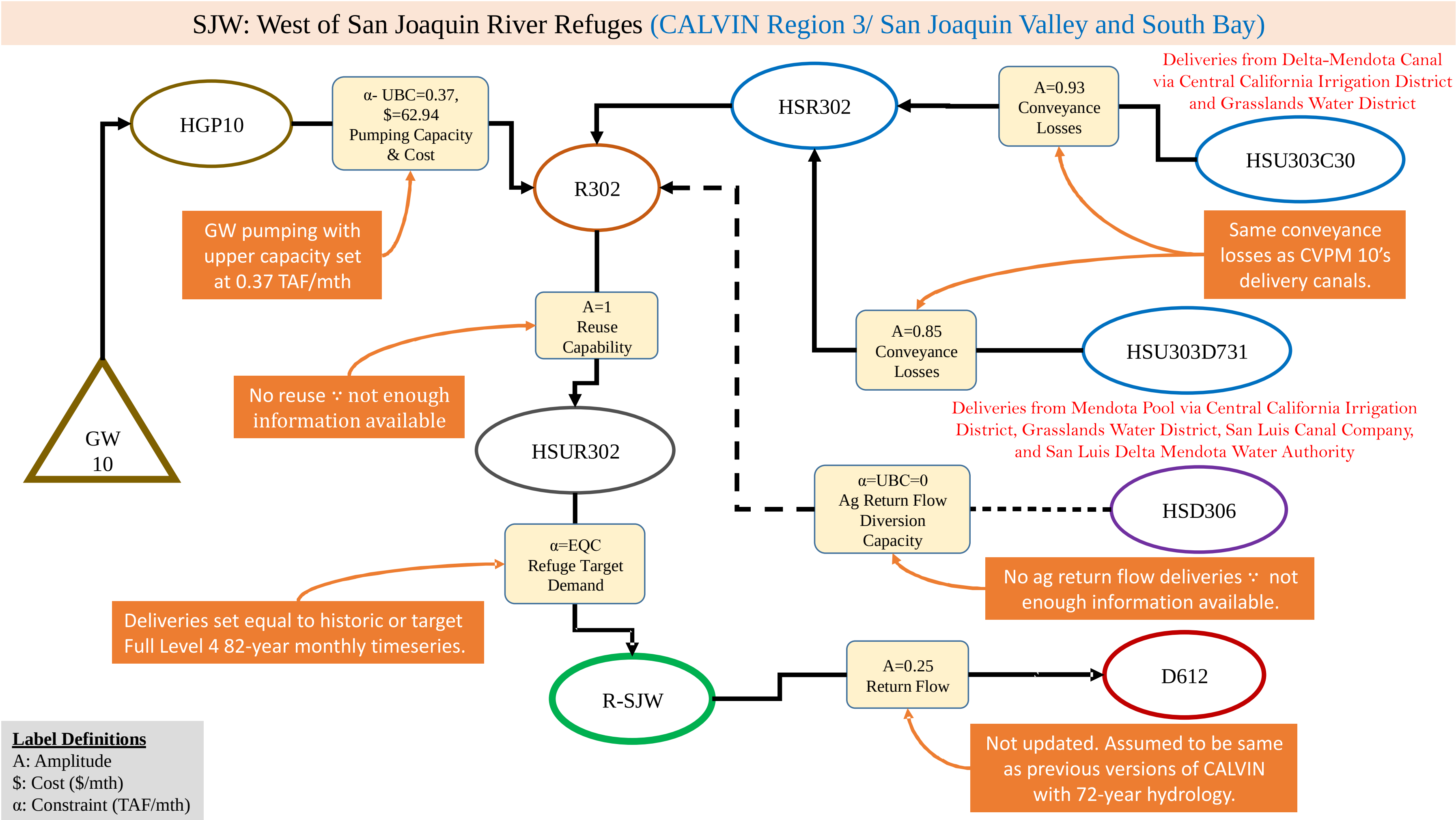
SUT: Sutter NWR (CALVN Region 2/ Lower Sacramento Valley)



SJE: East of San Joaquin River Refuges (CALVIN Region 3/ San Joaquin Valley and South Bay)



Label Definitions
A: Amplitude
$: Cost ($/mth)
α: Constraint (TAF/mth)

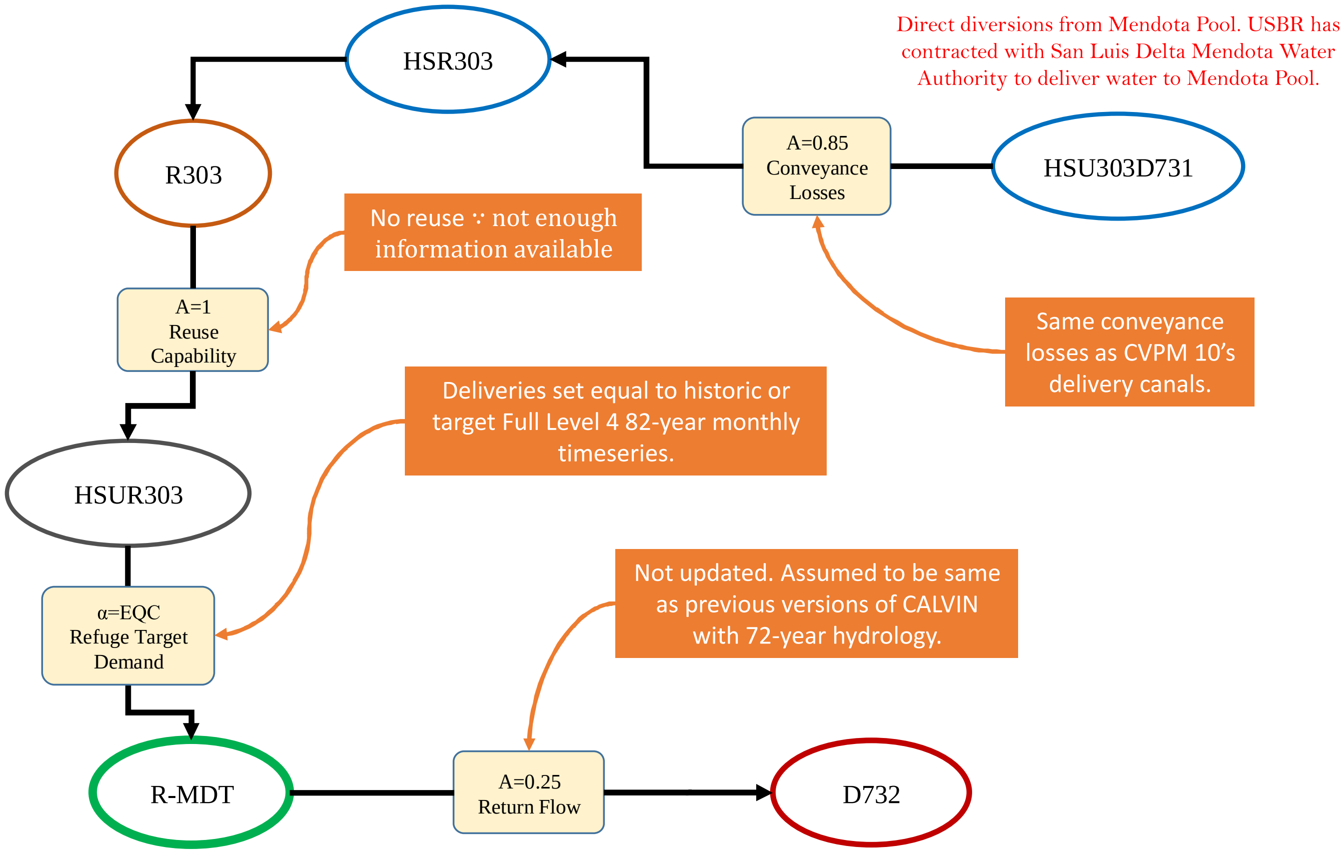


SJW: West of San Joaquin River Refuges (CALVIN Region 3/ San Joaquin Valley and South Bay)
HGP10
α- UBC=0.37, $=62.94 Pumping Capacity & Cost
R302
HSR302
A=0.93 Conveyance Losses
Deliveries from Delta-Mendota Canal via Central California Irrigation District and Grasslands Water District
HSU303C30
GW pumping with upper capacity set at 0.37 TAF/mth
Same conveyance losses as CVPM 10's delivery canals.
A=1 Reuse Capability
A=0.85 Conveyance Losses
HSU303D731
No reuse ∵ not enough information available
GW 10
HSUR302
Deliveries from Mendota Pool via Central California Irrigation District, Grasslands Water District, San Luis Canal Company, and San Luis Delta Mendota Water Authority
α=UBC=0 Ag Return Flow Diversion Capacity
HSD306
α=EQC Refuge Target Demand
No ag return flow deliveries ∵ not enough information available.
Deliveries set equal to historic or target Full Level 4 82-year monthly timeseries.
A=0.25 Return Flow
D612
R-SJW
Not updated. Assumed to be same as previous versions of CALVIN with 72-year hydrology.
Label Definitions
A: Amplitude
$: Cost ($/mth)
α: Constraint (TAF/mth)

MDT: Mendota Wildlife Area (CALVIN Region 3/ San Joaquin Valley and South Bay)

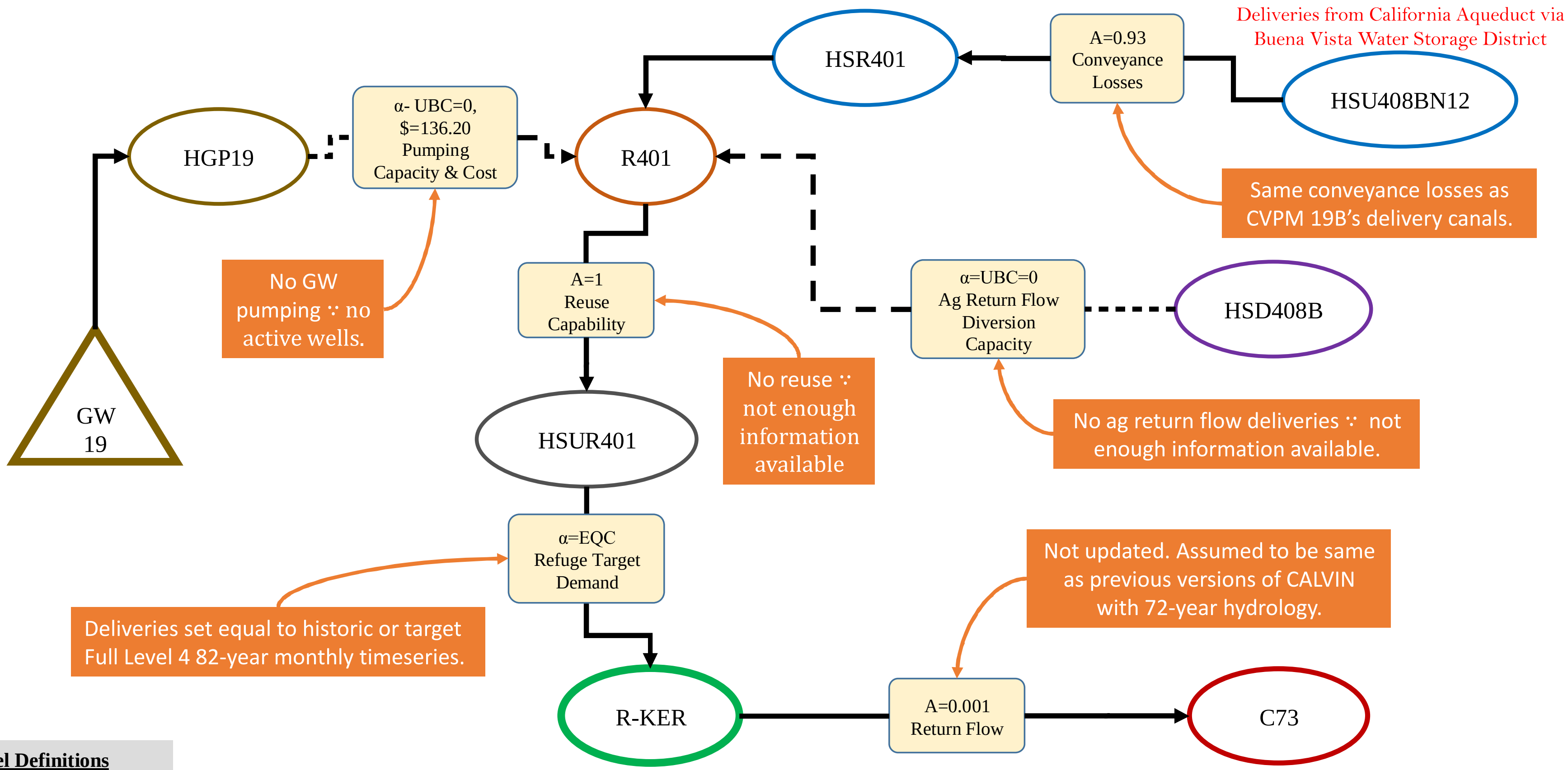
Note:

- No GW pumping because, according to WMP, water quality conditions are very poor and there are considerations of using GW to meet management needs.
- No explicit ag return flow connection. Mendota WA not a part of an Ag district, instead it directly pumps water from the Mendota Pool while includes return flows from upstream ag regions.



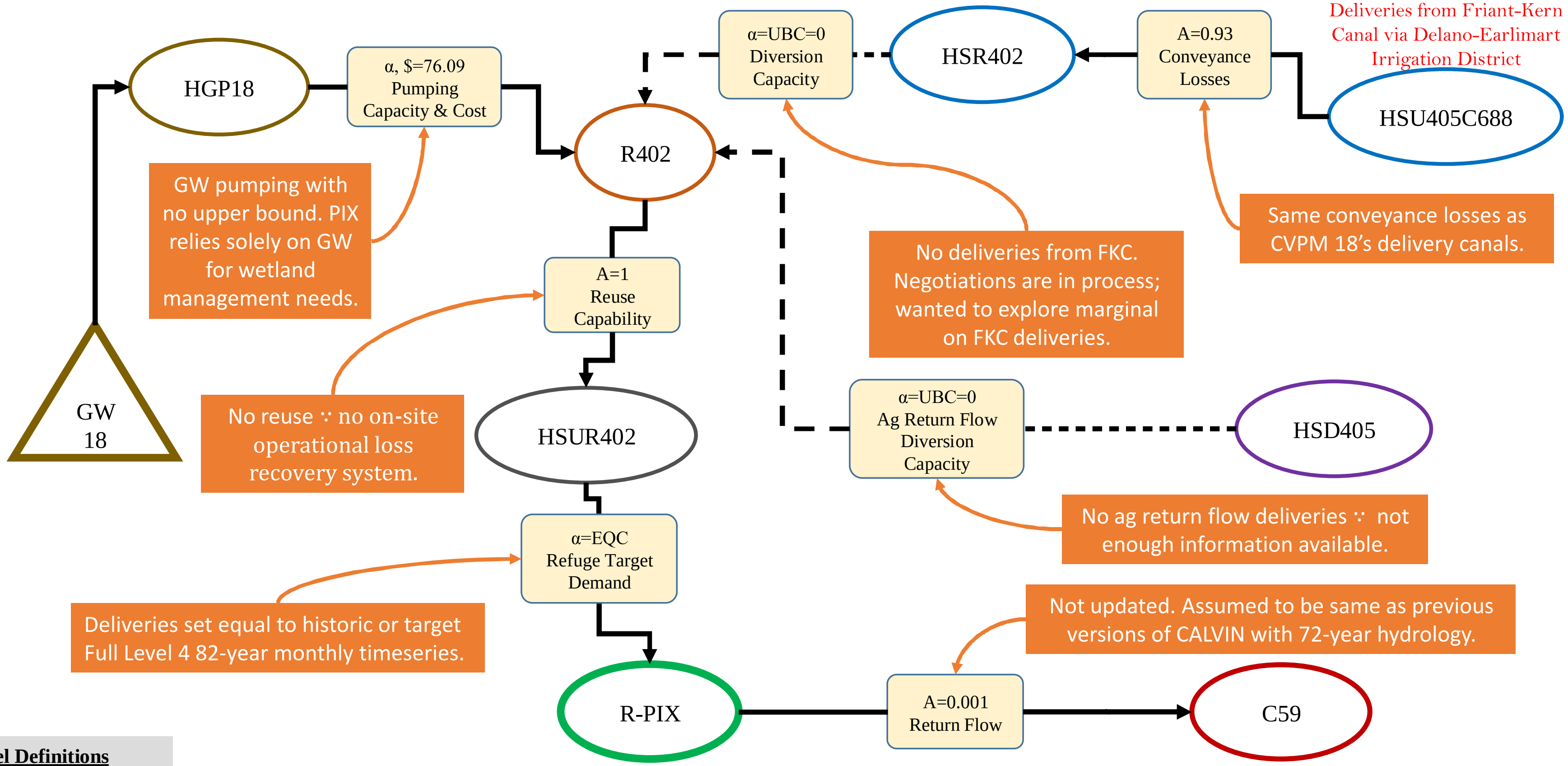
Label Definitions
A: Amplitude
$: Cost ($/mth)
α: Constraint (TAF/mth)

KER: Kern National Wildlife Refuge (CALVIN Region 4/ Tulare Basin)



Label Definitions
A: Amplitude
$: Cost ($/mth)
α: Constraint (TAF/mth)

PIX: Pixley National Wildlife Refuge (CALVIN Region 4/ Tulare Basin)



Label Definitions
A: Amplitude
$: Cost ($/mth)
α: Constraint (TAF/mth)

APPENDIX 3

Water Year Types (1920 – 2003)

Source: \DRR2013_Existing_FullDem_082313\CONV\Run\Lookup\wytypes.table

! This table is used to look up year-type indices (Dustin Jones 11/22/99)
! Updated 06/09/2005 by Messele Ejeta. SACindex and SJRindex updated using values from CDEC.
! AmerD893 updated using the sum of unimpaired inflow to Folsom from April to September
! SHASTAindex updated based on Full Natural Inflow to Shasta. If total inflow to Shasta in any
! given year is less than 3.2 maf, it is Shasta critical year (value of 4). Also, if the total
! inflow in any two consecutive years is such that the total inflow of each year is less than
! 4.0 maf and the total consecutive two year deficiency is higher than 0.8 maf below the two
! year total of 8.0 mark, the second year becomes Shasta critical year.
! FEATHERindex was updated in a similar fashion as Shasta Index.
! Amer403030 is not used, so it was not updated.

WATER YEAR	SACindex	SJRindex	SHASTAindex	AmerD893	FEATHERindex	Trinityindex	Amer403030
1920	2	2	1	1	0	3	2
1921	2	2	1	1	0	3	2
1922	2	1	1	1	0	4	2
1923	3	2	3	1	0	4	3
1924	5	5	4	2	1	5	6
1925	4	3	1	1	0	2	5
1926	4	4	3	1	0	4	5
1927	1	2	1	1	0	2	1
1928	2	3	1	1	0	3	2
1929	5	5	3	1	0	5	6
1930	4	5	2	1	0	4	5
1931	5	5	4	2	1	5	6
1932	4	2	4	1	0	4	5
1933	5	4	4	1	0	4	6
1934	5	5	4	2	1	5	6
1935	3	2	1	1	0	4	3
1936	3	2	1	1	0	3	3
1937	3	1	2	1	0	4	3
1938	1	1	1	1	0	1	1
1939	4	4	3	2	0	5	5
1940	2	2	1	1	0	2	2
1941	1	1	1	1	0	1	1
1942	1	1	1	1	0	2	1
1943	1	1	1	1	0	3	1
1944	4	3	3	1	0	5	5
1945	3	2	1	1	0	3	3
1946	3	2	1	1	0	2	3
1947	4	4	3	1	0	4	5
1948	3	3	1	1	0	3	3
1949	4	3	2	1	0	3	5
1950	3	3	2	1	0	4	3
1951	2	2	1	1	0	2	2
1952	1	1	1	1	0	2	1
1953	1	3	1	1	0	2	1
1954	2	3	1	1	0	2	2
1955	4	4	2	1	0	4	5

WATER YEAR	SACindex	SJRindex	SHASTAindex	AmerD893	FEATHERindex	Trinityindex	Amer403030
1956	1	1	1	1	0	1	1
1957	2	3	1	1	0	3	2
1958	1	1	1	1	0	1	1
1959	3	4	1	1	0	3	3
1960	4	5	1	1	0	3	5
1961	4	5	1	1	0	3	5
1962	3	3	1	1	0	3	3
1963	1	2	1	1	0	2	1
1964	4	4	3	1	0	4	5
1965	1	1	1	1	0	2	1
1966	3	3	1	1	0	3	3
1967	1	1	1	1	0	2	1
1968	3	4	1	1	0	3	3
1969	1	1	1	1	0	1	1
1970	1	2	1	1	0	2	1
1971	1	3	1	1	0	2	1
1972	3	4	1	1	0	3	3
1973	2	2	1	1	0	2	2
1974	1	1	1	1	0	1	1
1975	1	1	1	1	0	2	1
1976	5	5	3	2	0	4	6
1977	5	5	4	2	1	5	7
1978	2	1	1	1	0	1	2
1979	3	2	2	1	0	4	3
1980	2	1	1	1	0	2	2
1981	4	4	2	2	0	4	5
1982	1	1	1	1	0	1	1
1983	1	1	1	1	0	1	1
1984	1	2	1	1	0	2	1
1985	4	4	3	1	0	4	5
1986	1	1	1	1	0	2	1
1987	4	5	3	2	0	4	5
1988	5	5	3	2	1	4	6
1989	4	5	1	1	0	3	5
1990	5	5	3	2	0	4	6
1991	5	5	4	1	1	5	6
1992	5	5	4	2	0	4	6
1993	2	1	1	1	0	2	2
1994	5	5	4	2	0	5	6
1995	1	1	1	1	0	1	0
1996	1	1	1	1	0	2	0
1997	1	1	1	1	0	2	0
1998	1	1	1	1	0	1	0
1999	1	2	1	1	0	2	0
2000	2	2	1	1	0	2	0
2001	4	4	1	2	0	4	0
2002	4	4	1	1	0	3	0
2003	2	3	1	1	0	2	0

