Drought Water Right Allocation Tool Applied to the San Joaquin River Basin

By

WESLEY WALKER

B.S. (Loyola Marymount University) 2011

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:

Jay R. Lund, Chair

Jon Herman

Samuel Sandoval-Solis

Committee in Charge

2017

Drought Water Right Allocation Tool Applied to the San Joaquin River Basin

Abstract

California's water rights system allocates water to users based on priority, where lower priority, "junior" rights are curtailed first in a drought. California's most recent drought tested and brought attention to the weaknesses in the state's administration of water rights during surface water shortages. The Drought Water Rights Allocation Tool (DWRAT) was developed to suggest surface water right curtailments during drought, by mathematically representing and combining water law and hydrology. DWRAT incorporates water right uses, priorities, and a statistical flow forecasting model into a pair of linear programs to suggest water allocations among water rights holders. In doing so, DWRAT represents the logic of California water rights law mathematically, providing a precise and transparent framework for the complicated and often controversial technical aspects of curtailing water rights use during drought. DWRAT is compiled within an Excel workbook, with a user-friendly interface and open-source solver. Models have been developed for use in California's Eel, Russian, San Joaquin, and Sacramento River basins. Current or forecasted flow volumes can be input to the model to provide decision makers a legally and hydrologically integrated curtailment analysis. DWRAT also can account for water user return flows, which are especially important in large basins such as the Sacramento and San Joaquin, where return flows can substantially affect estimating water availability. DWRAT can be used to assess water allocation reliability by estimating the probability of right holders' curtailment over a range of hydrologic conditions. This thesis details methods and analysis of DWRAT applied to the San Joaquin River basin.

Acknowledgements

I would like to thank my thesis committee for their comments, insight, and support. I'd especially like to thank my committee chair, Dr. Jay Lund, for his guidance and support over the last year and a half, and for the opportunity to be part of the DWRAT team.

Special thanks are due to all of the DWRAT team members, past and present, for their help and guidance. I'd also like to thank my colleagues in the Center of the Universe for their help and friendship.

Lastly, but most importantly, I'd like to thank my family for all of their support and encouragement. I'm forever grateful to my wife, Brianne, for her constant support, encouragement, partnership, and for editing all of my papers!

Abstract iii

Acknowledgements iv

Figures vi

Tables viii

Chapter 1 – Introduction 1
California Water Rights 1
California State Water Resources Control Board 2
Drought Water Rights Allocation Tool 4
Hydrologic Connectivity 5
Estimating Unimpaired Flow 7
Water User Demand and Priority 7
Riparian and Appropriative Linear Programs 8
DWRAT Applications 10

Chapter 2 – San Joaquin River Basin DWRAT 11
Unimpaired Flow Data 13
Water Right User Demand Data 15
Modeling Issues for Large Basins 16
Return Flows 17
Flow Model – Scaling Ratio Analysis 19

Chapter 3 – San Joaquin DWRAT Results 24
2014 Results 24
2015 Results 30
2015 Results with Return Flows 34
Forecast Flow Analysis 37

Chapter 4 – Water Right Reliability and Error Analysis 43
Implicit Stochastic Optimization (ISO) Applied to DWRAT 43
Estimating Shortage Probabilities and Curtailment Rules for the San Joaquin DWRAT 44
Monte Carlo Analysis for Shortage Probability 51
Results Without Flow Correlation 54
Flow Error Analysis 57
Conclusions 62

Chapter 5 – Conclusions and Future Work 63
Additional Data Needs and Future Work 63