APPENDIX 4

Historic and Full Level 4 CVPIA refuge delivery timeseries

Historic and Full Level 4 deliveries to CVPIA Refuges

		CALVIN Group -->	SRW	SRW	SRW	GLD	SUT	SJE	SJE	SJW	SJW	SJW	SJW	SJW	SJW	SJW	SJW	SJW	MDT	KER	PIX
		Refuge -->	SAC	COL	DEL	GRL	SUT	MER	SNL_East Bear Creek	SNL_West Bear Creek	SNL_San Luis	SNL_Kesterson	SNL_Freitas	VLT	LSB	NGS_China Island	NGS_Salt Slough	GRS	MEN	KRN	PIX
Historic Deliveries (AF) Wetter Conditions	3	MAR	684	689	66	22	1,122	1,194	210	450	1,768	909	376	145	937	546	559	2,613	571	401	13
	4	APR	552	528	312	475	624	1,026	129	789	725	560	363	153	549	434	493	2,598	520	295	52
	5	MAY	1,365	738	1,321	1,818	1,251	1,295	145	704	1,106	719	335	150	918	443	554	14,243	1,217	488	31
	6	JUN	1,922	995	1,473	2,271	1,285	1,488	159	760	1,636	503	260	192	918	445	730	8,445	2,125	105	11
	7	JUL	1,946	688	602	2,353	476	1,384	213	341	405	193	205	282	1,039	686	694	3,642	2,458	68	3
	8	AUG	4,183	464	2,479	2,718	182	1,346	118	213	185	194	110	1,594	1,739	882	985	10,817	2,304	1,712	77
	9	SEP	7,490	3,178	5,146	6,119	2,362	1,938	596	654	1,817	1,254	181	2,830	3,279	917	1,050	51,930	4,812	4,140	162
	10	OCT	8,326	4,636	5,243	8,534	2,658	2,089	655	1,049	4,088	2,021	666	2,566	4,455	902	1,004	47,364	6,191	4,369	157
	11	NOV	5,280	3,180	3,411	4,145	2,603	1,442	392	1,383	3,067	1,401	508	1,421	2,807	757	1,227	13,166	2,851	4,618	124
	12	DEC	3,773	2,330	1,863	3,645	1,768	818	475	679	1,181	884	569	513	1,219	1,041	997	7,275	749	2,741	89
	1	JAN	1,717	1,171	413	1,751	959	527	323	535	1,063	730	629	537	1,494	687	788	5,568	966	848	86
	2	FEB	466	630	139	190	1,016	435	190	601	1,433	763	645	912	1,591	852	669	9,425	1,415	916	47
Historic Deliveries (AF) Drier Conditions	3	MAR	1,296	651	283	25	909	1,072	274	516	1,361	797	440	227	822	452	525	1,424	606	121	3
	4	APR	836	465	348	798	668	847	240	560	827	588	222	249	626	328	515	2,846	688	46	32
	5	MAY	1,260	672	1,133	1,951	1,828	1,011	216	610	1,335	739	331	243	894	334	626	12,520	1,506	245	81
	6	JUN	1,621	768	1,153	2,068	794	1,266	173	659	1,084	418	179	314	778	390	471	4,872	2,123	146	30
	7	JUL	1,139	576	638	2,045	343	1,083	29	240	291	223	155	212	773	508	447	2,121	2,255	42	2
	8	AUG	3,475	487	2,168	3,159	145	1,125	0	72	121	275	85	1,935	1,631	499	685	7,597	2,253	1,250	47
	9	SEP	7,870	2,768	4,490	5,286	2,121	1,707	143	487	1,833	1,155	165	2,456	3,215	656	1,003	45,350	4,907	3,270	126
	10	OCT	8,337	4,618	4,688	8,041	2,330	2,277	483	1,254	3,742	1,722	629	2,366	4,028	748	1,179	35,424	6,303	4,431	152
	11	NOV	4,598	2,805	3,175	4,097	2,372	1,536	699	1,138	2,467	1,293	563	1,359	2,972	834	1,095	12,778	2,404	3,655	135
	12	DEC	2,889	2,063	1,768	3,498	1,448	878	310	679	1,557	1,023	782	843	1,771	1,082	879	5,503	1,136	2,479	131
	1	JAN	2,236	1,506	1,199	1,298	1,068	787	600	433	1,713	755	670	449	1,962	1,110	810	7,093	1,646	1,216	108
	2	FEB	616	405	162	93	1,007	658	189	596	2,162	611	796	656	1,379	818	630	6,289	1,697	930	69
Full Level 4 Deliveries (AF) Non-critical Shasta Index (i.e. 1 < Index < 4)	3	MAR	1,250	625	350	30	3,420	600	1,380	1,010	1,000	750	440	730	1,220	640	620	2,410	1,060	600	0
	4	APR	300	125	770	710	1,200	950	1,450	1,320	1,250	1,000	320	320	860	530	570	3,660	780	400	400
	5	MAY	2,250	625	1,440	2,060	1,440	800	1,220	1,170	1,500	1,000	380	230	1,090	540	710	15,430	1,890	1900	650
	6	JUN	2,750	1,250	2,500	2,420	1,680	1,000	450	740	1,500	600	240	330	1,310	590	720	8,780	2,790	1500	350
	7	JUL	4,200	2,250	2,880	2,430	1,680	1,050	290	300	1,250	600	200	300	1,270	820	730	4,090	2,590	1500	350
	8	AUG	6,700	3,125	2,880	3,110	1,680	1,500	140	140	1,000	800	110	2,090	2,220	910	960	11,970	2,730	2500	600
	9	SEP	7,900	4,325	3,840	8,650	4,000	2,700	1,430	910	1,000	1,000	170	3,060	3,770	1,070	1,060	54,140	5,540	3800	800
	10	OCT	9,850	4,375	3,840	12,620	4,800	2,700	2,290	1,730	4,000	1,500	680	2,860	4,640	1,050	1,100	43,580	5,600	4300	950
	11	NOV	8,800	4,375	2,400	5,280	3,500	2,000	1,650	1,400	3,000	1,000	570	2,830	3,430	980	1,100	13,990	2,790	3800	700
	12	DEC	3,500	4,675	2,100	4,200	2,500	1,200	980	680	1,500	750	720	730	1,630	1,270	940	7,130	900	3000	700
	1	JAN	1,250	2,375	1,200	1,810	1,800	1,000	1,180	470	1,000	500	690	1,130	1,890	1,060	820	6,850	1,542	1000	250
	2	FEB	1,250	1,875	800	690	2,300	500	840	830	1,000	500	770	1,390	1,650	980	660	7,950	1,442	700	250
Full Level 4 Deliveries (AF) Critical Shasta Index (i.e. Index = 4)	3	MAR	1,175	513	263	23	3,170	550	1,218	908	750	563	330	683	1,070	528	495	2,085	935	600	0
	4	APR	225	100	578	533	963	825	1,320	1,180	938	750	240	265	765	465	468	3,348	630	400	380
	5	MAY	1,725	513	1,080	1,545	1,165	675	1,095	1,025	1,125	750	285	173	940	480	615	13,355	1,440	1425	650
	6	JUN	2,100	1,025	1,875	1,815	1,355	800	338	555	1,125	450	180	248	1,208	520	668	8,130	2,165	1287.5	350
	7	JUL	3,200	1,863	2,160	1,823	1,355	775	218	225	938	450	150	225	1,125	708	683	3,993	1,965	1500	350
	8	AUG	5,125	2,575	2,160	2,333	730	1,200	105	105	750	600	83	1,568	1,938	778	855	10,893	2,055	2500	600
	9	SEP	6,025	3,563	2,880	7,178	2,875	2,125	1,203	788	750	750	128	2,295	3,060	920	853	43,205	4,215	3200	800
	10	OCT	7,525	3,288	2,880	10,433	3,850	2,125	1,940	1,478	3,000	1,125	510	2,145	3,718	895	870	34,788	4,250	4000	950
	11	NOV	6,725	3,613	1,800	4,180	3,025	1,500	1,303	1,103	2,250	750	428	2,428	2,868	805	885	11,310	2,115	3350	700
	12	DEC	2,675	3,950	1,575	3,243	2,025	775	740	513	1,125	563	540	558	1,288	1,015	775	5,988	675	2550	700
	1	JAN	950	1,963	900	1,398	1,563	800	885	353	750	375	518	988	1,498	820	653	5,505	1,207	1000	125
	2	FEB	950	1,550	600	658	2,050	475	723	698	750	375	578	1,178	1,338	765	503	6,133	1,104	700	100
Historic (TAF) Wetter Conditions			18	7	11	16	7	10	2	4	8	4	2	5	9	4	5	94	14	7	0
Historic (TAF) Drier Conditions			17	6	10	15	7	8	1	3	7	4	2	6	9	3	4	77	14	5	0
Δ Historic			*1*	*1*	*1*	*0*	*0*	*2*	*0*	*1*	*1*	*0*	*0*	*0*	*1*	*1*	*1*	*18*	*0*	*2*	*0*
Full L2/L4 Deliveries (TAF) Non-critical Shasta Index			25	12	15	19	15	9	6	6	9	6	2	7	12	5	5	100	17	12	3
Full L2/L4 Deliveries (TAF) Critical Shasta Index			20	10	11	15	12	7	5	5	6	4	1	5	10	4	5	85	13	11	3
Δ Full L2/L4			*6*	*2*	*4*	*4*	*3*	*2*	*1*	*1*	*2*	*1*	*0*	*2*	*2*	*1*	*1*	*15*	*4*	*1*	*0*

Historic Deliveries: Historic Level 2 and incremental Level 4 deliveries to CVPIA refuges between 2001 and 2014.

Wetter Conditions: For historic deliveries, averaged deliveries during wet, above normal and below normal Water Years. For Full Level 4, 100 % Level 2 and 100% incremental Level 4 deliveries during non-critical Shasta Lake Index.

Drier Conditions: For historic deliveries, averaged deliveries during critical and dry Water Years. For Full Level 4, 75% of Level 2 and 100% of incremental Level 4 deliveries during critical Shasta Lake Index.

Historic and Full Level 4 Deliveries to CALVIN Refuge Nodes during wetter and drier conditions, and 82-year long term average (TAF/mth)

		Historic Deliveries (TAF/yr) Wetter Conditions								Historic Deliveries (TAF/yr) Drier Conditions								Historic Deliveries (TAF/yr) 82-year Average							
CALVIN Group -->		**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**	**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**	**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**
3	**MAR**	1.4	0.0	1.1	1.4	8.3	0.6	0.0	0.4	2.2	0.0	0.9	1.3	6.6	0.6	0.0	0.1	1.7	0.0	1.0	1.4	7.7	0.6	0.0	0.3
4	**APR**	1.4	0.5	0.6	1.2	6.7	0.5	0.1	0.3	1.6	0.8	0.7	1.1	6.8	0.7	0.0	0.0	1.5	0.6	0.6	1.1	6.7	0.6	0.0	0.2
5	**MAY**	3.4	1.8	1.3	1.4	19.2	1.2	0.0	0.5	3.1	2.0	1.8	1.2	17.6	1.5	0.1	0.2	3.3	1.9	1.5	1.4	18.6	1.3	0.0	0.4
6	**JUN**	4.4	2.3	1.3	1.6	13.9	2.1	0.0	0.1	3.5	2.1	0.8	1.4	9.2	2.1	0.0	0.1	4.1	2.2	1.1	1.6	12.2	2.1	0.0	0.1
7	**JUL**	3.2	2.4	0.5	1.6	7.5	2.5	0.0	0.1	2.4	2.0	0.3	1.1	5.0	2.3	0.0	0.0	2.9	2.2	0.4	1.4	6.6	2.4	0.0	0.1
8	**AUG**	7.1	2.7	0.2	1.5	16.7	2.3	0.1	1.7	6.1	3.2	0.1	1.1	12.9	2.3	0.0	1.2	6.8	2.9	0.2	1.3	15.4	2.3	0.1	1.5
9	**SEP**	15.8	6.1	2.4	2.5	63.9	4.8	0.2	4.1	15.1	5.3	2.1	1.9	56.3	4.9	0.1	3.3	15.6	5.8	2.3	2.3	61.2	4.8	0.1	3.8
10	**OCT**	18.2	8.5	2.7	2.7	64.1	6.2	0.2	4.4	17.6	8.0	2.3	2.8	51.1	6.3	0.2	4.4	18.0	8.4	2.5	2.7	59.5	6.2	0.2	4.4
11	**NOV**	11.9	4.1	2.6	1.8	25.7	2.9	0.1	4.6	10.6	4.1	2.4	2.2	24.5	2.4	0.1	3.7	11.4	4.1	2.5	2.0	25.3	2.7	0.1	4.3
12	**DEC**	8.0	3.6	1.8	1.3	14.4	0.7	0.1	2.7	6.7	3.5	1.4	1.2	14.1	1.1	0.1	2.5	7.5	3.6	1.7	1.3	14.3	0.9	0.1	2.6
1	**JAN**	3.3	1.8	1.0	0.8	12.0	1.0	0.1	0.8	4.9	1.3	1.1	1.4	15.0	1.6	0.1	1.2	3.9	1.6	1.0	1.0	13.1	1.2	0.1	1.0
2	**FEB**	1.2	0.2	1.0	0.6	16.9	1.4	0.0	0.9	1.2	0.1	1.0	0.8	13.9	1.7	0.1	0.9	1.2	0.2	1.0	0.7	15.8	1.5	0.1	0.9

		Full Level 4 Deliveries (TAF/yr) Wetter Conditions								Full Level 4 Deliveries (TAF/yr) Drier Conditions								Full Level 4 Deliveries (TAF/yr) 82-year Average							
CALVIN Group -->		**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**	**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**	**SRW**	**GLD**	**SUT**	**SJE**	**SJW**	**MDT**	**PIX**	**KER**
3	**MAR**	2.2	0.0	3.4	2.0	8.8	1.1	0.0	0.6	2.0	0.0	3.2	1.8	7.4	0.9	0.0	0.6	2.2	0.0	3.4	2.0	8.7	1.0	0.0	0.6
4	**APR**	1.2	0.7	1.2	2.4	9.8	0.8	0.4	0.4	0.9	0.5	1.0	2.1	8.4	0.6	0.4	0.4	1.2	0.7	1.2	2.4	9.7	0.8	0.4	0.4
5	**MAY**	4.3	2.1	1.4	2.0	22.1	1.9	0.7	1.9	3.3	1.5	1.2	1.8	18.7	1.4	0.7	1.4	4.2	2.0	1.4	2.0	21.7	1.8	0.6	1.8
6	**JUN**	6.5	2.4	1.7	1.5	14.8	2.8	0.4	1.5	5.0	1.8	1.4	1.1	13.1	2.2	0.4	1.3	6.3	2.4	1.6	1.4	14.6	2.7	0.3	1.5
7	**JUL**	9.3	2.4	1.7	1.3	9.6	2.6	0.4	1.5	7.2	1.8	1.4	1.0	8.5	2.0	0.4	1.5	9.1	2.4	1.6	1.3	9.4	2.5	0.3	1.5
8	**AUG**	12.7	3.1	1.7	1.6	20.2	2.7	0.6	2.5	9.9	2.3	0.7	1.3	17.6	2.1	0.6	2.5	12.4	3.0	1.6	1.6	19.9	2.7	0.6	2.5
9	**SEP**	16.1	8.7	4.0	4.1	66.2	5.5	0.8	3.8	12.5	7.2	2.9	3.3	52.7	4.2	0.8	3.2	15.7	8.5	3.9	4.0	64.7	5.4	0.8	3.7
10	**OCT**	18.1	12.6	4.8	5.0	61.1	5.6	1.0	4.3	13.7	10.4	3.9	4.1	48.5	4.3	1.0	4.0	17.6	12.4	4.7	4.9	59.8	5.5	0.9	4.3
11	**NOV**	15.6	5.3	3.5	3.7	28.3	2.8	0.7	3.8	12.1	4.2	3.0	2.8	22.8	2.1	0.7	3.4	15.2	5.2	3.4	3.6	27.7	2.7	0.7	3.8
12	**DEC**	10.3	4.2	2.5	2.2	15.4	0.9	0.7	3.0	8.2	3.2	2.0	1.5	12.4	0.7	0.7	2.6	10.0	4.1	2.4	2.1	15.0	0.9	0.7	3.0
1	**JAN**	4.8	1.8	1.8	2.2	14.4	1.5	0.3	1.0	3.8	1.4	1.6	1.7	11.5	1.2	0.1	1.0	4.7	1.8	1.8	2.1	14.1	1.5	0.2	1.0
2	**FEB**	3.9	0.7	2.3	1.3	15.7	1.4	0.3	0.7	3.1	0.7	2.1	1.2	12.3	1.1	0.1	0.7	3.8	0.7	2.3	1.3	15.4	1.4	0.2	0.7

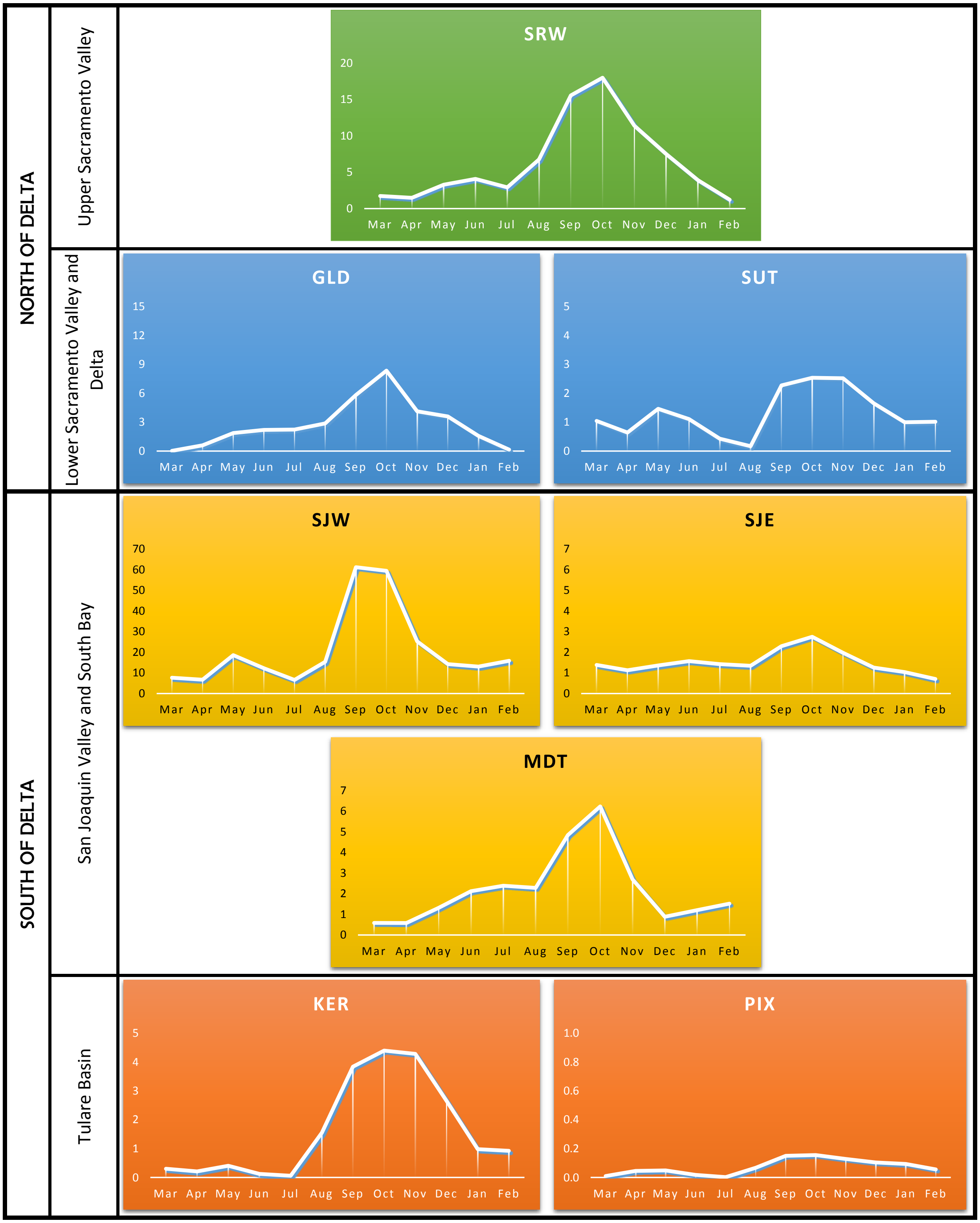
Historic Deliveries: Historic Level 2 and incremental Level 4 deliveries to CVPIA refuges between 2001 and 2014.

82-year average: Monthly averaged 82-year refuge delivery timeseries used in CALVIN.

Wetter Conditions: For historic deliveries, averaged deliveries during wet, above normal and below normal Water Years. For Full Level 4, 100 % Level 2 and 100% incremental Level 4 deliveries during non-critical Shasta Lake Index.

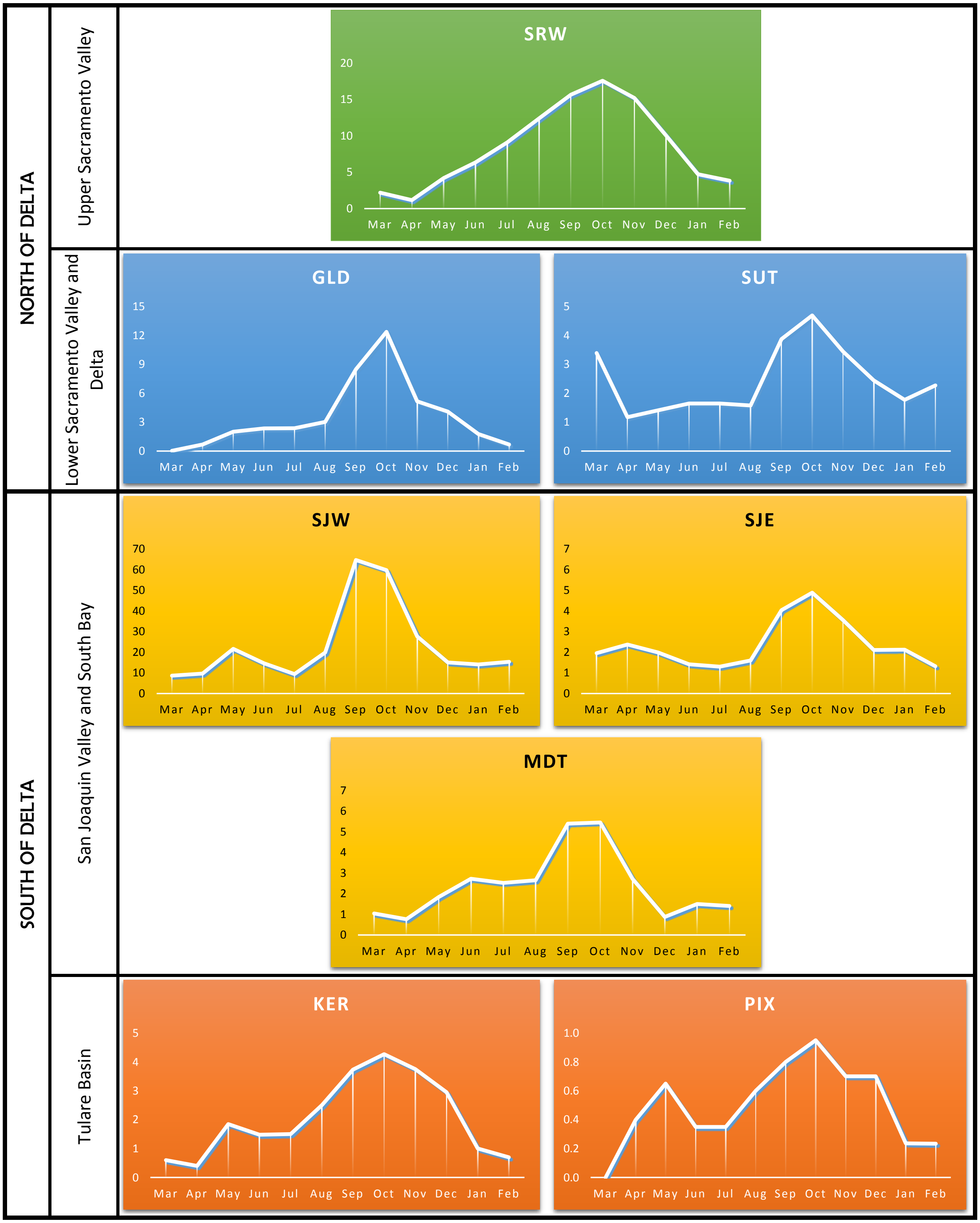
Drier Conditions: For historic deliveries, averaged deliveries during critical and dry Water Years. For Full Level 4, 75% of Level 2 and 100% of incremental Level 4 deliveries during critical Shasta Lake Index.

Historic Level 2 and incremental Level 4 Refuge Deliveries (TAF/mth, 82-year long-term average)



NOTE: Figures are **not** drawn to same scale.

Full Level 4 Refuge Deliveries (TAF/mth, 82-year long-term average)



NOTE: Figures are **not** drawn to same scale.

APPENDIX 5

Upper bounds on groundwater pumping for refuge management

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1											**GW Deliveries to the CVPIA Refuges (Acre-Feet)**													
2											**San Luis**				**North Grasslands**									
3	**Unit Name -->**	**Sacramento**	**Delevan**	**Colusa**	**Gray Lodge**	**Sutter**	**Merced**	**East Bear Creek**	**San Luis Unit**	**West Bear Creek**	**East of Hwy 165**	**Kesterson**	**Freitas**	**West of Hwy 165**	**China Island**	**Salt Slough**	**Los Banos**	**Volta**	**Grasslands RCD**	**Mendota**	**Pixley**	**Kern**		
4	**CALVIN Group -->**	**SRW**	**SRW**	**SRW**	**GLD**	**SUT**	**SJE**	**SJE**			**SJW**			**SJW**	**SJW**	**SJW**	**SJW**	**SJW**	**SJW**	**MDT**	**PIX**	**KER**		
5	**WY**	**All**	**All**	**All**	**2010**	**-**	**2010**	**2010**						**2010**	**2010**	**2009**	**2010**	**All**	**2009**	**All**	**2009**	**All**		
7	**MAR**	0	0	0	0	215	1,600	0			0			0	5	0	0	0	0	0	0	0	Table 1 of WMP Monthly GW use in a specific WY (AF/mth)	Maximum of the two is used to develop upper bound on GW capacity.
8	**APR**	0	0	0	496	334	42	0			0			0	5	0	0	0	0	0	116	0		
9	**MAY**	0	0	0	691	67	71	0			0			0	5	0	0	0	404	0	0	0		
10	**JUN**	0	0	0	124	1,783	37	0			0			0	5	0	0	0	400	0	0	0		
11	**JUL**	0	0	0	117	1,423	43	0	*WMP combines San Luis Units and West Bear Creek units into "East of Highway 165" unit.*		0			0	5	0	0	0	350	0	0	0		
12	**AUG**	0	0	0	191	1,028	0	0			0	*WMP combines Kesterson and Frietas untis into "West of Highway 165" unit.*		0	5	0	0	0	278	0	107	0		
13	**SEP**	0	0	0	364	3,043	0	0			0			0	5	0	0	0	1,153	0	104	0		
14	**OCT**	0	0	0	1,953	3,363	89	0			0			0	5	0	0	0	1,407	0	62	0		
15	**NOV**	0	0	0	24	106	1,845	0			360			0	5	0	0	0	1,222	0	128	0		
16	**DEC**	0	0	0	33	1,308	2,009	0			0			0	5	0	0	0	1,789	0	75	0		
17	**JAN**	0	0	0	365	998	2,006	0			360			0	5	0	0	0	1,291	0	0	0		
18	**FEB**	0	0	0	0	174	1,706	0			360			0	5	0	0	0	465	0	0	0		
20	**Min** (rounded up)	0	0	0	0	70	0	0			0			0	10	0	0	0	0	0	0	0		
21	**Avg** (rounded up)	0	0	0	370	1,160	790	0			90			0	10	0	0	0	0	0	50	0		
22	**Max** (rounded up)	0	0	0	1,950	3,360	2,010	0			360			0	10	0	0	0	0	0	130	0		
24	**Annual WY**	0	0	0	4,358	13,841	9,448	0			1,080			0	60	0	0	0	8,759	0	592	0		
25	**Annual Min (WY 2001 - 2010)**	0	0	0	1,036		0	0			400			0	0	0	0	0	0	0	585	0	Table 5 of WMP Long-term annual GW use (AF/yr)	
26	**Annual Avg (WY 2001 - 2010)**	0	0	0	5,651	No WMP prepared.	6,328	0			468			10	72	65	60	0	0	0	738	0		
27	**Annual Max (WY 2001 - 2010)**	0	0	0	11,564		12,211	0			1,080			10	85	80	150	0	0	0	852	0		
28	**Annual Max**	0	0	0	16,000	No WMP prepared.		0							1,250		500	0	0	0		0	Section D5 GW well capacity (AF/yr)	
29	**Limiting Factor on GW Pumping**	WQ	WQ	WQ	Safe yield cap	*not enough information available*	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	WQ	Pump Capacity; plan to install more in 2011	WQ	General discussion in WMP	
30																								

31 **Source:**

32 **All except Sutter NWR** Refuge Water Management Plan.

33 **Sutter NWR** Rachel Esralew, Hydrologist, USFWS, in an e-mail based on stats in the Sutter Water Supply Report

34

35 **Information used in CALVIN.**

	CALVIN Refuge Group	GW UB (TAF/mth)	Comment
36	**CALVIN Refuge Group**	**GW UB (TAF/mth)**	**Comment**
37	**SRW**	0.00	Sum of maximum historical monthly GW used as water supply source at Sacramento, Delevan and Colusa NWR. Source: Table 1 of Water Management Plans. - Karandev Singh 6.4.2015
38	**GLD**	1.95	Maximum historical monthly GW used as water supply source at Gray Lodge WA. Source: Table 1 of Water Management Plan. - Karandev Singh 6.4.2016
39	**SUT**	3.36	Maximum of maximum monthly GW used as water supply source at Sutter NWR assuming "New Level 2 and Level 4" delivery schedule and historical surface water deliveries from SEWD and Sutter Bypass. Source: E-mail correspondence with Rachel Esralew, Hydrologist, USFWS regarding the Sutter NWR delivery alternatives explored in the Sutter NWR Water Supply Report published Nov 2014. - Karandev Singh 6.4.2017
40	**SJW**	0.37	Sum of maximum historical monthly GW used as water supply source at San Joaquin Basin Action Plan refuges west of the San Joaquin River which includes China Island and Salt Slough from North Grasslands, San Luis unit, West Bear Creek, Frietas and Kesterson from San Luis NWR, Los Banos WA, Volta WA, and Grasslands RCD. Grasslands RCD engaged in a three year pilot project to test viability of GW was water supply source, however, no long term decision was made at the time. This network flow configuration assumed no use of GW within Grasslands RCD
41	**SJE**	2.01	Sum of maximum historical monthly GW used as water supply source at t San Joaquin Basin Action Plan refuges west of the San Joaquin River which includes East Beak Creek from San Luis NWR and Merced Unit of Merced NWR. Source: Table 1 of Water Management Plan. - Karandev Singh 6.4.2019
42	**PIX**		Pixley relies solely on GW for meeting its Level 2 and Level 4 deliveries. Historically, on-site pump capacity limited production to a portion of Level 2 delivery. WMP indicated that the refuge was planning to install two more pumps in 2011. This network flow configuraiton assumes that the refuge that enough pump capacity to satisfy its Level 2 and Level 4 demands.
43	**KER**	0.00	Maximum historical monthly GW used as water supply source at Kern NWR. Source: Table 1 of Water Management Plan. - Karandev Singh 6.4.2021

Cell: F3
Comment: Karandev Singh:
Maximum GW needed to meet the "New" L2+L4 demands assuming historical SEWD deliveries. "New" L2 and L4 deliveries recommend some changes in the monthly deliveries, however, annual L2 and L4 delivery remains the same.

Source: Rachel Esralew, Hydrologist, USFWS, in an e-mail based on stats in the Sutter Water Supply Report

Cell: G3
Comment: Karandev Singh:
Merced Unit only; rest are non-CVPIA refuges

Cell: S3
Comment: Karandev Singh:
Grasslands RCD engaged in a 3-year pilot project to test viability of GW as water supply source, however, no long term decision was made at the time. Thereforem it is assumed that no GW is used within RCD to satisfy L2 and L4 demand.

Cell: U3
Comment: Karandev Singh:
L2 deliveries are met by on-site GW wells. All the GW use is reported under Federal Level 2 deliveries column, instead of the "Refuge Groundwater" column.

In 2010, at the time of the report, refuge only had one well on site, however, they were planning on another two. The data below is for one well which has a limited capacity and cannot be used to meet L2 and L4 demand in full. CALVIN assumes that entire L2 and L4 demand will be met by GW.

Cell: E7
Comment: Karandev Singh:
No information provided in the WMP

Cell: E17
Comment: Karandev Singh:
Information provided for Jan 2007

Cell: E18
Comment: Karandev Singh:
Information provided for February 2006

Cell: N26
Comment: Karandev Singh:
2001 - 2004 average

Cell: O28
Comment: Karandev Singh:
cumulative yield of three functioning wells

Cell: Q28
Comment: Karandev Singh:
Cumulative yield of two active GW wells

APPENDIX 6

CalSim II-to-CALVIN Mapping

Description	CALVIN Link	CalSim Link	Hydrology	Conveyance	Regulations	Base/ EREC	ERIF	HOEC	HOIF
Min Flow Trinity EOS	SR-CLE	S1LEVEL2	N	N	N	DRR	Base	Base	Base
Min Flow Trinity EOS (Modified)	SR-CLE	S1_2							
Min Flow d/s Lewiston	D94_Sink D94	C100_MIF	N	N	N	DRR	Base	Base	Base
Min Flow d/s Whskytwn	SR-WHI_D73	C3_MIF	Y	N	N	ERIF	Base	Base	Base
Min Flow Shasta EOS (Modified)	SR-SHA	S4_2							
Shasta EOS	SR-SHA	S4LEVEL2	N	N	N	DRR	Base	Base	Base
Min Flow d/s Keswick	D5_D73	C5_MIF	N	Y	N	DRR	Base	Base	HOIF
Min Flow @ Red Bluff	D77_D75	C112_MIF	N	N	N	DRR	Base	Base	Base
Navigation Flow @ Wilkins	D61_C301	C129_MIF	N	N	N	DRR	Base	Base	Base
Flood Flow into Sutter Bypass	D66A_D43A	D117	N	N	Y	DRR	Base	HOEC	Base
Flood Flow @ Colusa & Moulton	D30_D43A	D124	N	N	Y	DRR	Base	HOEC	Base
Flood Flow @ Colusa & Moulton	D30_D43A	D125	N	N	Y	DRR	Base	HOEC	Base
Flood Flow @ Tisdale	D61_D61B	D126	N	N	Y	DRR	Base	HOEC	Base
Flood Flow @ Freemont	D43_C306	D160	Y	Y	Y	EREC	ERIF	HOEC	ERIF
Flood Flow @ Sacramento Weir	C7_C20	D166A	Y	N	Y	EREC	Base	HOEC	Base
Flood Flow into Yolo Bypass	C20_D55	C157	Y	Y	Y	EREC	ERIF	HOEC	ERIF
Min Flow Ther Aftby Outlet	C25_C31	C203_MIF	Y	Y	N	EREC	Base	Base	HOIF
Min Flow d/s Thrm Div Dam	C23_C25	C200A_MIF	N	N	N	DRR	Base	Base	Base
Flow @ Verona/ Feather Confluence	D42_D43	C223_MIF	Y	Y	N	ERIF	Base	Base	HOIF
Min Flow d/s Nimbus	D9_D85	C9_MIF	N	Y	N	DRR	Base	Base	HOIF
Min Flow d/s Black Butte	SR-BLB_C9	C17301_MIF	Y	N	Y	EREC	Base	HOEC	Base
Min Flow @ Stony Creek	C9_C12	C173A_MIF	Y	N	N	EREC	Base	Base	Base
Min Flow @ H St Bridge	D64_C8	C303_MIF	N	N	N	DRR	Base	Base	Base
Min Flow @ Freeport	D503_D511	C400_MIF	N	Y	Y	DRR	ERIF	HOEC	HOIF
Min Flow near Rio Vista	D507_D509	C405_MIF	N	Y	N	DRR	HOIF	Base	HOIF
Min Delta Outflow	D541_Required Delta Outflow	D407	N	Y	Y	DRR	ERIF	HOEC	HOIF
Surplus Delta Outflow	D541_Surplus Delta Outflow	C407							
WQ and residence time	D503_PMP-Isolated Facility	D400							
DXC	D511_D513	C401B	N	Y	Y	DRR	ERIF	HOEC	HOIF
Tracy PP	PMP-Tracy_D701	D418	Y	Y	Y	EREC	ERIF	HOEC	HOIF
Tracy PP	PMP-Tracy_D701	TRACYALLOWOUT	N	N	N	DRR	Base	Base	Base
Banks PP	PMP-Banks_D800	D419	Y	Y	Y	EREC	ERIF	HOEC	HOIF
Banks PP	PMP-Banks_D800	BANKSALLOWOUT	N	Y	N	DRR	ERIF	Base	Base
Min Flow near Vernalis	D616_C42	C639_VAMPDO	N	N	N	DRR	Base	Base	Base
Min Flow at Chowchilla Bypass confluence	D624_C48	C588_MIF	N	N	N	DRR	Base	Base	Base
d/s Friant Dam/ Mendota Pool	D609_D608	C605A_VAMPDO	N	N	Y	DRR	Base	HOEC	Base
Flood Flow into James Bypass	C54_D608	I607	N	N	N	DRR	Base	Base	Base
Min Flow @ Mokelumne confluence	C37_C38	C501_VAMPDO	N	N	Y	DRR	Base	HOEC	Base
Min Flow @ Calaveras - SJR confluence	C41_C42	C508_VAMPDO	N	N	N	DRR	Base	Base	Base
Min Flow d/s Goodwin	D672_D675	C520_MIF	Y	Y	N	EREC	Base	Base	HOIF
Min Flow @ Stanislaus - SJR confluence	D675_D676	C528_MIF	Y	Y	N	EREC	Base	Base	HOIF
Min Flow Lagrange Bridge	D662_D663	C540_MIF	N	N	N	DRR	Base	Base	Base
Min Flow d/s Don Pedro	SR-DNP_D662	C81VAMP	Y	N	N	EREC	Base	Base	Base

Min Flow @ Shaffer Bridge	D649_D695	C562_MIF	N	N	N	DRR	Base	Base	Base
Min Flow Crocker Huffman	D645_D646	C561_MIF	N	N	N	DRR	Base	Base	Base
Kern River Intertie	C73_D859	I860	N	N	N	DRR	Base	Base	Base
Min Flow u/s Wheatland	C33_C308		?	?	?	Existing	Base	Base	Base
Min Flow d/s Camp Far West	SR-CFW_C33		?	?	?	Existing	Base	Base	Base
Min Flow d/s Rolins	N201_N202		?	?	?	Existing	Base	Base	Base
Min Flow u/s Rollins	C35_SR-RLL-CMB		?	?	?	Existing	Base	Base	Base
Min Flow Daguerre Dam	C83_C31		?	?	?	Existing	Base	Base	Base
Min Flow d/s Englebright	SR-ENG_C28		?	?	?	Existing	Base	Base	Base
Min Flow d/s Camanche	SR-CMN_C38		?	?	?	Existing	Base	Base	Base
Folsom Dam Flood Ctrl	SR-FOL_SR-FOL		?	?	?	Existing	Base	Base	Base
NOD Div Byps Flow									
Flow below Goodwin	D672_D675								
Salinity @ Vernalis	D616_C42								
Min Flow d/s Woodbridge									
Max salinity @ Vernalis									
NDOI									
Spring X2									
Fall X2									
Delta WQ									
OMR Flows									

Base/EREC: Existing Regulations and Existing Conveyance
CalSim timeseries are exported from DRR 2009 (2005A01E) for the HEXT2014 CALVIN run. DRR 2009 uses 2005 LOD and hydrology for developing unimpaired timeseries.However, the base run in BDCP studies (No Action Alternative, NAA) uses 2030 LOD and hydrology to develop unimparied flows. This comparison was conducted to determine whether a constrained timeseries are hydrology dependent and if it is, which CalSim run to use: DRR 2009 or BDCP NAA.

ERIF: Existing Regulations w/ Isolated Facility
This comparison was conducted to determine whether a constrained timeseries are conveyance dependent. Constrained timeseries from the base/EREC scenario were compared to the BDCP preferred alternative (2a-H3).

HOIF: High Outflow w/ Isolated Facility
This comparison was conducted to determine whether a constrained timeseries are regulation dependent. Constrained timeseries from ERIF scenario are compared to the BDCP's high outflow w/o Isolated Facility scenario (2a-H4).

HOEC: High Outflow and Existing Conveyance
BDCP study only includes HOEC with climate change: Early Long Term (ELT) scenario with 15 cm sea level rise (SLR), and Late Long Term (LLT) scenario with 45 cm SLR. There is no one-to-one comparable study with historical hydrology, high outflow requirements and existing conveyance. The two HOEC studies with SLR 15 and SLR 45 were compared to assess the affect of SLR. If significant affect was observed, ERIF and HOIF were compared both of which use historical hydrology and 0 SLR leaving regulatory conditions the only difference between the two runs. Any significant difference would indicate that a constrained timeseries is regulation dependent and therefore, HOEC SLR 15cm timeseries was chosen. If no siginificant difference is observed between ERIF and HOIF, then HOEC SLR 15 is compared to the Base run, and a decision is made whether to map to the Base run or the HOEC SLR 15 run.

Note:
"Existing" indicates that the timeseries was created or obtained from other sources than CalSim.There is no way to determine the effects of regulatory and conveyance scenarios on these timeseries and are assumed to be independent of hydrology, conveyance and regulatory scenarios.
"Base" indicates whether the constrained timeseries changes for the regulatory and conveyance scenarios relative to the Base case or EREC scenario.

APPENDIX 7

Comparison of required minimum in-stream flows, and pump and weir operations

Minimum In-Stream Flow Requirement (TAF/yr, Long-Term 82 Year Average)

Results summarized by regulatory and conveyance scenario

	EREC	ERIF	HOEC	HOIF
Upper Sacramento Valley				
Trinity River downstream Lewinston Lake	607	607	607	607
Clear Creek	126	126	126	126
Sacramento River downstream Keswick Reservoir (Temperature Control)	2,646	2,646	2,646	2,767
Sacramento River downstream Red Bluff Diversion Dam	2,392	2,392	2,392	2,392
Stony Creek downstream Black Butte Lake	17	17	17	17
Stony Creek downstream Black Butte Lake	6	6	6	6
Sacramento River near Wilkins Slough	3,272	3,272	3,272	3,272
Lower Sacramento Valley and Delta				
Feather River downstream Thermalito Diversion Dam	547	547	547	547
Feather River downstream Thermalito Complex	869	869	869	1,572
Yuba River downstream Englebright Lake	317	317	317	317
Yuba River near Marysville	438	438	438	438
Bear River upstream Lake Rollins and Crombie	1	1	1	1
Bear River downstream Lake Rollins and Crombie	33	33	33	33
Bear River downstream Camp Far West	23	23	23	23
Bear River downstream Camp Far West	10	10	10	10
Feather River/ Sacramento River Confluence (at Verona)	1,223	1,223	1,223	1,660
American River downstream Lake Natoma/ Nimbus Dam	1,088	1,088	1,088	1,092
American River/ Sacramento River Confluence (near H Street)	228	228	228	228
Consumnes River	361	361	364	361
Mokelumne River downstream Camache Reservoir	157	157	157	157
Calaveras River near Delta	102	102	102	102
Sacramento River near Hood	3,540	3,193	2,568	2,436
Sacramento River at Rio Vista	941	2,388	941	2,388
Minimum Required Delta Outflow	4,994	5,079	5,157	5,061
San Joaquin Valley and South Bay				
San Joaquin River at Vernalis	3,068	3,068	3,068	3,068
Stanislaus River downstream Goodwin Dam	353	353	353	324
Stanislaus River near Ripon	353	353	353	324
Tuolumne River downstream New Don Pedro Dam (VAMP)	7	7	7	7
Tuolumne River downstream La Grange Dam (FERC)	220	220	220	220
Upper Merced River	170	170	170	170
Lower Merced River	82	82	82	82
Fresno River (Channel Flow)	2	2	2	2
San Joaquin River at Mendota Pool	117	117	155	117
Tulare Basin				
Southern California				
Mono Lake Restoration Flows	74	74	74	74
Lower Owens River Restoration Flows	30	30	30	30
Owens Lake Dust Mitigation Requirement	40	40	40	40

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnel)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnel)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnel)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnel)

Constrained Operations in CALVIN (TAF/yr, Long-Term 82 Year Average)

Results summarized by regulatory and conveyance scenario

	EREC	ERIF	HOEC	HOIF
Upper Sacramento Valley				
Spills into Sutter Bypass from Sacramento River	4	4	19	4
Lower Sacramento Valley and Delta				
Moulton/ Colusa Weir Diversions into Sutter Bypass	895	895	1,064	895
Tisdale Weir Diversions into Sutter Bypass	891	891	955	891
Freemont Weir Spills into Yolo Bypass	1,478	1,910	1,814	1,910
Sacramento Weir Spills into Yolo Bypass	107	107	165	107
Yolo Bypass Inflows	2,222	2,653	2,620	2,653
Isolated Facility Diversions from Sacramento River	0	2,713	0	2,263
Delta Cross Channel Inflows	3,780	3,264	3,699	3,181
Banks Pumping Plant	2,719	3,232	1,866	2,689
Tracy Pumping Plant	2,176	2,261	1,577	2,268
San Joaquin Valley and South Bay				
Tulare Basin				
James Bypass Inflows into Mendota Pool	146	146	146	146
Kern River Intertie/ Buena Vista Pumping Plant Spills into CA Aqu	24	24	24	24
Southern California				

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnel)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnel)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnel)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnel)

APPENDIX 8

Impact of warm-dry climate scenario on hydrologic inputs to CALVIN

Comparison of CALVIN inputs under historic and warm-dry hydrology

Average Annual Flows (TAF/yr, Long-Term 82 Year Average)

	Historic Hydrology	Warm-Dry Hydrology	
Upper Sacramento Valley	11,820	9,335	-21%
Reservoir Inflows (+)	7,282	6,155	-15%
Local Surface Water Inflows (+)	4,566	3,497	-23%
Local Depletions (-)	425	626	47%
Local Accretions (+)	160	160	0%
Net Groundwater Inflows (+)	237	149	-37%
Lower Sacramento Valley and Delta	13,059	8,553	-35%
Reservoir Inflows (+)	10,358	7,637	-26%
Local Surface Water Inflows (+)	2,701	1,994	-26%
Local Depletions (-)	1,094	2,108	93%
Local Accretions (+)	34	34	0%
Net Groundwater Inflows (+)	1,060	996	-6%
San Joaquin Valley and South Bay	7,616	4,595	-40%
Reservoir Inflows (+)	6,326	3,962	-37%
Local Surface Water Inflows (+)	236	237	1%
Local Depletions (-)	81	464	470%
Local Accretions (+)	450	260	-42%
Net Groundwater Inflows (+)	686	599	-13%
Tulare Basin	4,900	2,902	-41%
Reservoir Inflows (+)	2,873	1,621	-44%
Local Surface Water Inflows (+)	0	0	0%
Local Depletions (-)	662	1,161	75%
Local Accretions (+)	476	354	-26%
Net Groundwater Inflows (+)	2,213	2,087	-6%
Southern California	3,118	2,934	-6%
Reservoir Inflows (+)	0	0	0%
Local Surface Water Inflows (+)	1,215	1,030	-15%
Local Depletions (-)	0	0	0%
Local Accretions (+)	0	0	0%
Net Groundwater Inflows (+)	1,904	1,904	0%
STATEWIDE	40,514	28,318	-30%
Reservoir Inflows (+)	26,839	19,375	-28%
Local Surface Water Inflows (+)	8,718	6,759	-22%
Local Depletions (-)	2,263	4,358	93%
Local Accretions (+)	1,119	807	-28%
Net Groundwater Inflows (+)	6,100	5,734	-6%

APPENDIX 9

CALVIN Constraint relaxation summary

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average)

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnel)
H####: Historic Hydrology; C####: Warm-Dry Hydrology: ####G: No long-term GW overdraft

	Original	HEREC	HERECG	CEREC	CERECG
Minimum in-stream flows *	28,453	28,453	28,453	28307 (-1%)	28307 (-1%)
Upper Sacramento Valley	9,064	9,064	9,064	9,061	9,061
Lower Sacramento Valley and Delta	14,871	14,871	14,871	**14751 (-1%)**	**14751 (-1%)**
San Joaquin Valley and South Bay	4,373	4,373	4,373	4,370	4,370
Tulare Basin	0	0	0	0	0
Southern California	144	144	144	**125 (-13%)**	**125 (-13%)**
Refuge Deliveries (Historic) *	449	449	449	449	449
Upper Sacramento Valley	78	78	78	78	78
Lower Sacramento Valley and Delta	49	49	49	49	49
San Joaquin Valley and South Bay	301	301	301	301	301
Tulare Basin	21	21	21	21	21
Southern California	0	0	0	0	0
Refuge Deliveries (Full Level2/ Level4) *	544	544	544	544	544
Upper Sacramento Valley	102	102	102	102	102
Lower Sacramento Valley and Delta	72	72	72	72	72
San Joaquin Valley and South Bay	338	338	338	338	338
Tulare Basin	31	31	31	31	31
Southern California	0	0	0	0	0
Constrained Operations (Gates, Weirs, etc.) *	14,442	14,442	14,442	14,429	14,429
Upper Sacramento Valley	4	4	4	4	4
Lower Sacramento Valley and Delta	14,268	14,268	14,268	14,257	14,257
San Joaquin Valley and South Bay	0	0	0	0	0
Tulare Basin	170	170	170	**168 (-1%)**	**168 (-1%)**
Southern California	0	0	0	0	0

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnel)
H####: Historic Hydrology; C####: Warm-Dry Hydrology; ####G: No long-term GW overdraft

	Original	HERIF	HERIFG	CERIF	CERIFG
Minimum in-stream flows *	29,639	29,639	29,639	29473 (-1%)	29473 (-1%)
Upper Sacramento Valley	9,064	9,064	9,064	9,058	9,058
Lower Sacramento Valley and Delta	16,057	16,057	16,057	**15921 (-1%)**	**15921 (-1%)**
San Joaquin Valley and South Bay	4,373	4,373	4,373	4,369	4,369
Tulare Basin	0	0	0	0	0
Southern California	144	144	144	**125 (-13%)**	**125 (-13%)**
Refuge Deliveries (Historic) *	449	449	449	449	449
Upper Sacramento Valley	78	78	78	78	78
Lower Sacramento Valley and Delta	49	49	49	49	49
San Joaquin Valley and South Bay	301	301	301	301	301
Tulare Basin	21	21	21	21	21
Southern California	0	0	0	0	0
Refuge Deliveries (Full Level2/ Level4) *	544	544	544	544	544
Upper Sacramento Valley	102	102	102	102	102
Lower Sacramento Valley and Delta	72	72	72	72	72
San Joaquin Valley and South Bay	338	338	338	338	338
Tulare Basin	31	31	31	31	31
Southern California	0	0	0	0	0
Constrained Operations (Gates, Weirs, etc.) *	18,099	18,094	18,094	18,079	18,079
Upper Sacramento Valley	4	4	4	4	4
Lower Sacramento Valley and Delta	17,925	17,920	17,920	17,907	17,907
San Joaquin Valley and South Bay	0	0	0	0	0
Tulare Basin	170	170	170	**168 (-1%)**	**168 (-1%)**
Southern California	0	0	0	0	0

* Constraints vary by regulatory and conveyance scenario only.