References 65

Figures

Figure 1: 2015 SWRCB Curtailment Calculation Graph for Tuolumne River (SWRCB, 2015a) ... 3
Figure 2: Example basin demonstrating possible error from coarse curtailment method ... 4
Figure 3. DWRAT Model Workflow ... 5
Figure 4. Example Basin with 8 sub-basins (A-H) ... 6
Figure 5. San Joaquin River Basin (Stringfellow, 2014) ... 12
Figure 6. San Joaquin Basin Unimpaired Flow Gage Locations ... 14
Figure 7. Average Monthly Unimpaired Flow of the San Joaquin River at Vernalis ... 15
Figure 8. San Joaquin Basin Monthly User Demand by right from WRUDS 2010-2013 Demands ... 16
Figure 9. Distribution of Water Right Return Flow Factor for each Water Right ... 19
Figure 10. Shaded HUC-12's represent HUC's used in Figure 11 analysis ... 20
Figure 11. Scaling Ratio Variation of Dry Years for October, January, April, and May ... 21
Figure 12. Coefficient of Variation by HUC location for all dry years ... 23
Figure 13. Percent of Users and Normal Use Shorted vs. Basin Outlet Flow for Water Year 2014 ... 26
Figure 14. Percent of Users and Normal Use Shorted vs. SWRCB Actions for Water Year 2014. SWRCB curtailments apply only to appropriative users. ... 28
Figure 15. Percent of normal use shorted by DWRAT compared to SWRCB actions ... 30
Figure 16. Percent of Users and Normal Use Shorted vs. Basin Outlet Flow for Water Year 2015 ... 32
Figure 17. Percent of Users and Normal Use Shorted vs. SWRCB Actions for Water Year 2015 ... 33
Figure 18. Percent of normal use shorted by DWRAT compared to SWRCB actions on June 12, 2015 ... 34
Figure 19. Percent of Riparian Users and Use Shorted for Water Year 2015, with and without return flows ... 36
Figure 20. Percent of Appropriative Users and Use Shorted for Water Year 2015, with and without return flows as compared to SWRCB actions ... 37
Figure 21. Freshwater flow at San Joaquin basin outlet with CNRFC forecast flows higher in June and October, but lower in July-September than observed flow ... 38
Figure 22. Percent of Users and Percent of Normal Use Shorted for Riparian Users with 2016 forecast flows mostly lower than observed flow. ... 40
Figure 23. Percent of Users and Percent of Normal Use Shorted for Appropriative Users with 2016 forecast flows mostly lower than observed flow. ... 41
Figure 24. Total Number of Water Right Shortages vs. Flow at Vernalis in July ... 45
Figure 25. Total Volume Shorted vs. Flow at Vernalis in July ... 46
Figure 26. User Shortage Probability by Priority for July ... 47
Figure 27. Shortage Threshold by Priority for July ... 49
Figure 28. Shortage Probability and Threshold for Users in HUC 180400020405 in July ... 50

Figure 29. User Shortage Probability with Monte Carlo Analysis by Priority 53
Figure 30. Shortage Probability Difference, Monte Carlo vs. ISO by Priority....................... 54
Figure 31. User Shortage with Monte Carlo Analysis with no spatial flow correlation and historical dry-year scaling ratio distribution 55
Figure 32. User Shortage with Monte Carlo Analysis with no spatial flow correlation and full historical scaling ratio distribution 55
Figure 33. Shortage Probability Difference between Full and Dry-Year Distributions without spatial flow correlation.. 56
Figure 34. Flow Gage and Reservoir Data used for San Joaquin flow error analysis........ 58
Figure 35. DWRAT predicted flow vs. gaged flow at unregulated gage locations for 2015 59
Figure 36. DWRAT predicted flow vs. gaged flow at regulated gage locations for 2015 60
Figure 37. DWRAT predicted flow vs. gaged flow for Lower San Joaquin River for 2015 61

Tables

Table 1. Examples of Water Allocation Models 4
Table 2. Connectivity Matrix of example basin shown in Figure 4 6
Table 3. Riparian LP Constraints 9
Table 4. Appropriative LP Constraints 10
Table 5. Actual and Unimpaired Flow for San Joaquin Rivers 11
Table 6. Unimpaired Flow Reference Gage HUC Statistics 14
Table 7. San Joaquin Basin User Data per WRUDS 2010-2013 Demand 16
Table 8. DWRAT Return Flow Methods 18
Table 9. Beneficial Use Statistics for San Joaquin Basin 19
Table 10. Water Year 2014 – SWRCB Water Shortage Actions 26
Table 11. Water Year 2015 – SWRCB Water Shortage Actions 31
Table 12. Unimpaired Flow Gage Linear Regression to Vernalis in July 51

Chapter 1 – Introduction

In response to reduced surface water availability in 2014 and 2015, California's water rights regulatory agency, the State Water Resources Control Board ('the Board' or 'SWRCB'), issued water shortage notices for the Eel, Scott, Russian, Sacramento, and San Joaquin river basins (SWRCB, 2016a). The 2014 water shortage notices were the first issued by the Board since 1977. Despite improvements in data availability and technical knowledge between 1977 and 2014, little effort had been made to improve the methods and calculations used in curtailment decisions. Continued changes to water demands, regulatory requirements, and climate are likely to increase the need and frequency of surface water use curtailments (Lund, et. al. 2014). Given these changes and the challenges of managing California's complex water right system, the need for a legally sound, transparent, and data-based tool to inform water right curtailment decisions has become apparent. The Drought Water Rights Allocation Tool (DWRAT) was developed for this need, and has been developed and tested for use in California's Eel, Russian, Sacramento, and San Joaquin River Basins. This report details the methods, development, and analysis of DWRAT applied to the San Joaquin River basin.

California Water Rights

Unlike most western states, California employs a dual system of surface water rights that includes both riparian and appropriative rights. Riparian rights originate from English common law and began in California when the first State legislature declared in 1850, "the common law of England…is the rule of decision in all courts of this state" (Littleworth & Garner, 2007). Riparian rights are held by landowners adjacent to a stream and allow the owner to divert only what can be put to reasonable and beneficial use. The water diverted can only be used on the right holder's land adjacent to the stream and cannot be put into storage. In times of shortage, all hydrologically connected riparian users share any shortage proportionally to their use. Although riparian users are equal in priority with each other, in general they have seniority over appropriative users (Liebert, 2017). While most states have adjudicated riparian rights or converted them to appropriative rights, California maintains these rights as originally patented (Escriva-Bou, et. al., 2016).

Appropriative water rights originated in California to meet mining demands, as mining operations were typically located far from streams and miners did not own land adjacent to a stream. Accordingly, the appropriative doctrine does not require land ownership, diversions can be made to non-stream adjacent land, and diversions to storage are allowed. Under the appropriative doctrine, shortage is not shared equally. Shortage follows a "first in time, first in right" priority system, where junior or lower priority users are shorted before senior users (Liebert, 2017). The appropriative doctrine was formally recognized in California law by the state Supreme Court in *Irwin v. Phillips (1855)* and then by the state legislature in 1872 (Littleworth & Garner, 2007). To further complicate matters, appropriative rights in California are categorized as pre-1914 or post-1914. Pre-1914 rights are those established before implementation of the Water Commission Act in 1914, which created the State Water Commission (present-day Department of Water Resources). This act required that new applications for appropriative rights obtain a permit to authorize their claim. The priority of pre-1914 rights is based on the date of first use, while post-1914 priority is based on the permit application date (Liebert, 2017).

During times of surface water shortage, it is necessary to estimate the volume of water available for diversion by water users. This is more complicated than just observing stream gage readings. Riparian users have access to the "natural" flow of a stream, while appropriative users have access to a stream's "unimpaired" flow. These two terms are often used interchangeably, despite important differences between computations used for each value. Natural flow describes the flow that would have occurred in the system absent all anthropogenic influences on land use (wetlands, vegetation, groundwater) and channel conditions (floodplains, levees, storage). Unimpaired flow is used to describe a theoretically available flow with current land use and river channel conditions, but without storage regulation and stream diversions (DWR, 2016). Natural flow is much more difficult to calculate as it involves estimating pre-development land-use and vegetation conditions for which little documentation exists. Although several agencies (National Weather Service, U.S. Geologic Survey, CA Department of Water Resources) provide estimates of 'full natural flow' or 'FNF', these calculations are made using present-day stream channels and hydrologic conditions, which more closely represent unimpaired flows. To simplify and clarify, all streamflow data used in this report is referred to as unimpaired flow. For simplicity, and given the lack of available truly 'natural flow' data, DWRAT uses unimpaired flow estimates for both riparian and appropriative users.