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnel) H####: Historic Hydrology; C####: Warm-Dry Hydrology; ####G: No long-term GW overdraft					
	Original	**HHOEC**	**HHOECG**	**CHOEC**	**CHOECG**
Minimum in-stream flows *	27,685	27,667	27,667	27519 (-1%)	27519 (-1%)
Upper Sacramento Valley	9,064	9,064	9,064	9,061	9,061
Lower Sacramento Valley and Delta	14,066	14,048	14,048	**13943 (-1%)**	**13943 (-1%)**
San Joaquin Valley and South Bay	4,411	4,411	4,411	4,391	4,391
Tulare Basin	0	0	0	0	0
Southern California	144	144	144	**125 (-13%)**	**125 (-13%)**
Refuge Deliveries (Historic) *	449	449	449	449	449
Upper Sacramento Valley	78	78	78	78	78
Lower Sacramento Valley and Delta	49	49	49	49	49
San Joaquin Valley and South Bay	301	301	301	301	301
Tulare Basin	21	21	21	21	21
Southern California	0	0	0	0	0
Refuge Deliveries (Full Level2/ Level4) *	544	544	544	542 (-0.3%)	542 (-0.3%)
Upper Sacramento Valley	102	102	102	102	102
Lower Sacramento Valley and Delta	72	72	72	72	72
San Joaquin Valley and South Bay	338	338	338	**337 (-0.4%)**	**337 (-0.4%)**
Tulare Basin	31	31	31	31	31
Southern California	0	0	0	0	0
Constrained Operations (Gates, Weirs, etc.) *	13,950	13,950	13,950	13,929	13,929
Upper Sacramento Valley	19	19	19	19	19
Lower Sacramento Valley and Delta	13,761	13,761	13,761	13,750	13,750
San Joaquin Valley and South Bay	0	0	0	0	0
Tulare Basin	170	170	170	**160 (-6%)**	**160 (-6%)**
Southern California	0	0	0	0	0

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnel) H####: Historic Hydrology; C####: Warm-Dry Hydrology; ####G: No long-term GW overdraft					
	Original	**HHOIF**	**HHOIFG**	**CHOIF**	**CHOIFG**
Minimum in-stream flows *	30,070	30,070	30,070	29907 (-1%)	29907 (-1%)
Upper Sacramento Valley	9,185	9,185	9,185	9,180	9,180
Lower Sacramento Valley and Delta	16,425	16,425	16,425	**16303 (-1%)**	**16303 (-1%)**
San Joaquin Valley and South Bay	4,316	4,316	4,316	4,298	4,298
Tulare Basin	0	0	0	0	0
Southern California	144	144	144	**125 (-13%)**	**125 (-13%)**
Refuge Deliveries (Historic) *	449	449	449	449	449
Upper Sacramento Valley	78	78	78	78	78
Lower Sacramento Valley and Delta	49	49	49	49	49
San Joaquin Valley and South Bay	301	301	301	301	301
Tulare Basin	21	21	21	21	21
Southern California	0	0	0	0	0
Refuge Deliveries (Full Level2/ Level4) *	544	544	544	542 (-0.4%)	542 (-0.4%)
Upper Sacramento Valley	102	102	102	**101 (-1.1%)**	**101 (-1.1%)**
Lower Sacramento Valley and Delta	72	72	72	72	72
San Joaquin Valley and South Bay	338	338	338	**337 (-0.2%)**	**337 (-0.2%)**
Tulare Basin	31	31	31	31	31
Southern California	0	0	0	0	0
Constrained Operations (Gates, Weirs, etc.) *	17,031	17,030	17,030	17,009	17,009
Upper Sacramento Valley	4	4	4	4	4
Lower Sacramento Valley and Delta	16,857	16,855	16,855	16,844	16,844
San Joaquin Valley and South Bay	0	0	0	0	0
Tulare Basin	170	170	170	**161 (-5%)**	**161 (-5%)**
Southern California	0	0	0	0	0

* Constraints vary by regulatory and conveyance scenario only.

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) Results reported for historic hydrology with long-term GW overdraft, and varying regulatory and conveyance scenarios					
	Original	**HEREC**	**HERIF**	**HHOEC**	**HHOIF**
Local Depletions +	2,264	2,264	2,264	2,264	2,264
Upper Sacramento Valley	426	426	426	426	426
Lower Sacramento Valley and Delta	1,094	1,094	1,094	1,094	1,094
San Joaquin Valley and South Bay	81	81	81	81	81
Tulare Basin	662	662	662	662	662
Southern California	0	0	0	0	0
Local Accretions +	1,119	1,119	1,119	1,119	1,119
Upper Sacramento Valley	160	160	160	160	160
Lower Sacramento Valley and Delta	34	34	34	34	34
San Joaquin Valley and South Bay	450	450	450	450	450
Tulare Basin	476	476	476	476	476
Southern California	0	0	0	0	0

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) Results reported for historic hydrology with no long-term GW overdraft, and varying regulatory and conveyance scenarios					
	Original	**HERECG**	**HERIFG**	**HHOECG**	**HHOIFG**
Local Depletions +	2,264	2,264	2,264	2,264	2,264
Upper Sacramento Valley	426	426	426	426	426
Lower Sacramento Valley and Delta	1,094	1,094	1,094	1,094	1,094
San Joaquin Valley and South Bay	81	81	81	81	81
Tulare Basin	662	662	662	662	662
Southern California	0	0	0	0	0
Local Accretions +	1,119	1,119	1,119	1,119	1,119
Upper Sacramento Valley	160	160	160	160	160
Lower Sacramento Valley and Delta	34	34	34	34	34
San Joaquin Valley and South Bay	450	450	450	450	450
Tulare Basin	476	476	476	476	476
Southern California	0	0	0	0	0

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) Results reported for warm-dry hydrology with long-term GW overdraft, and varying regulatory and conveyance scenarios					
	Original	**CEREC**	**CERIF**	**CHOEC**	**CHOIF**
Local Depletions +	4,360	4245 (-3%)	4245 (-3%)	4165 (-4%)	4162 (-5%)
Upper Sacramento Valley	627	**625 (-0.4%)**	**625 (-0.4%)**	**626 (-0.2%)**	**625 (-0.4%)**
Lower Sacramento Valley and Delta	2,108	**2102 (-0.3%)**	**2102 (-0.3%)**	**2102 (-0.3%)**	**2101 (-0.3%)**
San Joaquin Valley and South Bay	464	**464 (-0.1%)**	**464 (-0.1%)**	**463 (-0.1%)**	**464 (-0.1%)**
Tulare Basin	1,161	**1055 (-9%)**	**1055 (-9%)**	**973 (-16%)**	**972 (-16%)**
Southern California	0	0	0	0	0
Local Accretions +	808	808	808	808	808
Upper Sacramento Valley	160	160	160	160	160
Lower Sacramento Valley and Delta	34	34	34	34	34
San Joaquin Valley and South Bay	260	260	260	260	260
Tulare Basin	354	354	354	354	354
Southern California	0	0	0	0	0

CALVIN Constraints by Type and Region (TAF/yr, Long-Term 82 Year Average) Results reported for warm-dry hydrology with no long-term GW overdraft, and varying regulatory and conveyance scenarios					
	Original	**CERECG**	**CERIFG**	**CHOECG**	**CHOIFG**
Local Depletions +	4,360	4245 (-3%)	4245 (-3%)	4165 (-4%)	4162 (-5%)
Upper Sacramento Valley	627	**625 (-0.4%)**	**625 (-0.4%)**	**626 (-0.2%)**	**625 (-0.4%)**
Lower Sacramento Valley and Delta	2,108	**2102 (-0.3%)**	**2102 (-0.3%)**	**2102 (-0.3%)**	**2101 (-0.3%)**
San Joaquin Valley and South Bay	464	**464 (-0.1%)**	**464 (-0.1%)**	**463 (-0.1%)**	**464 (-0.1%)**
Tulare Basin	1,161	**1055 (-9%)**	**1055 (-9%)**	**973 (-16%)**	**972 (-16%)**
Southern California	0	0	0	0	0
Local Accretions +	808	808	808	808	808
Upper Sacramento Valley	160	160	160	160	160
Lower Sacramento Valley and Delta	34	34	34	34	34
San Joaquin Valley and South Bay	260	260	260	260	260
Tulare Basin	354	354	354	354	354
Southern California	0	0	0	0	0

+ Base constraints vary by hydrology only.

APPENDIX 10

CALVIN model results

a. Deliveries to agricultural and urban nodes assuming optimized operations

b. Deliveries to refuge nodes assuming optimized operations

c. Opportunity cost of refuge deliveries

d. Opportunity cost of expanding surface water conveyance

e. Opportunity cost of expanding groundwater conveyance

f. Source of additional refuge water supplies

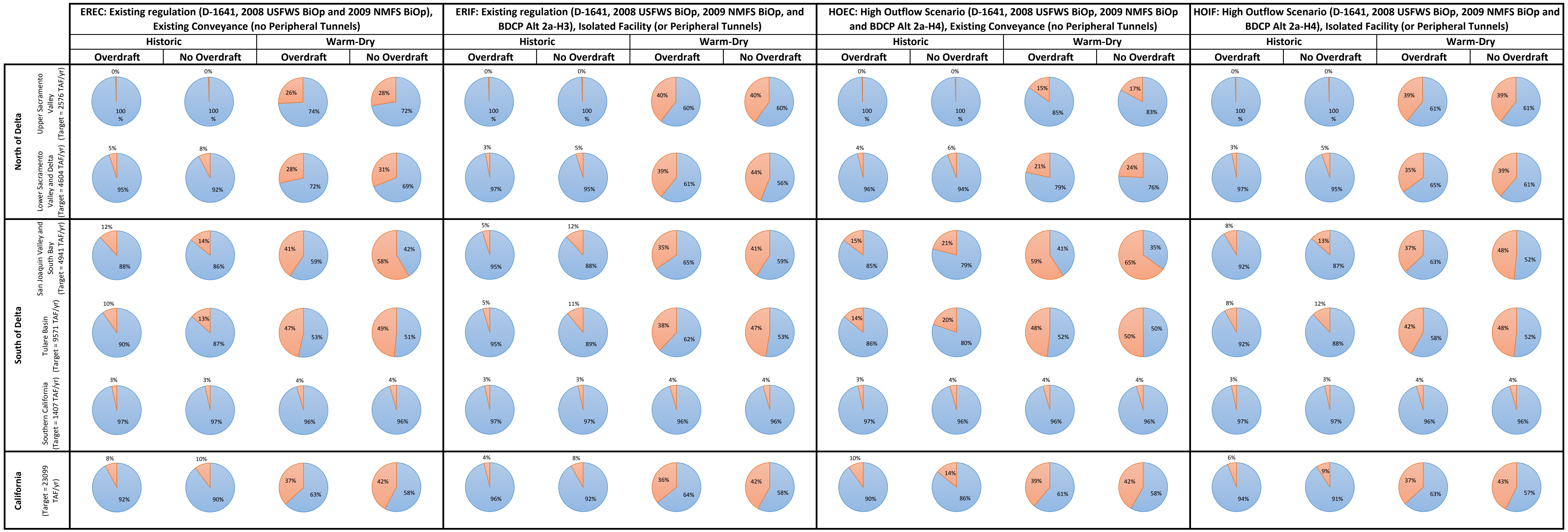
g. Water trading opportunities and associated costs

APPENDIX 10a

Deliveries to agricultural and urban nodes assuming optimized operations

Target versus Actual Water Deliveries for Agricultural Use (TAF/yr)

Delivery Scarcity



Upper Sacramento Valley	**Target**	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576	2,576
	Delivery	2,565	2,565	1,909	1,864	2,564	2,564	1,558	1,539	2,567	2,566	2,184	2,134	2,566	2,566	1,568	1,559
	Scarcity	11	11	668	712	13	13	1,019	1,037	9	10	393	442	11	11	1,009	1,017
Lower Sacramento Valley and Delta	**Target**	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604	4,604
	Delivery	4,366	4,247	3,294	3,174	4,471	4,386	2,798	2,580	4,434	4,330	3,617	3,493	4,466	4,357	2,994	2,831
	Scarcity	238	357	1,310	1,430	133	218	1,806	2,025	170	274	987	1,111	138	247	1,610	1,774
San Joaquin Valley and South Bay	**Target**	4,941	4,940	4,940	4,940	4,941	4,940	4,940	4,940	4,940	4,940	4,940	4,941	4,940	4,940	4,941	4,940
	Delivery	4,358	4,245	2,927	2,053	4,700	4,356	3,228	2,915	4,213	3,902	2,023	1,728	4,521	4,278	3,113	2,550
	Scarcity	583	695	2,013	2,888	241	584	1,712	2,026	727	1,038	2,918	3,213	420	662	1,828	2,390
Tulare Basin	**Target**	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571	9,571
	Delivery	8,647	8,282	5,106	4,916	9,135	8,519	5,915	5,046	8,235	7,683	4,956	4,778	8,809	8,424	5,574	4,959
	Scarcity	924	1,289	4,466	4,655	437	1,052	3,656	4,526	1,336	1,888	4,615	4,794	762	1,147	3,997	4,612
Souther California	**Target**	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407
	Delivery	1,360	1,360	1,344	1,344	1,360	1,360	1,345	1,344	1,360	1,345	1,344	1,344	1,360	1,360	1,344	1,344
	Scarcity	47	47	63	63	47	47	62	63	47	62	63	63	47	47	63	63
California	**Delivery**	21,296	20,700	14,579	13,351	22,229	21,185	14,844	13,423	20,810	19,827	14,123	13,477	21,722	20,985	14,592	13,243
	Scarcity	1,803	2,399	8,520	9,747	870	1,914	8,255	9,676	2,289	3,271	8,976	9,622	1,376	2,113	8,507	9,856
	Target	23,099	23,099	23,098	23,099	23,099	23,099	23,099	23,098	23,098	23,098	23,099	23,099	23,098	23,099	23,099	23,099

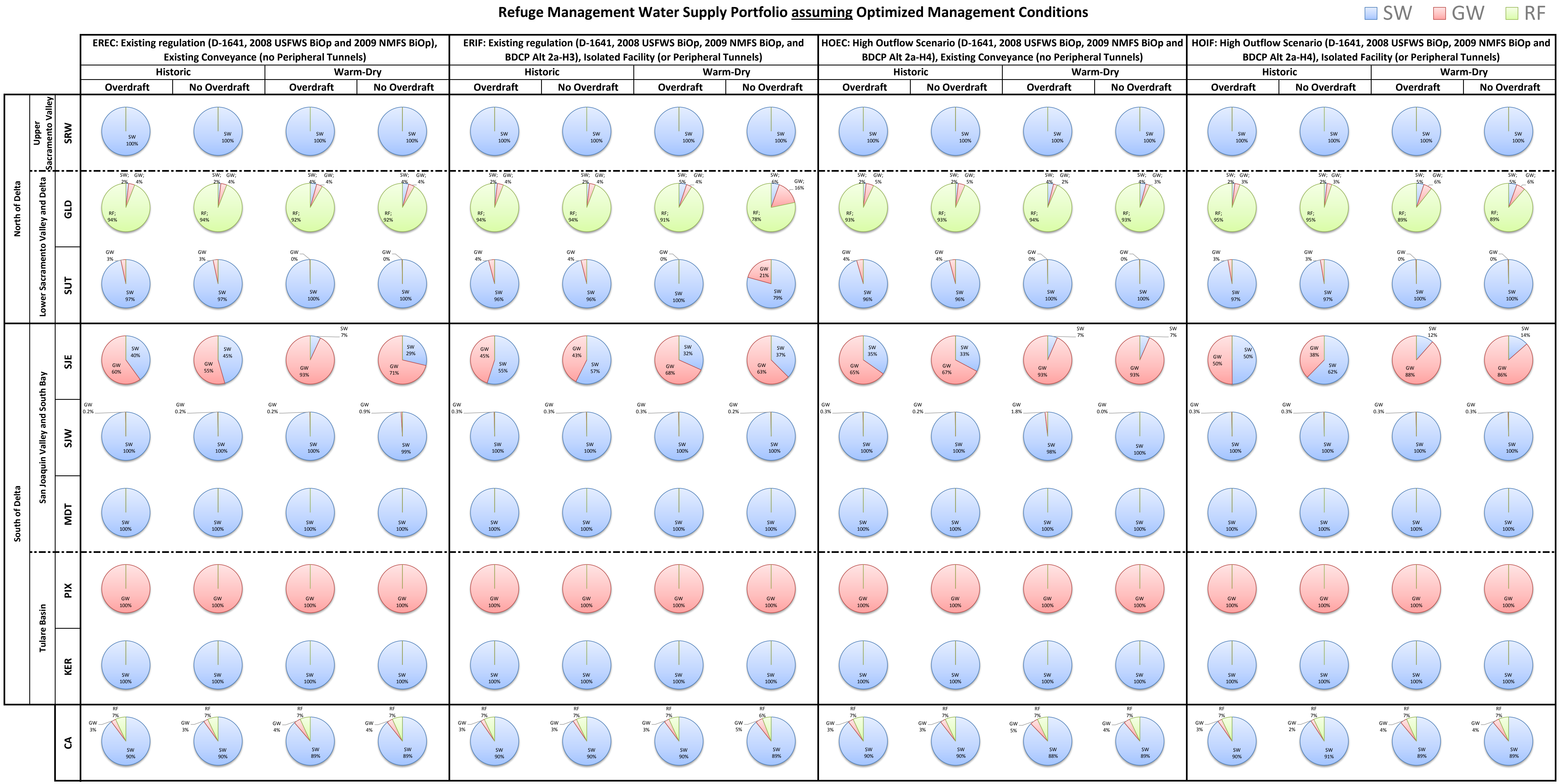
Target versus Actual Water Deliveries for Urban Use (TAF/yr)

Upper Sacramento Valley	Target	395	395	395	395	395	395	395	395	395	395	395	395	395	395	395	395
	Delivery	395	395	395	395	395	395	395	395	395	395	395	395	395	395	395	395
	Scarcity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lower Sacramento Valley and Delta	Target	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900
	Delivery	1,899	1,899	1,869	1,856	1,899	1,899	1,856	1,845	1,899	1,899	1,878	1,861	1,899	1,899	1,866	1,853
	Scarcity	1	1	31	43	1	1	44	55	1	1	22	39	1	1	34	47
San Joaquin Valley and South Bay	Target	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702	1,702
	Delivery	1,702	1,702	1,649	1,628	1,702	1,702	1,672	1,648	1,702	1,700	1,639	1,592	1,702	1,702	1,667	1,646
	Scarcity	0	0	53	74	0	0	30	54	0	3	63	110	0	0	35	56
Tulare Basin	Target	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541	1,541
	Delivery	1,535	1,535	1,497	1,477	1,535	1,535	1,497	1,494	1,535	1,519	1,497	1,472	1,535	1,535	1,497	1,497
	Scarcity	6	6	44	64	6	6	44	47	7	22	45	69	6	6	44	45
Souther California	Target	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840	6,840
	Delivery	6,631	6,491	6,358	6,357	6,715	6,624	6,366	6,359	6,473	6,395	6,355	6,235	6,682	6,519	6,362	6,358
	Scarcity	209	349	481	483	125	216	474	481	366	445	485	605	158	321	478	482
California	Delivery	12,162	12,022	11,769	11,714	12,246	12,155	11,786	11,740	12,004	11,907	11,764	11,555	12,213	12,050	11,787	11,749
	Scarcity	216	356	609	664	132	223	592	638	374	471	615	823	165	328	591	629
	Target	12,378	12,378	12,378	12,378	12,378	12,378	12,378	12,378	12,378	12,378	12,378	12,379	12,378	12,378	12,378	12,378

APPENDIX 10b

Deliveries to refuge nodes assuming optimized operations

Refuge Management Water Supply Portfolio <u>assuming</u> Optimized Management Conditions



Optimizted Water Supply Portfolio for Historic CVPIA Refuge Deliveries (TAF/yr, Long-Term 82 Year Average)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8
SW	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*	*77.8*
GW	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8
SW	*15.3*	*15.3*	*15.8*	*15.8*	*15.2*	*15.2*	*15.8*	*12.6*	*15.1*	*15.2*	*15.8*	*15.8*	*15.4*	*15.5*	*15.8*	*15.8*
GW	*0.5*	*0.5*	*0.0*	*0.0*	*0.6*	*0.6*	*0.0*	*3.3*	*0.7*	*0.6*	*0.0*	*0.0*	*0.4*	*0.4*	*0.1*	*0.1*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Gray Lodge Wildlife Area (GLD)	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4
SW	*0.6*	*0.6*	*1.4*	*1.4*	*0.6*	*0.6*	*1.7*	*1.8*	*0.6*	*0.6*	*1.3*	*1.4*	*0.6*	*0.6*	*1.7*	*1.8*
GW	*1.4*	*1.3*	*1.3*	*1.3*	*1.4*	*1.3*	*1.2*	*5.5*	*1.7*	*1.5*	*0.8*	*0.9*	*1.2*	*1.1*	*1.9*	*2.0*
Ag Return Flows	*31.4*	*31.5*	*30.7*	*30.7*	*31.4*	*31.5*	*30.5*	*26.3*	*31.1*	*31.3*	*31.3*	*31.2*	*31.6*	*31.7*	*29.9*	*29.6*
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2
SW	*7.4*	*8.3*	*1.3*	*5.3*	*10.1*	*10.5*	*5.8*	*6.9*	*6.4*	*6.0*	*1.2*	*1.2*	*9.1*	*11.5*	*2.1*	*2.5*
GW	*11.0*	*10.0*	*17.0*	*13.1*	*8.3*	*7.8*	*12.5*	*11.5*	*12.0*	*12.4*	*17.0*	*17.0*	*9.2*	*6.9*	*16.1*	*15.8*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
West of San Joaquin River (SJE)	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4	256.4
SW	*255.8*	*255.9*	*255.8*	*254.1*	*255.6*	*255.7*	*255.8*	*255.8*	*255.7*	*255.9*	*251.8*	*256.4*	*255.7*	*255.7*	*255.6*	*255.6*
GW	*0.6*	*0.6*	*0.6*	*2.3*	*0.8*	*0.7*	*0.7*	*0.6*	*0.7*	*0.5*	*4.6*	*0.0*	*0.7*	*0.7*	*0.9*	*0.9*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Mendota Wildlife Area (MDT)	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
SW	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*	*26.7*
GW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ag Return Flows	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
SW (FKC Deliveries)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
GW	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Kern National Wildlife Refuge (KER)	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
SW	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*	*19.7*
GW	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Statewide																
Statewide	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0	449.0
SW	*403.2*	*404.3*	*398.5*	*400.8*	*405.7*	*406.3*	*403.3*	*401.2*	*402.0*	*401.9*	*394.3*	*399.0*	*405.0*	*407.4*	*399.3*	*399.9*
GW	*14.3*	*13.2*	*19.8*	*17.5*	*11.8*	*11.2*	*15.2*	*21.5*	*15.9*	*15.8*	*23.4*	*18.8*	*12.3*	*9.9*	*19.8*	*19.5*
Ag Return Flows	*31.4*	*31.5*	*30.7*	*30.7*	*31.4*	*31.5*	*30.5*	*26.3*	*31.1*	*31.3*	*31.3*	*31.2*	*31.6*	*31.7*	*29.9*	*29.6*

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

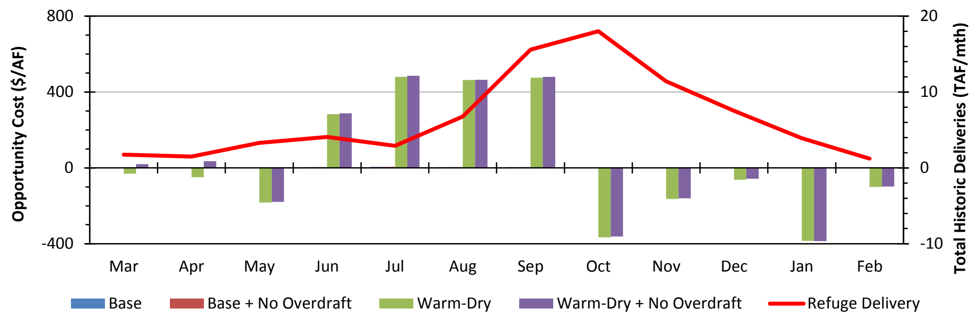
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

APPENDIX 10c

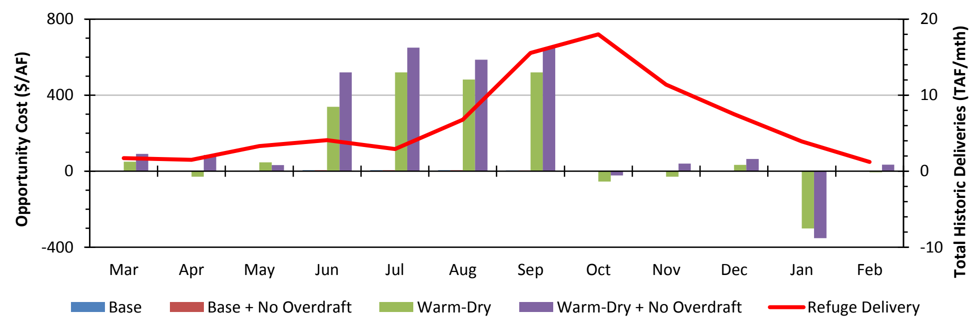
Opportunity cost of refuge deliveries

Opportunity Cost of Refuge Deliveries to SRW

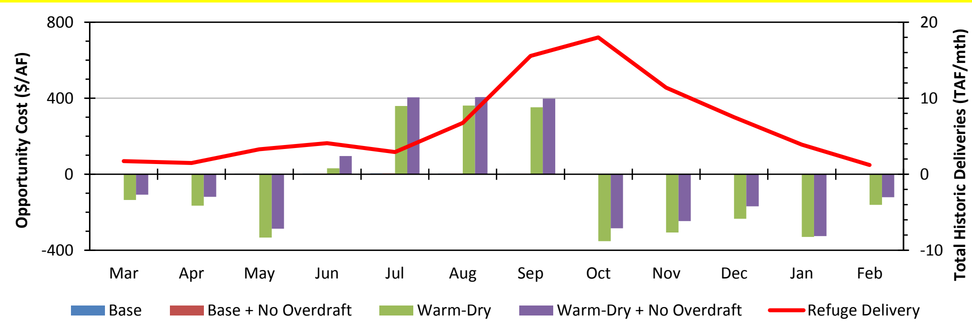
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



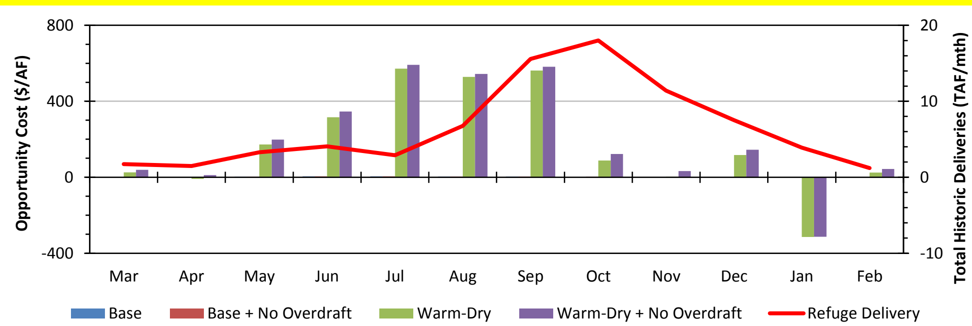
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

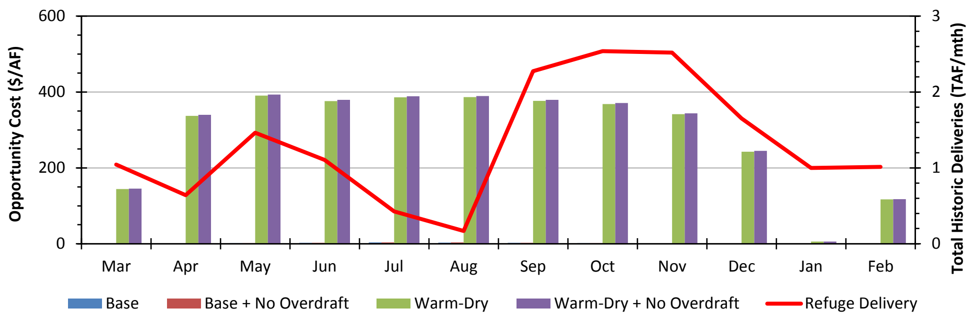
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

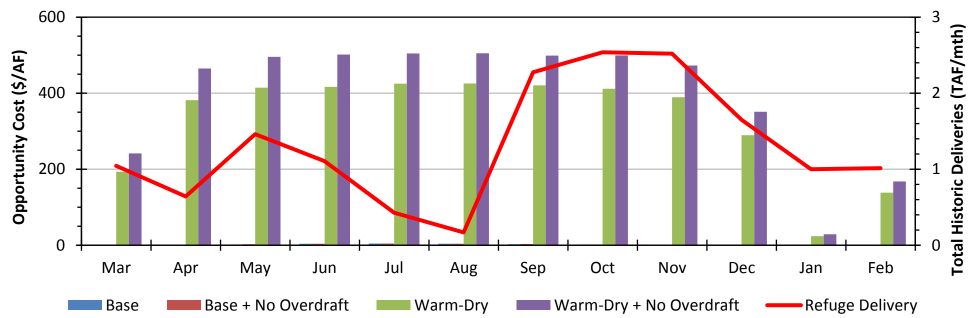
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to SUT

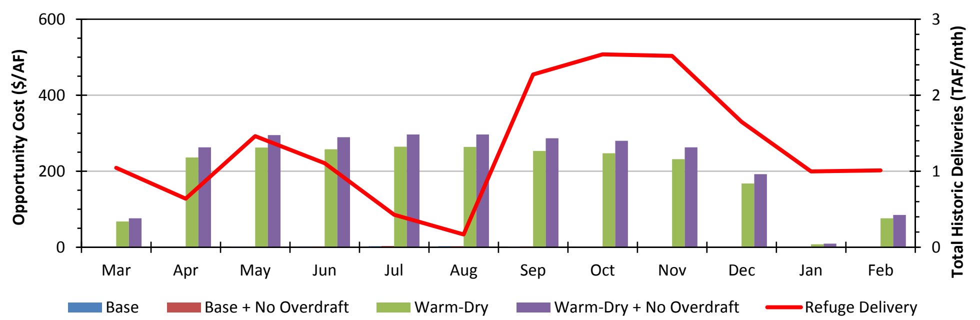
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



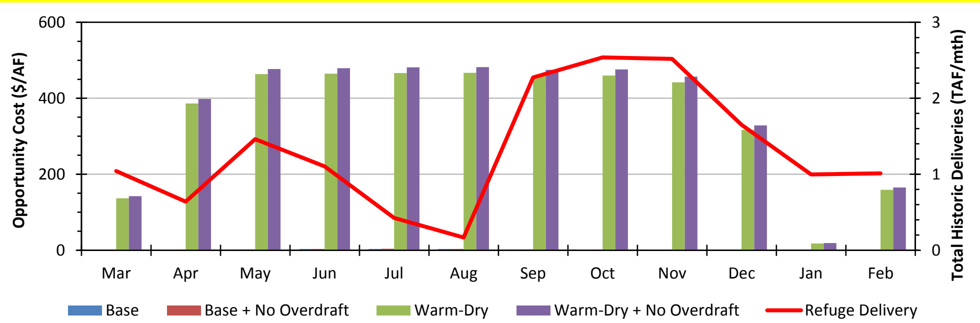
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

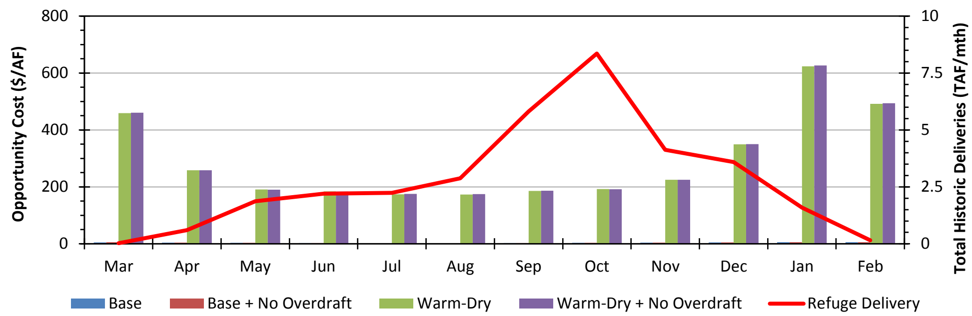
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

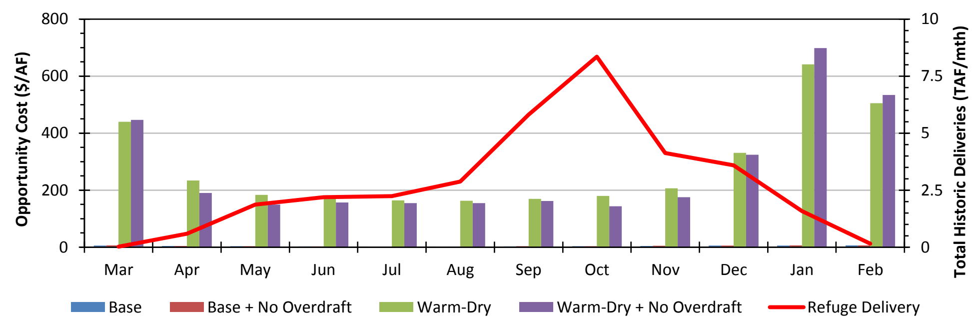
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to GLD

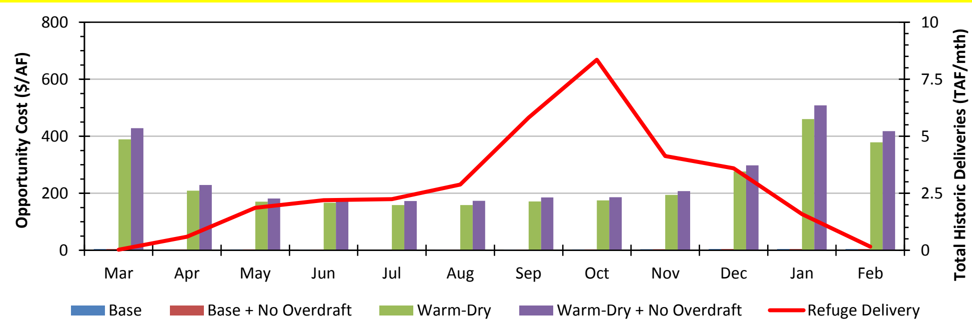
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



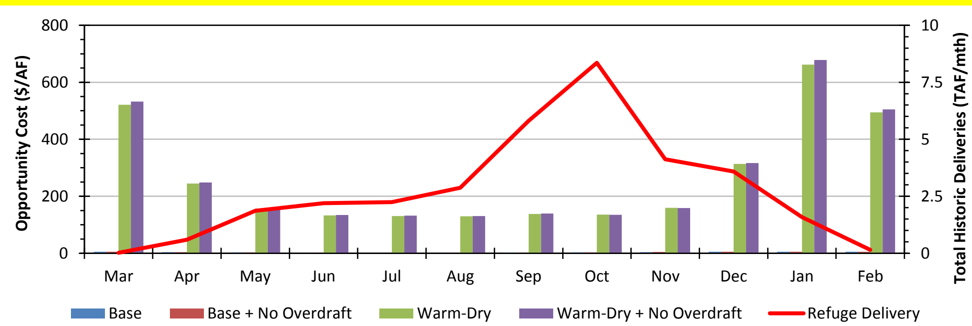
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



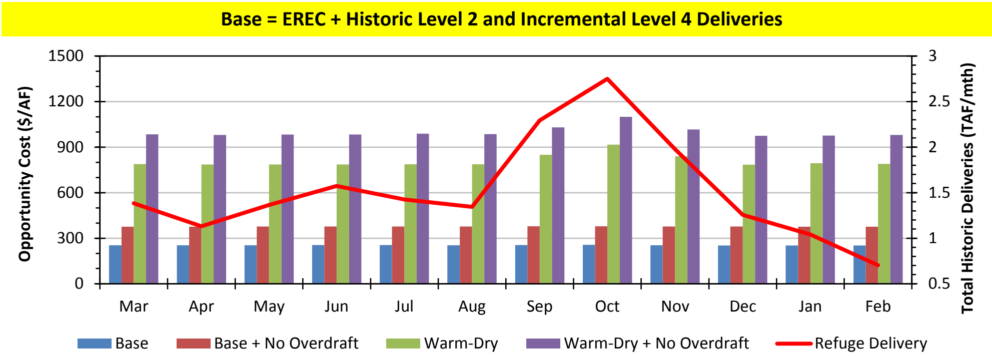
EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

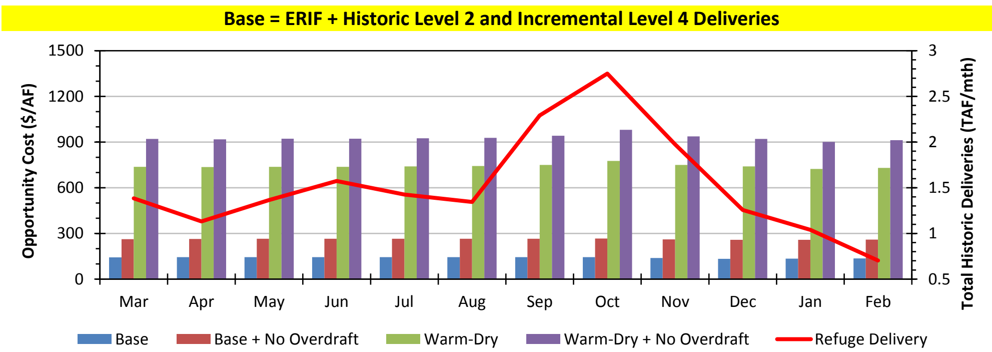
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

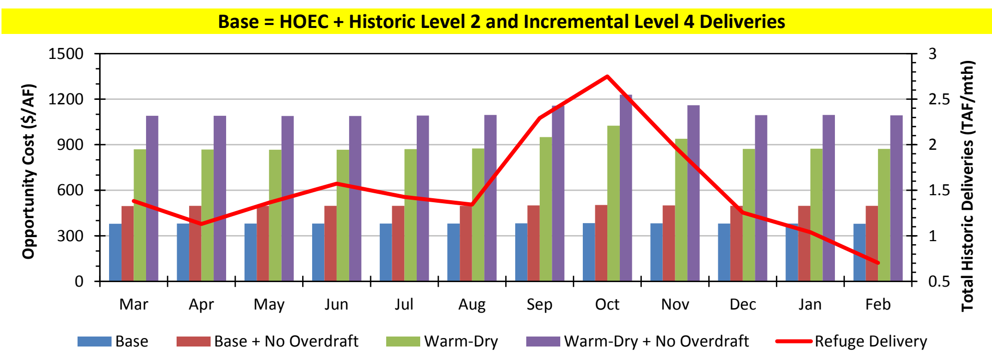
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

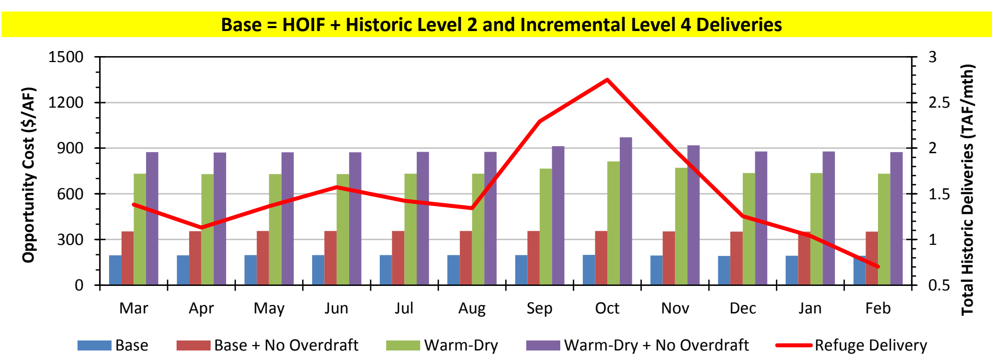
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to SJE









EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

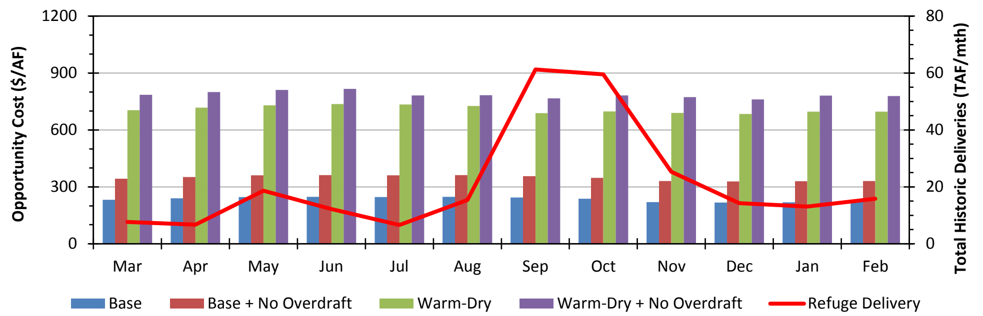
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

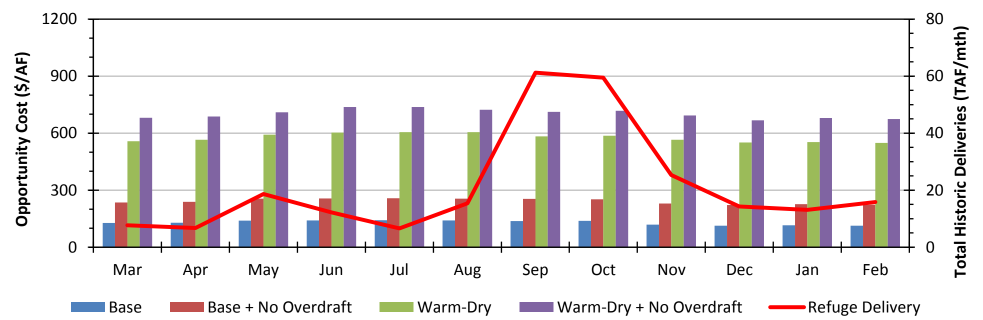
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to SJW

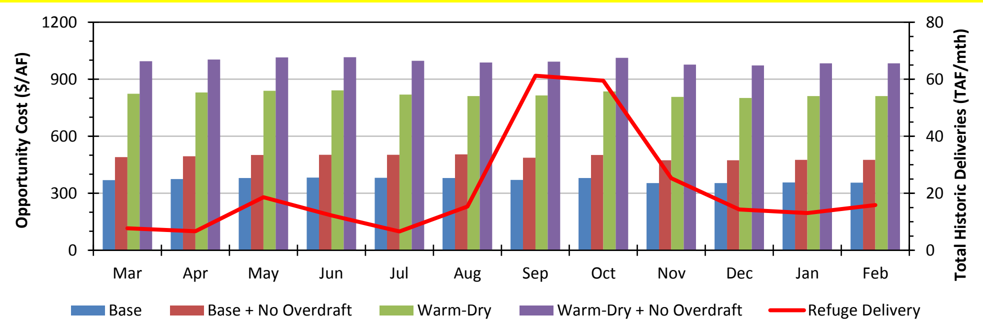
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



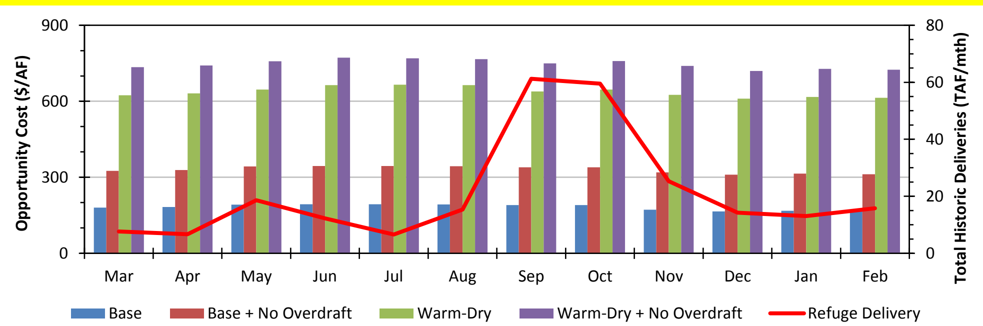
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



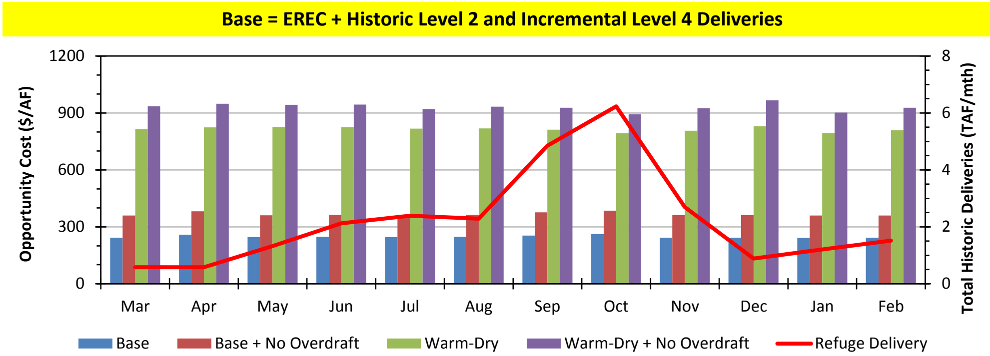
EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