California State Water Resources Control Board

Water rights in California are regulated and enforced by the State Water Resources Control Board. The Board is responsible for determining water availability, issuing water shortage notices, investigating water right compliance, and administering water right permits. Although the Board has considerably less regulatory power over riparian and pre-1914 appropriative right holders, the Board can take action to ensure that riparian and pre-1914 use follows the reasonable and beneficial use provisions in California's Constitution, as well as environmental and public trust laws (Escriva-Bou, et. al., 2016). In 2014, California's extreme drought led the Board to issue water shortage notices (curtailments) for the first time since 1977. These actions applied to post-1914 appropriative water right holders in the Eel, Russian, Sacramento, Scott, and San Joaquin basins. In 2015, the lack of hydrologic improvement in the Sacramento, Scott, and San Joaquin led to renewal of previous water shortage notices and further notices of unavailability to some pre-1914 appropriative users in the Sacramento and San Joaquin basins (SWRCB, 2016a).

In 2014 and 2015 the SWRCB determined water unavailability by comparing unimpaired flow estimates at the outlet of a watershed to the total upstream demand at that point. When the available unimpaired flow was less than calculated demand, the Board determined the water right priority date needed to reduce total use to equal available supply. An example of this analysis for the San Joaquin River Basin in 2015 is shown in Figure 1, which displays estimated supply (labeled as Daily FNF) along with pre-1914 and riparian demands for May-November in 2015. Post-1914 demands are not shown in this plot as they were previously issued water shortage notices on April

23, 2015. In 2015, the Board issued an Information Order requesting updated demands from all riparian and pre-1914 users. The solid green line indicates the retrospective riparian and pre-1914 demand.

In early June, the available supply dropped below estimated pre-1914 demands through priority year 1902. In response, the Board issued water unavailability notices to all 1903 and junior pre-1914 claims on June 12, 2015. Notices of unavailability remained in place through the remainder of the summer as available supply remained below demand. In late October available supply surpassed demand, and all pre-1914 users were allowed to resume diversions (SWRCB, 2015a).