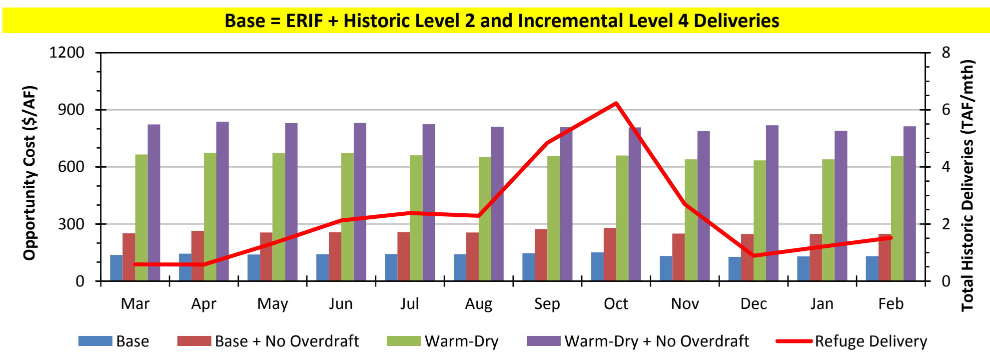
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

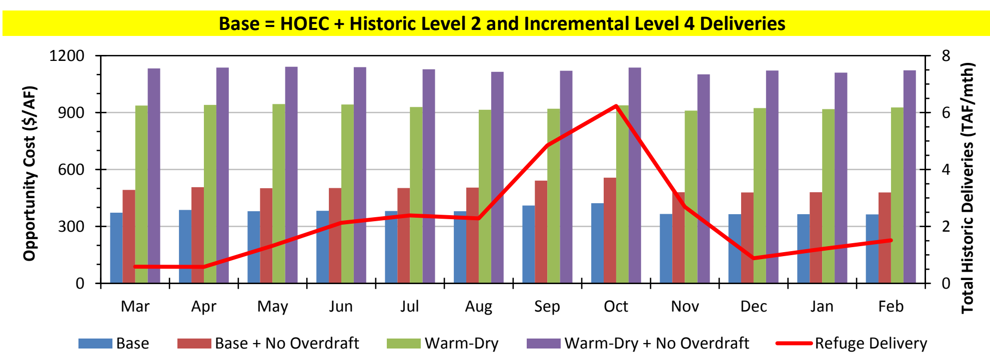
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

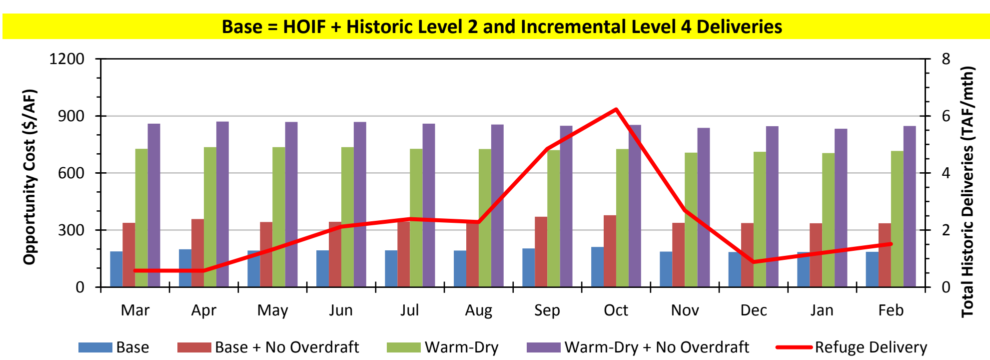
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to MDT









EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

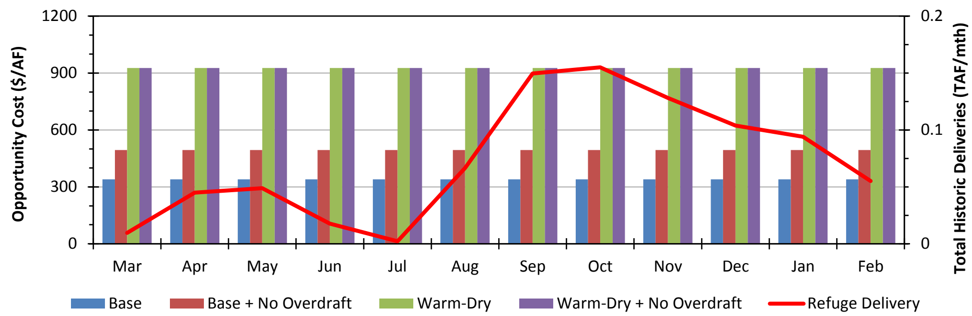
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

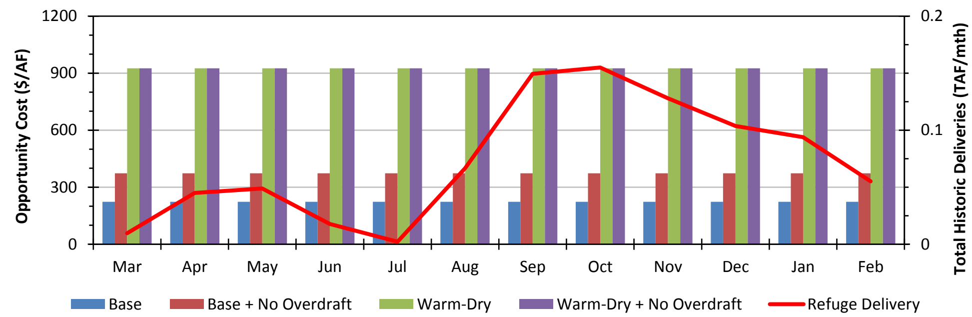
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to PIX

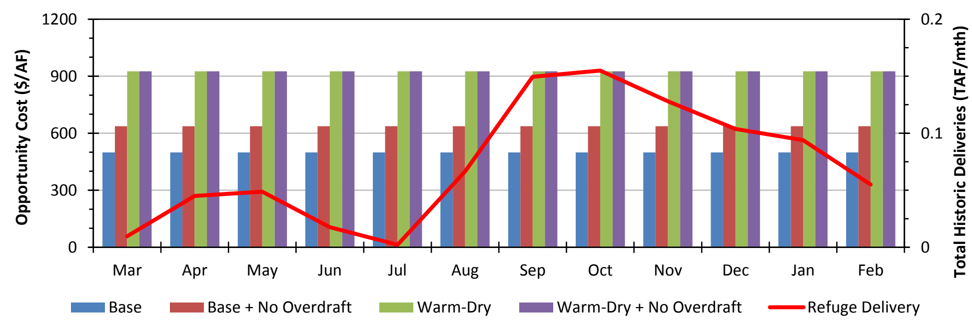
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



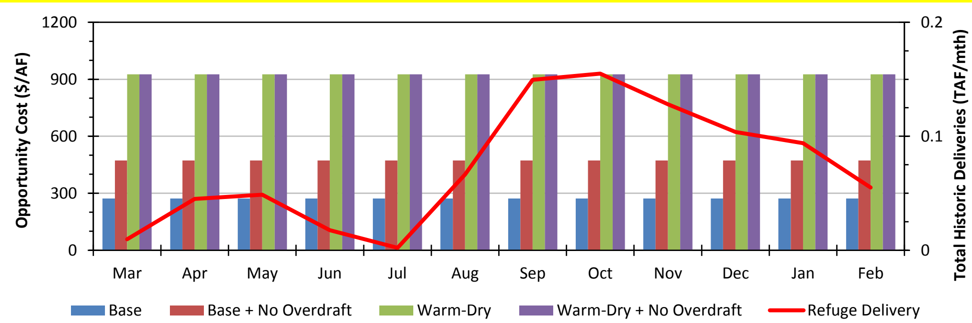
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

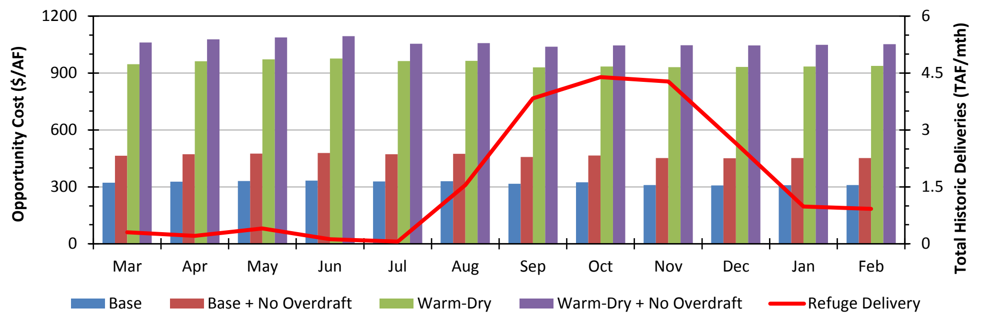
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

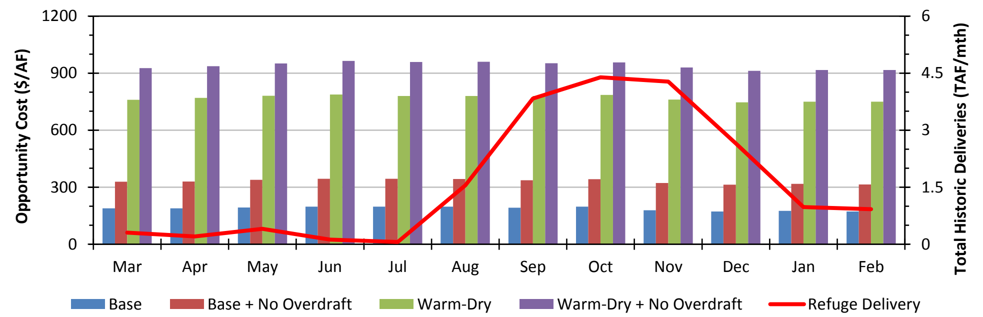
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Refuge Deliveries to KER

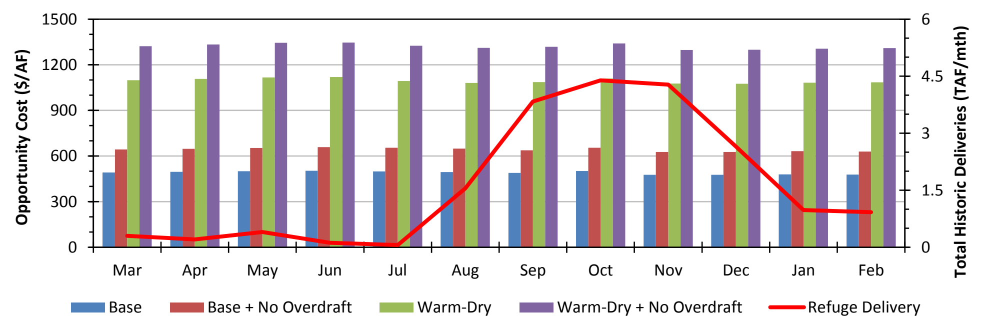
Base = EREC + Historic Level 2 and Incremental Level 4 Deliveries



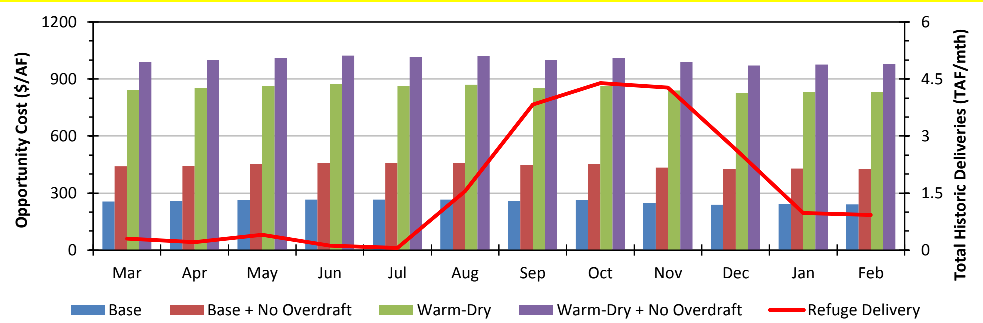
Base = ERIF + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOEC + Historic Level 2 and Incremental Level 4 Deliveries



Base = HOIF + Historic Level 2 and Incremental Level 4 Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

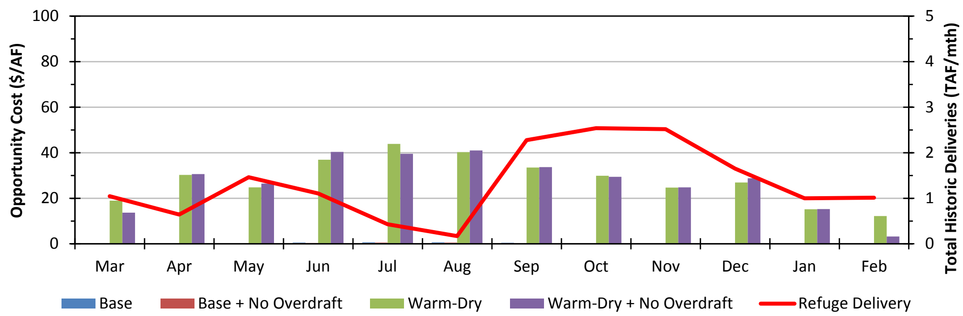
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

APPENDIX 10d

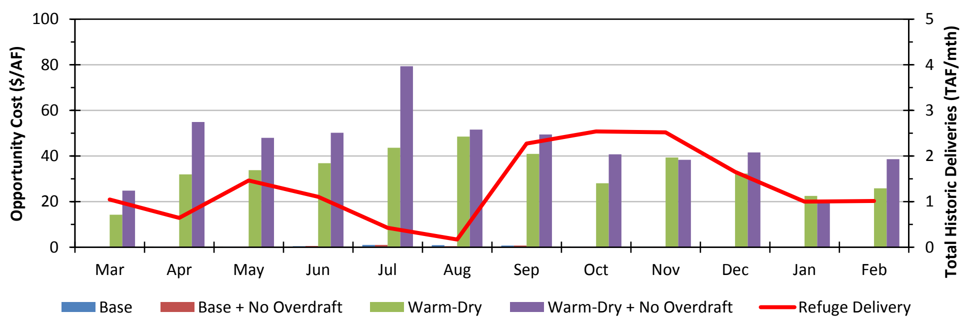
Opportunity cost of expanding surface water conveyance

Opportunity Cost of Expanding SEWD Deliveries to SUT

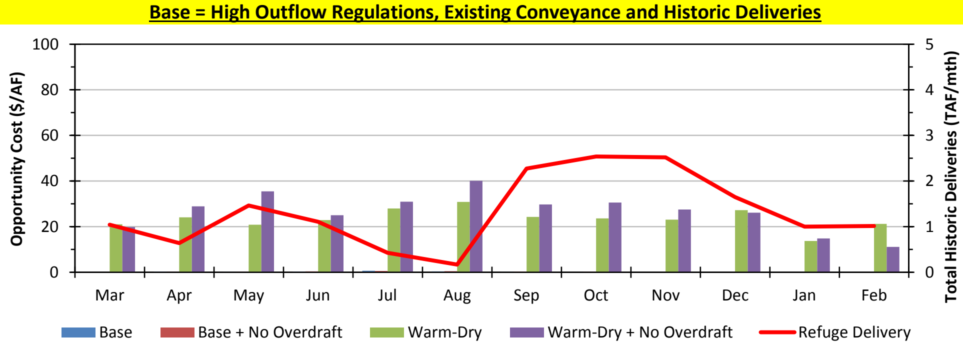
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



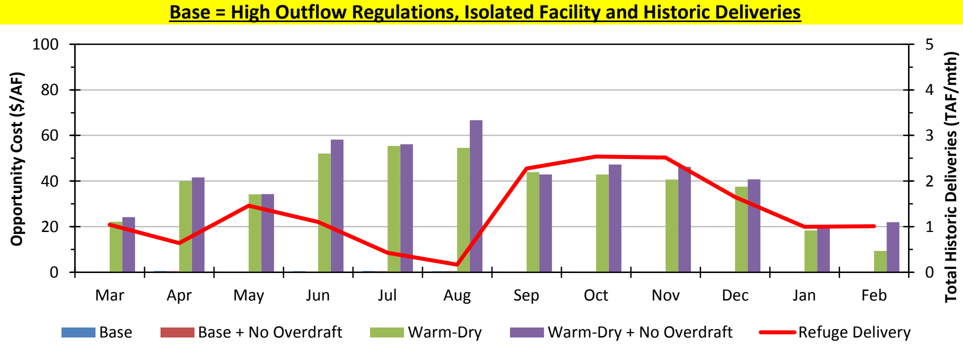
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

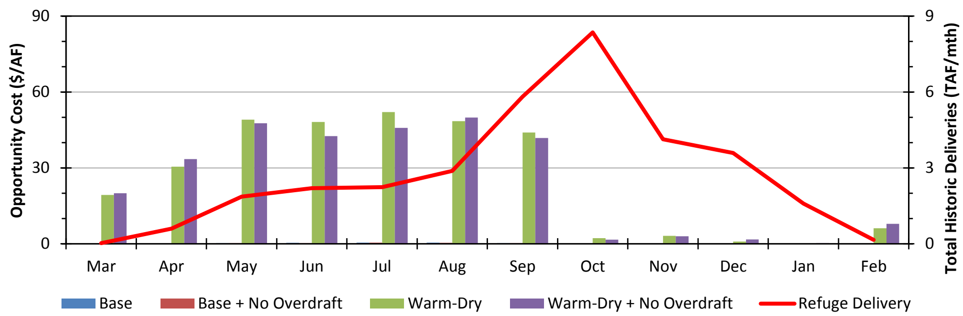
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

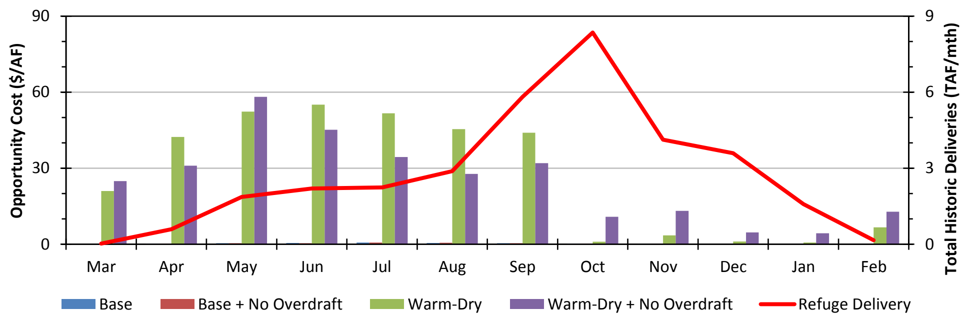
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding SW Deliveries to GLD

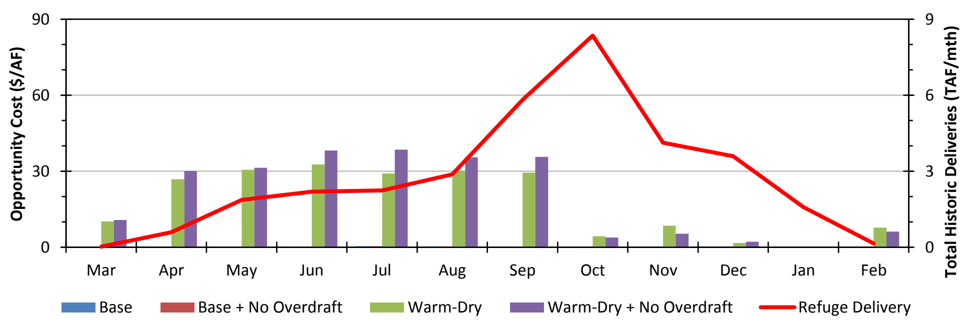
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



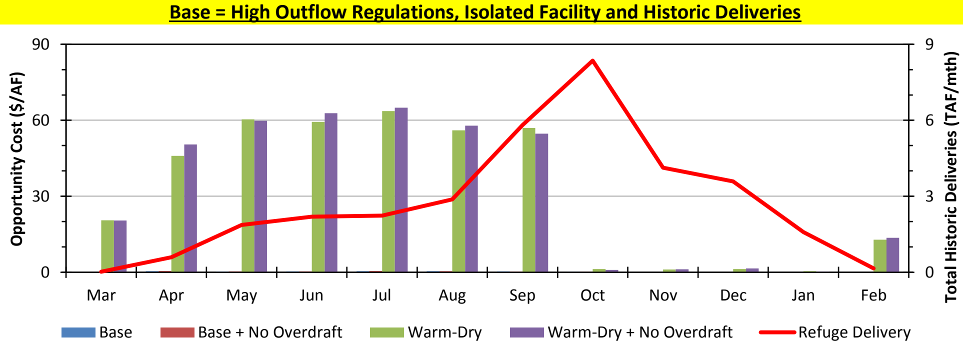
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

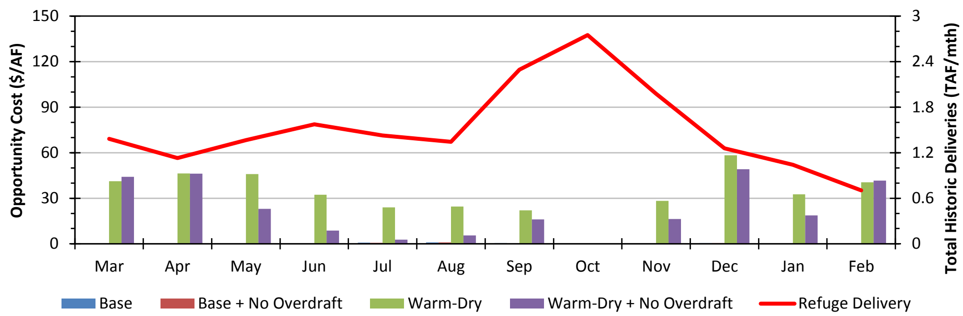
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

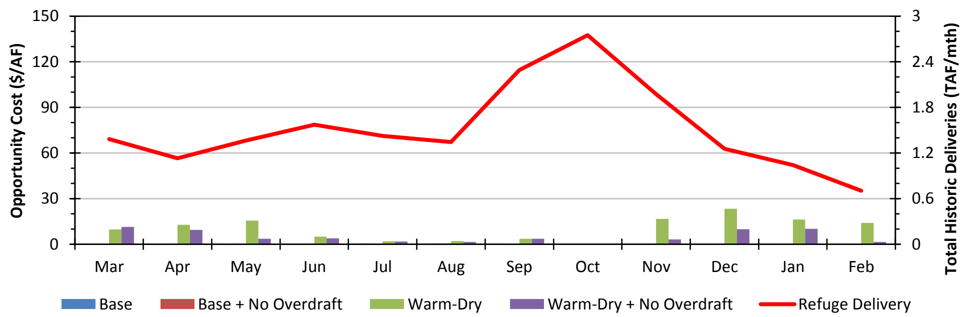
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding SW Deliveries to SJE

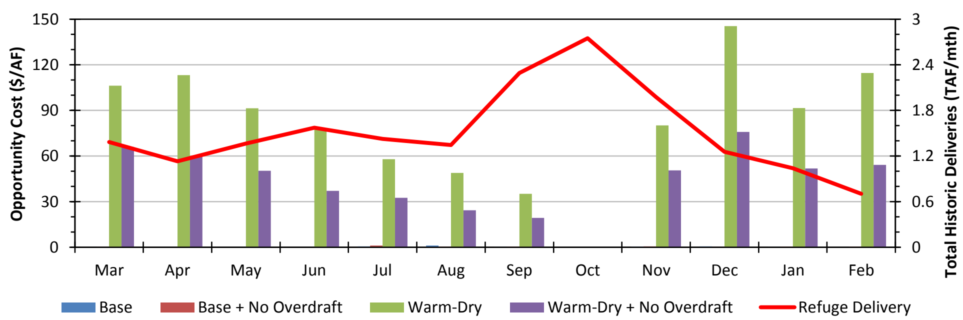
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



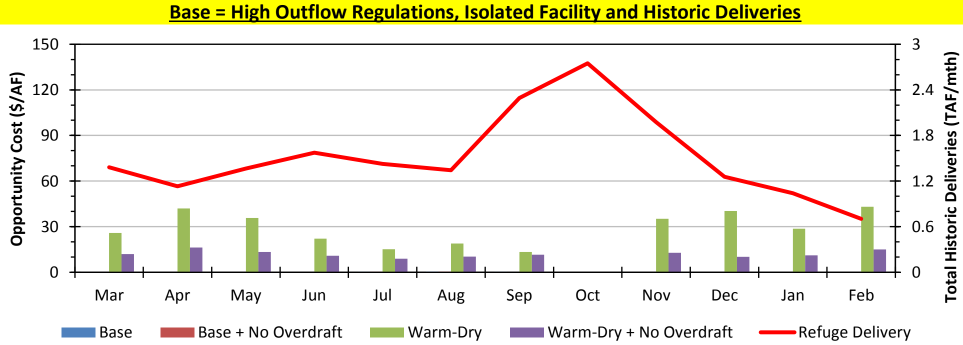
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

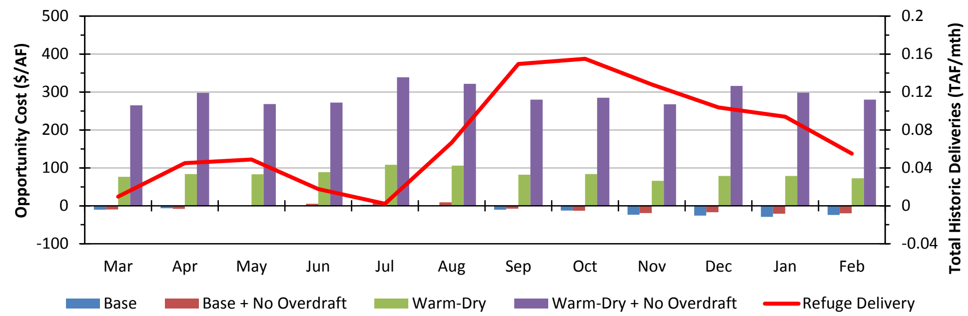
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

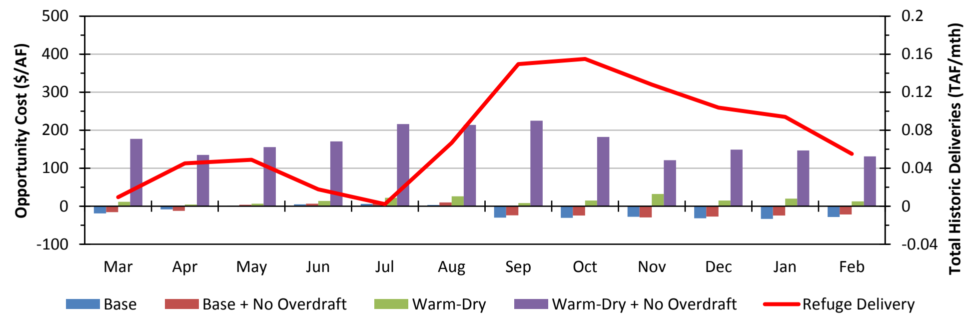
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding SW Deliveries to PIX

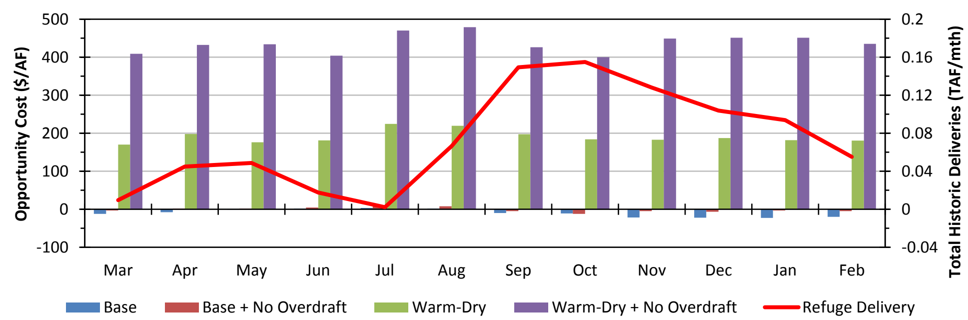
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



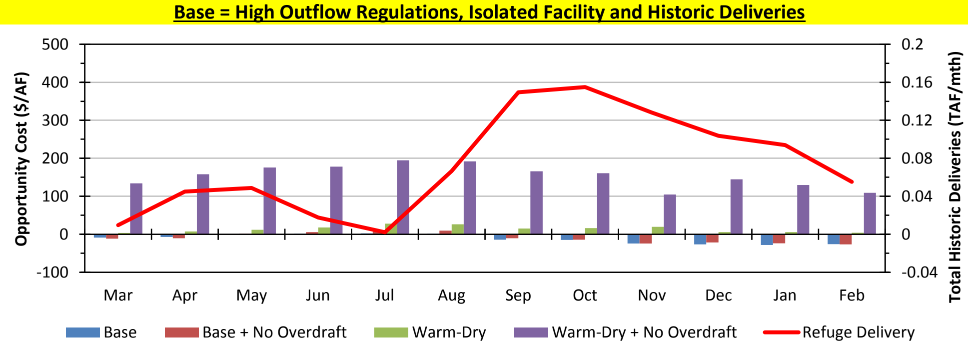
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

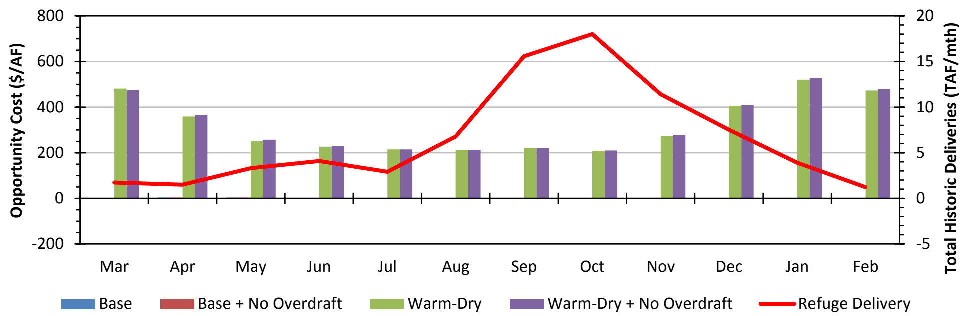
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

APPENDIX 10e

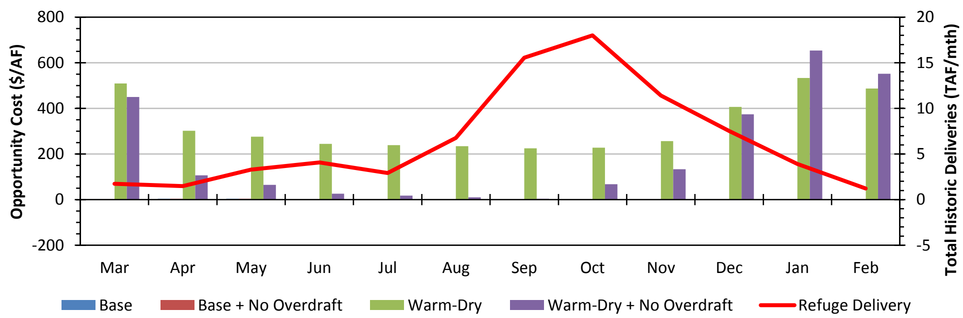
Opportunity cost of expanding groundwater conveyance

Opportunity Cost of Expanding GW Deliveries to SRW

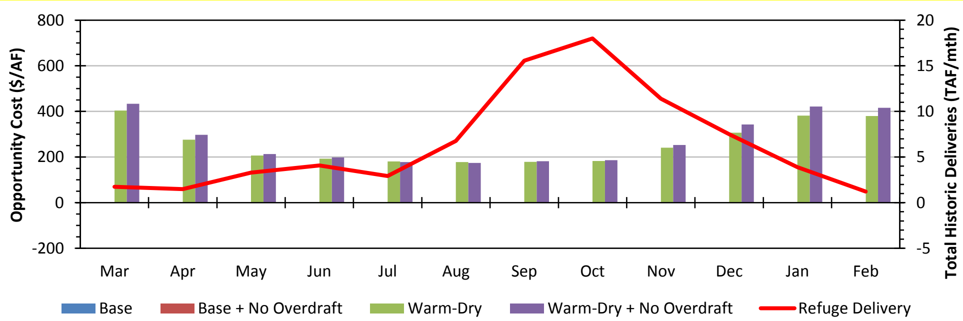
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



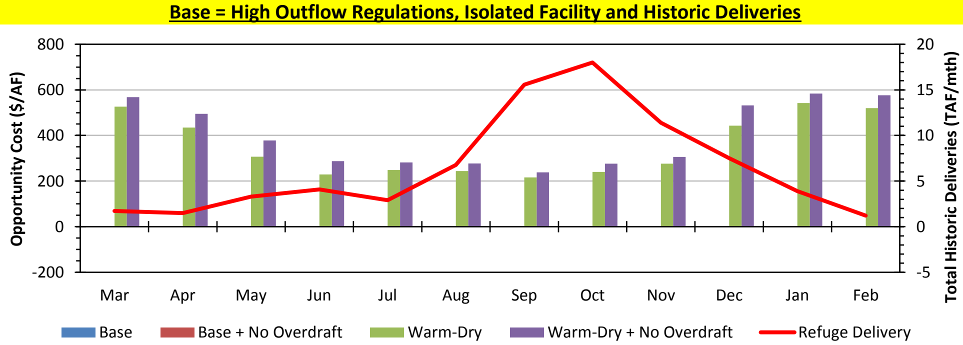
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

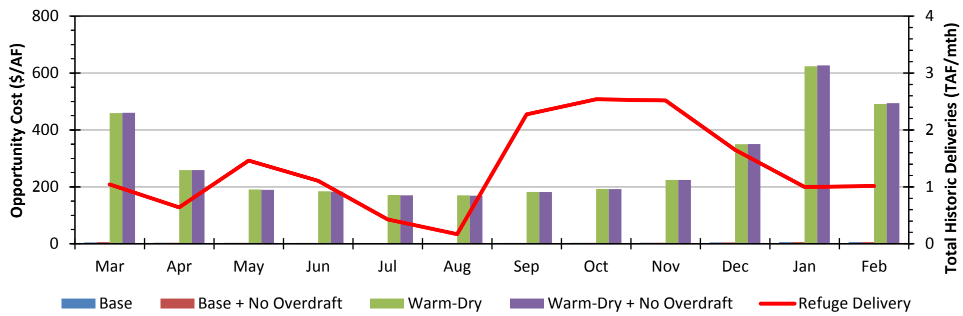
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

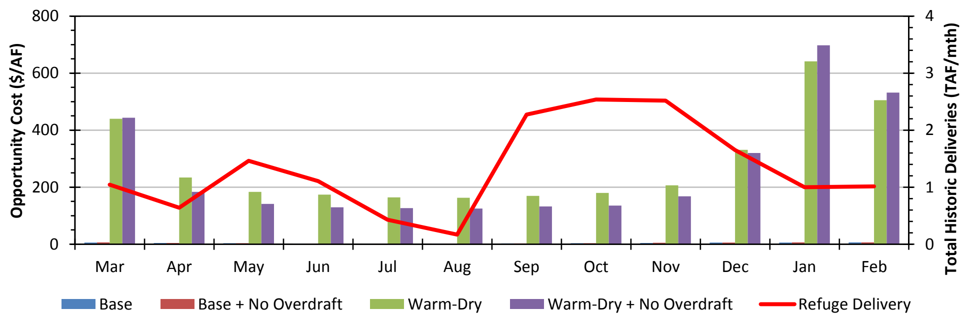
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding GW Deliveries to SUT

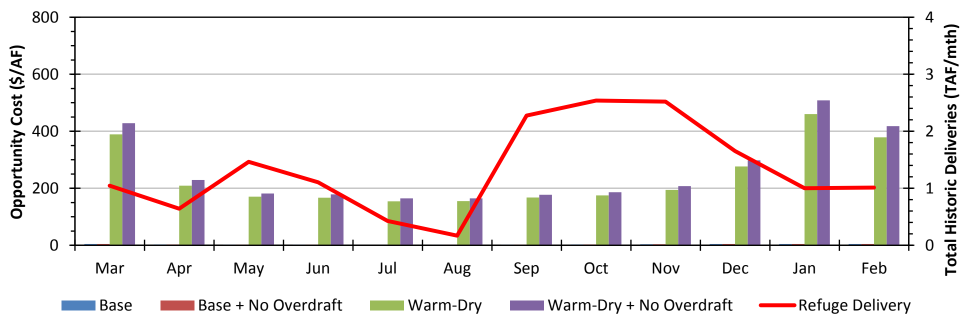
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



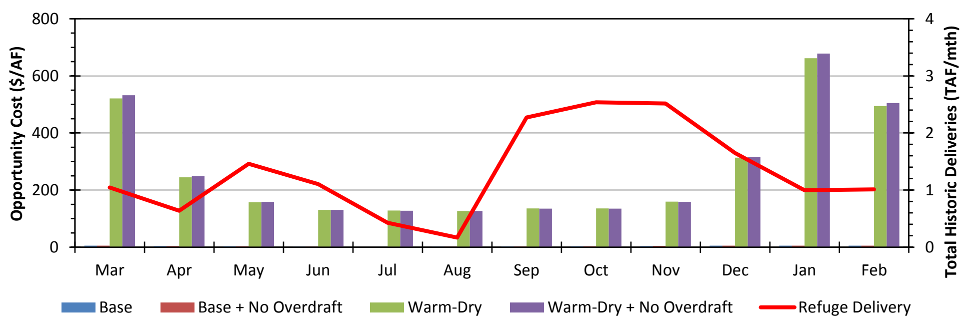
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

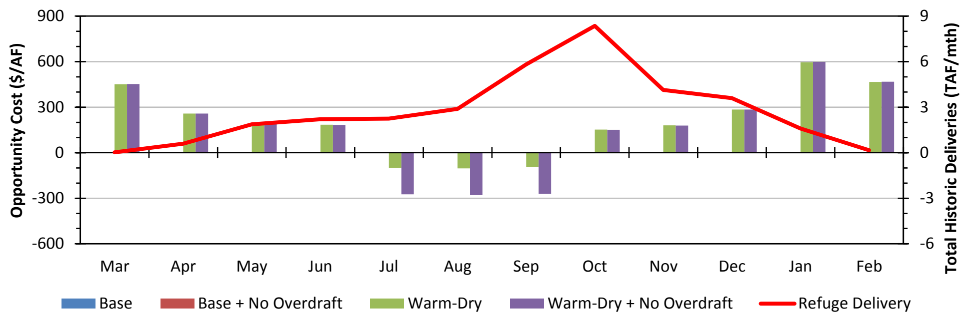
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

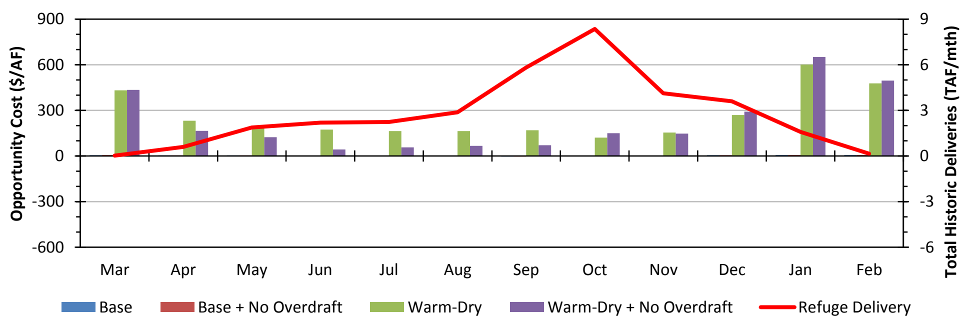
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding GW Deliveries to GLD

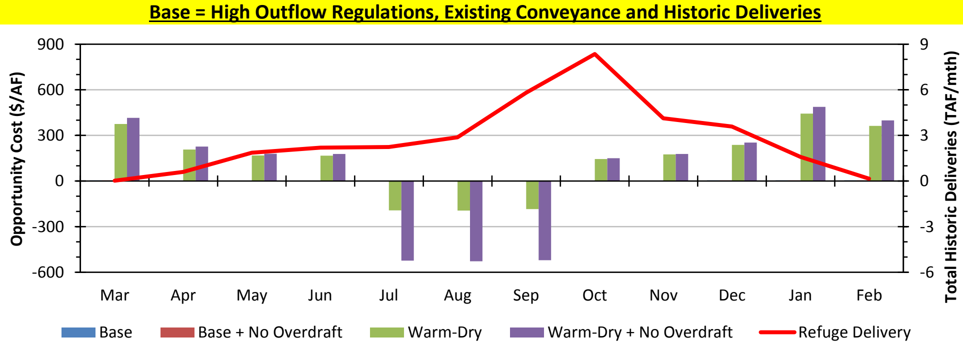
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



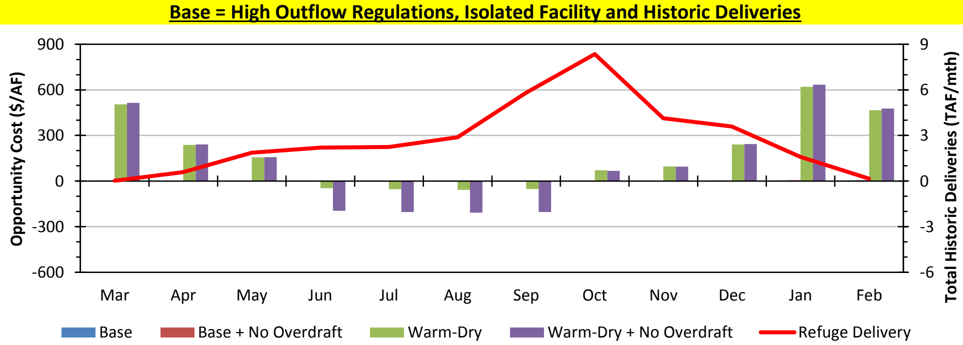
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

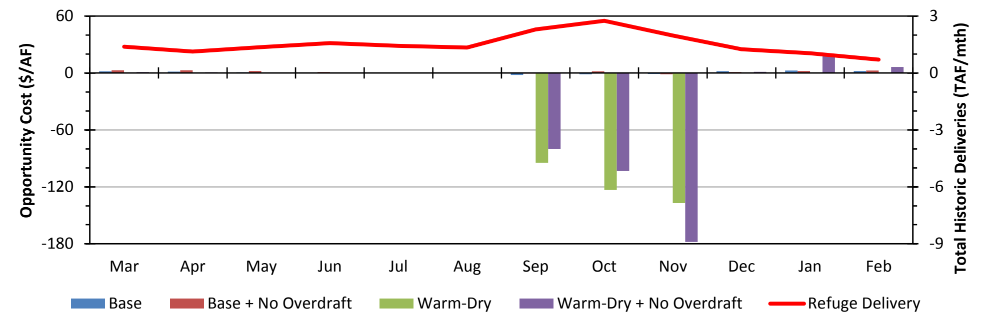
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

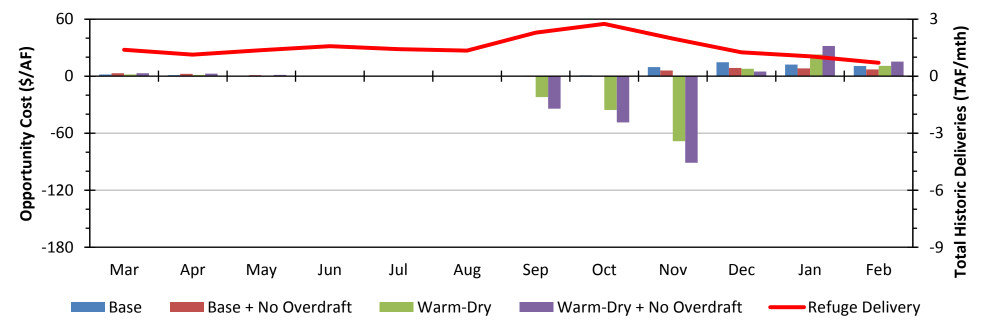
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding GW Deliveries to SJE

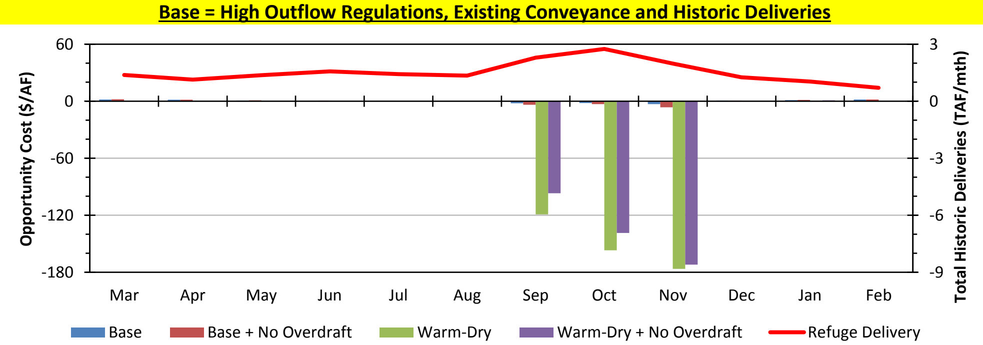
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



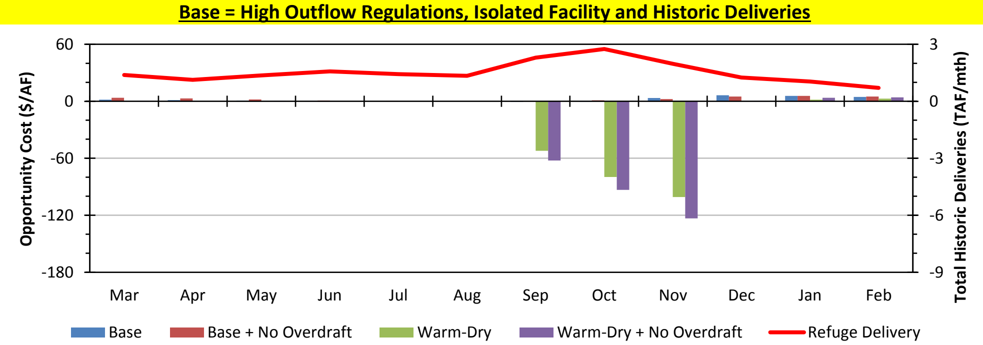
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

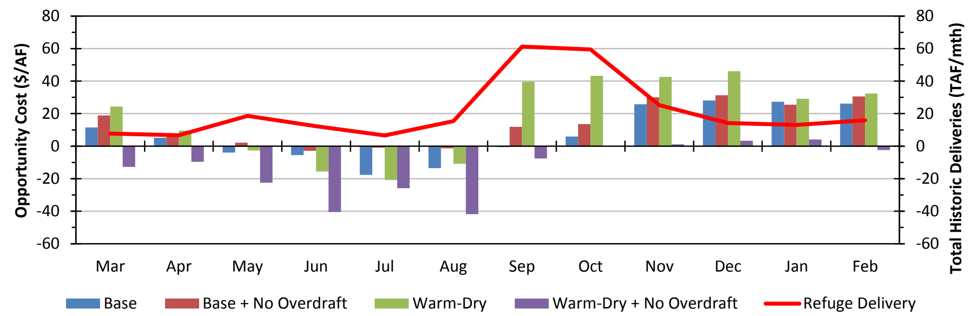
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

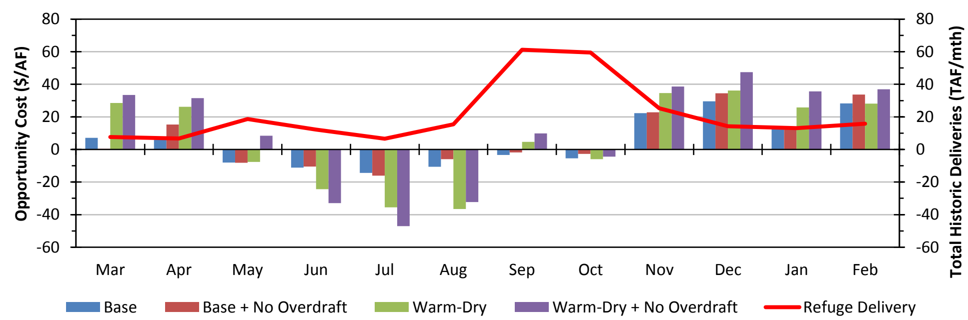
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding GW Deliveries to SJW

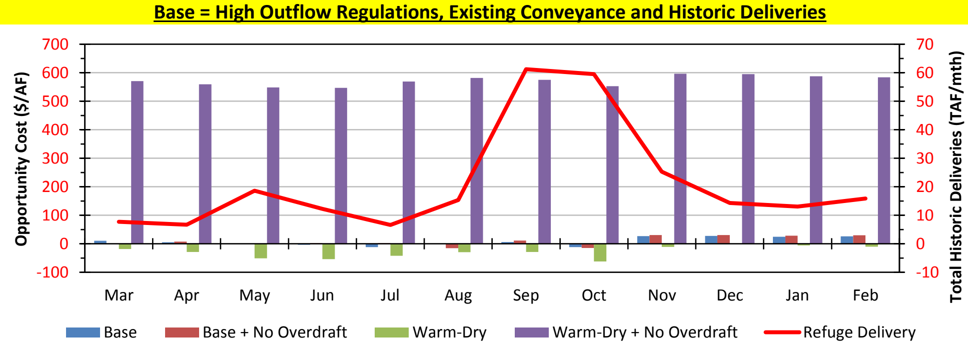
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



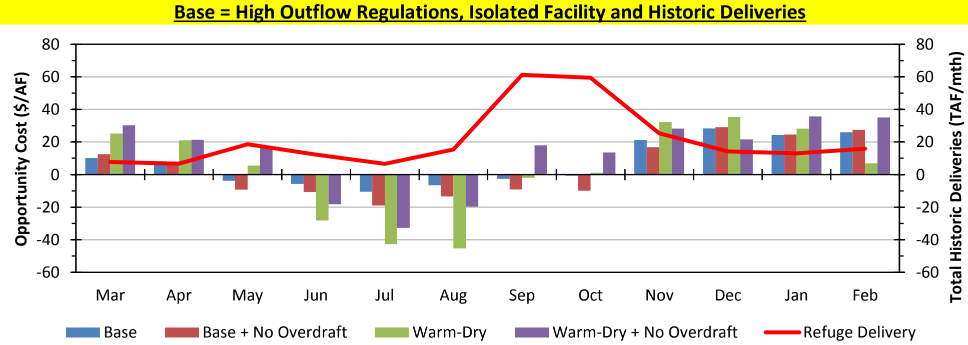
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

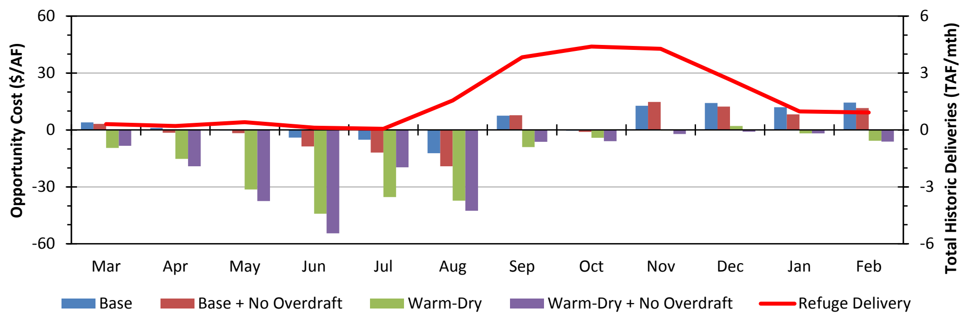
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

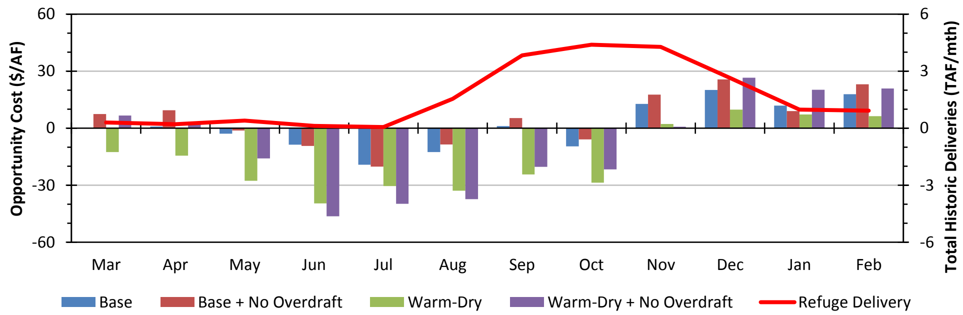
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Opportunity Cost of Expanding GW Deliveries to KER

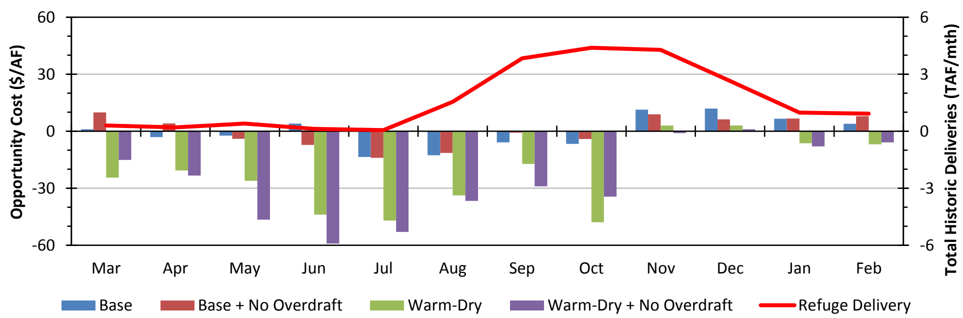
Base = Existing Regulations, Existing Conveyance and Historic Deliveries



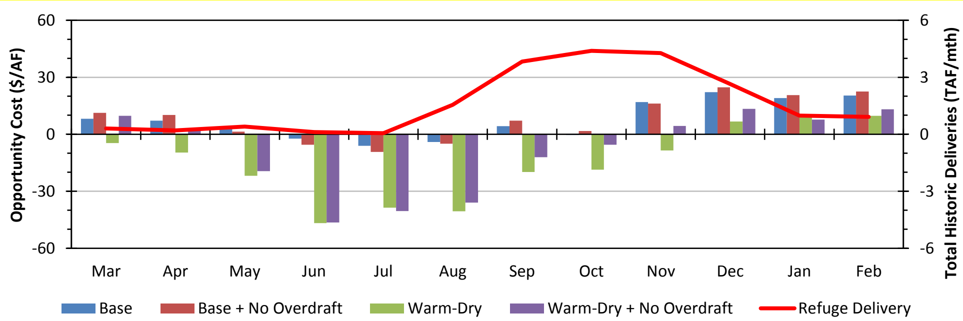
Base = Existing Regulations, Isolated Facility and Historic Deliveries



Base = High Outflow Regulations, Existing Conveyance and Historic Deliveries



Base = High Outflow Regulations, Isolated Facility and Historic Deliveries



EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)

ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)

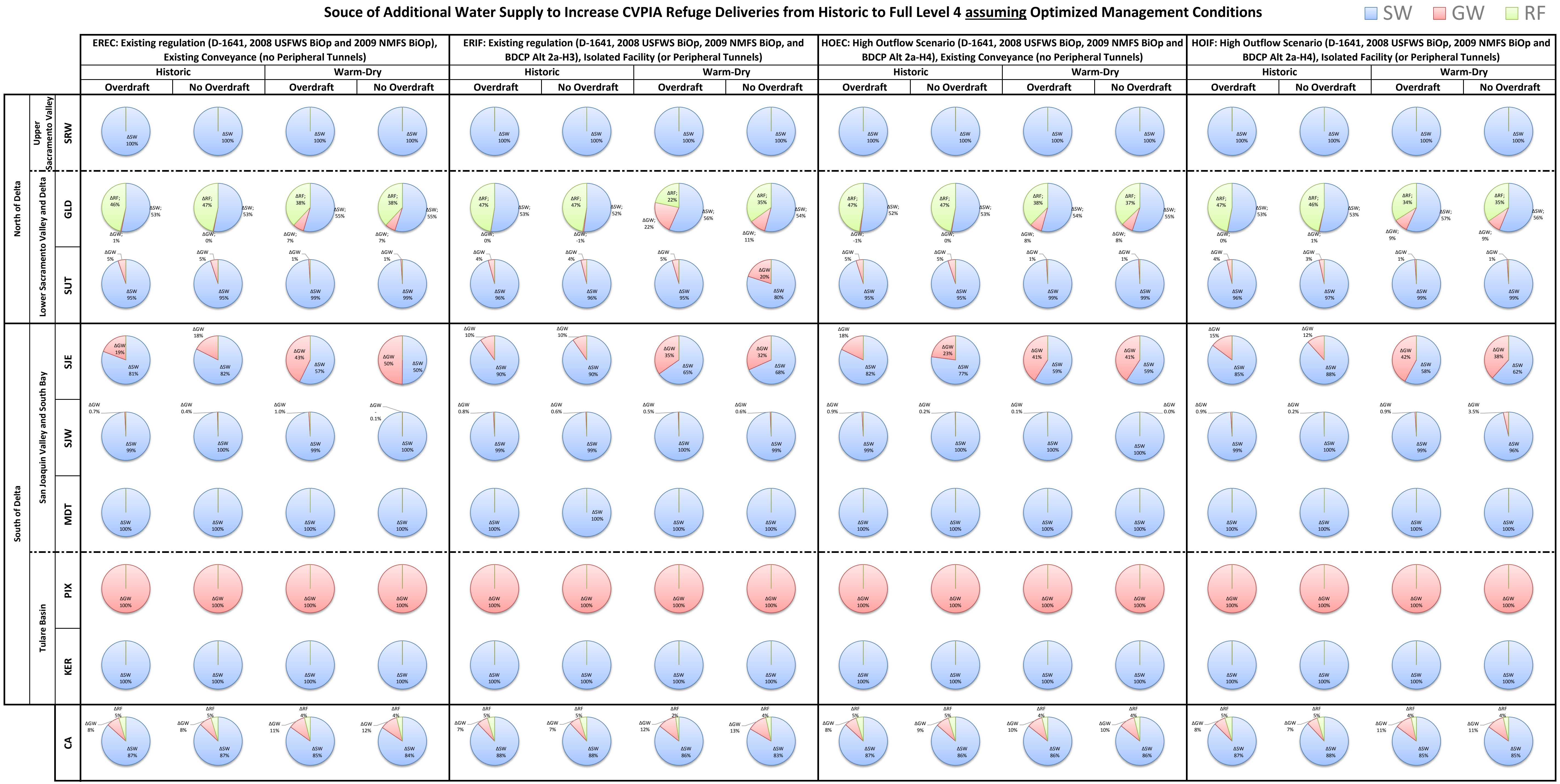
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)

HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

APPENDIX 10f

Source of additional refuge water supplies

Souce of Additional Water Supply to Increase CVPIA Refuge Deliveries from Historic to Full Level 4 assuming Optimized Management Conditions



Source of Additional Water Supply to meet Full Level 4 CVPIA Refuge Deliveries (TAF/yr, Long-Term 82 Year Average)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft	Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	23.4	23.4
SW	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*24.6*	*23.4*	*23.4*
GW	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
SW	*12.8*	*12.8*	*13.4*	*13.4*	*12.9*	*13.0*	*12.9*	*10.8*	*12.9*	*12.9*	*13.4*	*13.4*	*13.0*	*13.0*	*13.4*	*13.4*
GW	*0.7*	*0.7*	*0.1*	*0.1*	*0.6*	*0.5*	*0.6*	*2.7*	*0.7*	*0.7*	*0.1*	*0.1*	*0.5*	*0.5*	*0.1*	*0.1*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Gray Lodge Wildlife Area (GLD)	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
SW	*5.1*	*5.1*	*5.2*	*5.3*	*5.1*	*5.1*	*5.4*	*5.2*	*5.1*	*5.1*	*5.2*	*5.3*	*5.1*	*5.1*	*5.5*	*5.4*
GW	*0.1*	*0.0*	*0.7*	*0.7*	*0.0*	*-0.1*	*2.1*	*1.0*	*-0.1*	*0.0*	*0.8*	*0.8*	*0.0*	*0.0*	*0.9*	*0.9*
Ag Return Flows	*4.4*	*4.5*	*3.7*	*3.7*	*4.6*	*4.6*	*2.1*	*3.3*	*4.6*	*4.5*	*3.6*	*3.6*	*4.5*	*4.4*	*3.3*	*3.3*
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	9.0	9.0	10.4	10.4	9.7	9.7
SW	*8.4*	*8.6*	*6.0*	*5.2*	*9.4*	*9.4*	*6.8*	*7.1*	*8.6*	*8.0*	*5.3*	*5.3*	*8.9*	*9.2*	*5.6*	*6.0*
GW	*2.0*	*1.8*	*4.5*	*5.2*	*1.0*	*1.0*	*3.6*	*3.3*	*1.9*	*2.4*	*3.7*	*3.7*	*1.5*	*1.2*	*4.1*	*3.7*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
West of San Joaquin River (SJE)	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2
SW	*24.0*	*24.1*	*24.0*	*24.2*	*24.0*	*24.1*	*24.1*	*24.0*	*24.0*	*24.2*	*24.2*	*24.2*	*24.0*	*24.2*	*24.0*	*23.3*
GW	*0.2*	*0.1*	*0.2*	*0.0*	*0.2*	*0.1*	*0.1*	*0.2*	*0.2*	*0.0*	*0.0*	*0.0*	*0.2*	*0.0*	*0.2*	*0.9*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Mendota Wildlife Area (MDT)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
SW	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*	*2.2*
GW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ag Return Flows	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
SW (FKC Deliveries)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
GW	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*	*5.1*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Kern National Wildlife Refuge (KER)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
SW	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*	*5.0*
GW	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Ag Return Flows	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Statewide																
Statewide	94.8	94.8	94.7	94.7	94.8	94.8	94.7	94.7	94.8	94.8	93.3	93.3	94.8	94.8	92.8	92.8
SW	*82.2*	*82.6*	*80.5*	*80.0*	*83.3*	*83.4*	*81.1*	*79.1*	*82.4*	*81.9*	*80.0*	*80.1*	*82.9*	*83.4*	*79.2*	*78.8*
GW	*8.1*	*7.8*	*10.6*	*11.1*	*6.9*	*6.7*	*11.5*	*12.3*	*7.8*	*8.3*	*9.7*	*9.6*	*7.3*	*6.9*	*10.4*	*10.7*
Ag Return Flows	*4.4*	*4.5*	*3.7*	*3.7*	*4.6*	*4.6*	*2.1*	*3.3*	*4.6*	*4.5*	*3.6*	*3.6*	*4.5*	*4.4*	*3.3*	*3.3*

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

APPENDIX 10g

Water trading opportunities and associated costs

Region	ID	Name	EREC Historic With Overdraft	EREC Historic No Overdraft	EREC Warm-Dry With Overdraft	EREC Warm-Dry No Overdraft	ERIF Historic With Overdraft	ERIF Historic No Overdraft	ERIF Warm-Dry With Overdraft	ERIF Warm-Dry No Overdraft	HOEC Historic With Overdraft	HOEC Historic No Overdraft	HOEC Warm-Dry With Overdraft	HOEC Warm-Dry No Overdraft	HOIF Historic With Overdraft	HOIF Historic No Overdraft	HOIF Warm-Dry With Overdraft	HOIF Warm-Dry No Overdraft	
Upper Sacramento Valley (Δ = 25 TAF)	101	CVPM01	0	0	1	0.6	0	0	0.5	0.1	0	0	0	0.5	0	0	1.4	0.2	
	102	CVPM02	0.1	0.1	0.1	0.2	0	0	0.0	0.0	0.8	0	0.1	0.4	0.1	0.3	6.3	0.8	
	103A	CVPM03A	0	0	1.8	1.5	0	0	3.3	13.4	0	0	4	10.1	0	0	3	2.3	<-- R-SAC (Δ = 25 TAF)
	103B	CVPM03B	0	0	0.3	0.3	0	0	3.2	0.4	0	0	0.9	2.4	0	0	0.3	0.1	
	104	CVPM04	0	0	34.1	31.9	0	0.1	0	0.1	0	0	9.3	10.4	0	0	0.1	0	
Lower Sacramento Valley and Delta (Δ = 24 TAF)	202	CVPM05	0	0.1	3.3	3.4	0.1	0.3	35.8	40.2	0.1	0.3	0.6	1.5	0	-0.1	26.7	41.5	<-- R-SUT (Δ = 10 TAF) & R-GLD (Δ = 14 TAF)
	203	CVPM06	0	0	0.7	1.1	0	0	8.2	3.6	0	0	17.2	2.2	0	0	2.5	1.7	
	204	CVPM07	0	0	5	8.3	0	0	3.1	0.6	0	0	7.8	4	0	0	3.7	0.5	
	206	CVPM08	0	1.1	0	4.1	0	9.1	2.8	0.1	0.3	0.1	0	0	0.1	0	1.1	0.1	
	207	CVPM09	0.1	0.6	0.9	0.4	0.3	1.2	1.2	0.5	0.1	0.1	1.8	9.4	0.6	0.1	3.9	5	
San Joaquin and South Bay (Δ = 36 TAF)	302	CVPM10	0	0.3	2.9	18.7	1.5	1.3	4.8	4.1	24.8	3.8	0.3	0	0	0.2	2.3	32.5	<-- R-SJW (Δ = 10 TAF)
	303	CVPM11	0	6.9	1.6	0.2	0	0	3.3	4.3	0.8	0.1	0.4	19.9	0.1	0	0.3	1.1	<-- R-MDT (Δ = 24 TAF)
	305	CVPM12	0	0.2	3.5	0	17.3	0	1.3	8.8	0.3	0	0.2	15.8	28.5	0	0.3	1.3	
	306	CVPM13	0.5	0.2	0	17.3	0	0.4	0.1	0.2	0.2	0	0	0	1.2	0	0.0	0	<-- R_SJE (Δ = 2 TAF)
Tulare Basin (Δ = 10 TAF)	401	CVPM14A	0.1	0	1.1	3.1	0	0.1	2.6	3.3	0	1.3	0	0	1.4	0	0.5	7.8	
	402A	CVPM14B	1.9	0	0.8	0.1	0	0	0.5	0.5	0	0	0.1	0	0.1	0	1.5	0	
	402B	CVPM15A	2.9	5.2	3.1	0	6.3	2.4	1	7.9	0.1	39.9	0	0	4.7	0.7	6.5	0	
	403	CVPM15B	0	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0	0.5	
	404A	CVPM16	0.1	0	0	0	0	3.3	0	0	0	0	0	0	3.6	0	0	0	
	404B	CVPM17	0	0	21.6	0	12.4	0	0	0.1	0	0	0	0	1.7	0	0	0	
	405	CVPM18	37	6.2	7.2	7.2	0	2	31.5	7.2	27.9	2	7.2	7.2	2.3	0.5	31.5	7.2	<-- R-PIX (Δ = 5 TAF)
	407	CVPM19A	0	0	0	0	0	0	0	0.1	0	0	0	0	0.5	0	0	0.1	
	408A	CVPM19B	0.1	2.2	1.3	0	4.8	0	0.8	6.2	0.1	0.7	0	0	0	0.1	0.2	0.1	
	408B	CVPM20	0	0.1	0.7	0	0	0.9	0	0.5	0	0	0	0.1	0	0.2	0.1	0.1	<-- R-KER (Δ = 5 TAF)
	409A	CVPM21A	0	0.8	8	0	1.2	4.8	5.1	3.1	0	2.6	0	0	0.1	0.7	9.1	0.2	
	409B	CVPM21B	0	0.1	0	0	0.5	0	0.1	0	0.2	0	0	0.1	0	0.1	0	0	
	409C	CVPM21C	0.1	0	0.1	0	0	0	0	0.2	0	0	0	0.1	0	0	0	0	
Southern California	501	Ventura	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	502	Antelope Valley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	507	Coachella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	508	Palo Verde	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	509	East and West MWD	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	
	510	Imperial	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	511	San Diego	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	512	Bard WD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

APPENDIX 11

Percent change in evapotranspiration rate: derivation and assumptions

Calculating Reference Evapotranspiration using Hargreaves-Samani Simplified Equation

Equation

$$ET_o = 0.0135\ (KT)\ (R_a)\ (TD)^{0.5}\ (TC + 17.8)$$

Where

ET_o	Reference evapotranspiration
KT	Empirical coefficient (0.162 for interior regions and 0.19 for coastal region is recommended)
R_a	Extraterrestrial radiation (*mm/day*)
TD	Difference between daily maximum and minimum temperature (*degree Celsius*)
TC	Average daily temperature (*degree Celsius*)

Limitations of Hargreaves-Samani

- No explicit representation of relative humidity.
- Although 80% of the evapotranspiration can be explained by solar radiation and temperature, it is still missing important parameters like latitude, elevation, topography, storm pattern, advection, proximity to a large water body, etc.

Assumptions

1. Since temperature data from PRISM is only available at monthly time step, a uniform temperature pattern was assumed for the entire month.
2. Climate change only impacts temperature; all other parameters – crop coefficient, solar radiation, etc. – are not impacted by climate change
3. Daily maximum and minimum temperatures are impacted similarly

Equation for determining percent change in crop evapotranspiration

$$ET_c = k * ET_o$$

$$\Delta ET_c = \frac{ET_c - ET_c'}{ET_c}$$

$$\Delta ET_c = \frac{k * ET_o - k * ET_c'}{k * ET_c'}$$

$$\Delta ET_c = \frac{k * 0.0135\ (KT)\ (R_a)\ (TD)^{0.5}\ (TC + 17.8) - k * 0.0135\ (KT)\ (R_a)\ (TD')^{0.5}\ (TC' + 17.8)}{k * 0.0135\ (KT)\ (R_a)\ (TD')^{0.5}\ (TC' + 17.8)}$$

$$\Delta ET_c = \frac{k * 0.0135\ (KT)\ (R_a)\ [(TD)^{0.5}\ (TC + 17.8) - (TD')^{0.5}\ (TC' + 17.8)]}{k * \ 0.0135\ (KT)\ (R_a)\ (TD')^{0.5}\ (TC' + 17.8)}$$

$$\Delta ET_c = \frac{[(TD)^{0.5}\ (TC + 17.8) - (TD')^{0.5}\ (TC' + 17.8)]}{(TD')^{0.5}\ (TC' + 17.8)}$$ *... After assumption #2*

$$\Delta ET_c = \frac{(TD)^{0.5} * [TC + 17.8 - TC' - 17.8]}{(TD)^{0.5}\ (TC' + 17.8)}$$

$$\Delta ET_c = \frac{(TC - TC')}{(TC' + 17.8)}$$ *... After assumption #3*