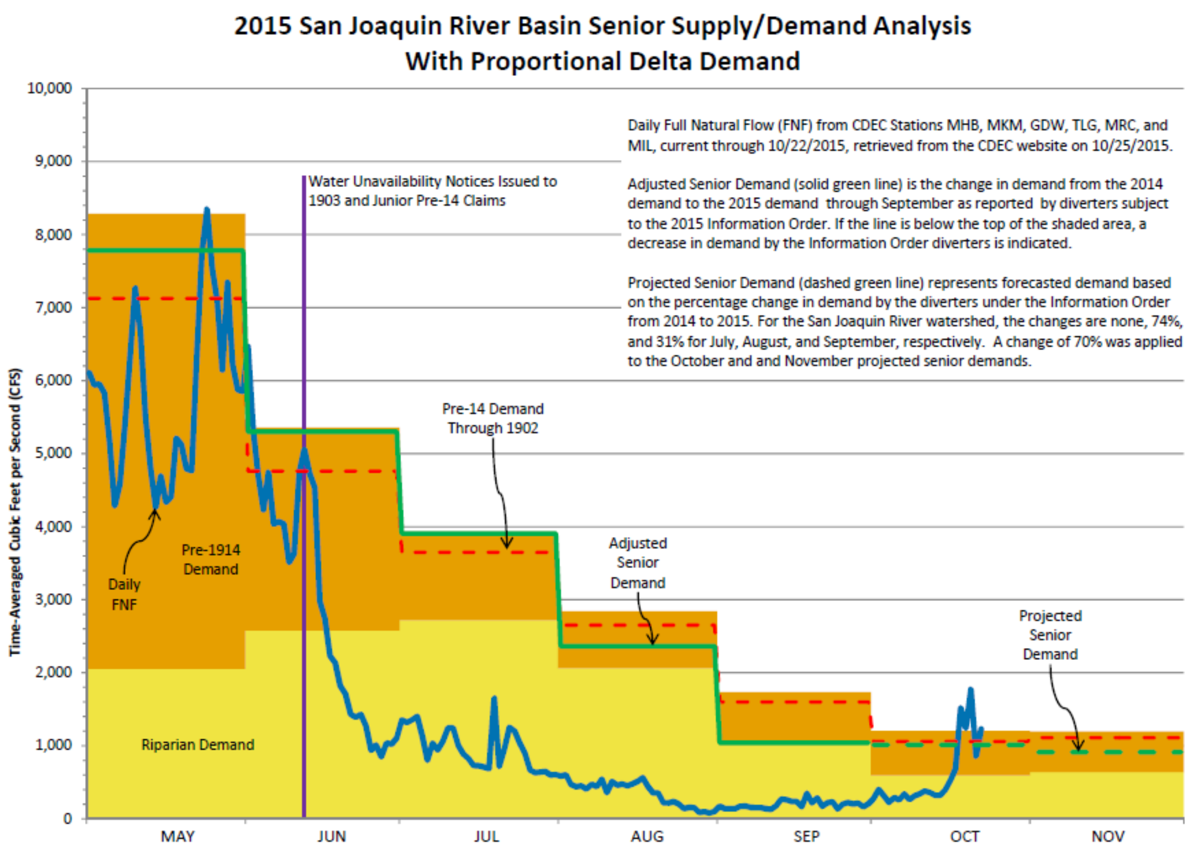

Figure 1: 2015 SWRCB Curtailment Calculation Graph for Tuolumne River (SWRCB, 2015a)

Several court cases have challenged the Board's curtailment and enforcement actions against riparian and pre-1914 right holders in 2015 (Lexis-Legal, 2016). While the Board's regulatory powers have largely been upheld, questions regarding the Board's method of determining water availability have limited the legal standing of their actions (SWRCB, 2016b). A major shortcoming of the methods used by the Board is the coarse consideration of the spatial variability in available water supply and user demand within a basin. Without considering spatial variability, the coarse methods potentially allow for under and over curtailment in different parts of the basin. Figure 2 demonstrates such a scenario. In this example basin, the coarse method would curtail the downstream junior user on the mainstem because of the upstream senior user's demand. However, the junior user should be able to exercise their right because their use would not "harm" the senior user's demand. The senior user only has physical access to the tributary flow, which is not enough to meet their demand. Accordingly, future drought scenarios dictate the need for a curtailment tool that can apply the legal principles of water rights, while also considering the spatial variability in water availability, user demand, and user priority.

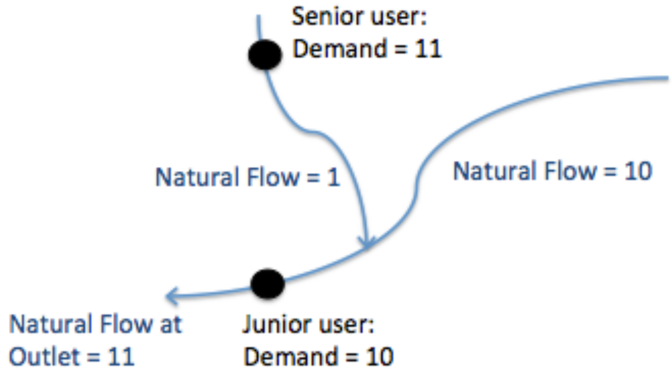

Figure 2: Example basin demonstrating possible error from coarse curtailment method

Drought Water Rights Allocation Tool

Several water allocation models have been developed and are in use in the Western U.S. These models account for, and in some cases optimize, allocations and management decisions for appropriative water right systems. Some examples of these models are summarized in **Table 1.**

Table 1. Examples of Water Allocation Models

Model Name	Used In	Capabilities
MODSIM (Labadie, 2010)	Industry/ Academia	- Water Rights Planning and River Operations Decision Support System. Optimizes flow allocation in accordance with user priorities, under a flow network of nodes and arcs.
Water Availability Model (WAM) Water Rights Analysis Package (WRAP) (Wurbs, 2015)	Texas	- WAM simulates natural water availability based on historical hydrology and a set of initial hydrologic conditions. - WRAP reads in water rights, geospatial data, and WAM data to simulate water allocations under the appropriative doctrine. The simulation iterates through each water right in priority order.
Water District #1 Accounting (Olenichak, 2015)	Idaho	- Calculates and keeps accounting for natural flow availability and projected water right use. Run on a daily basis.
StateMOD (Colorado, 2016)	Colorado	- Monthly/daily allocation and accounting model. Models physical stream conditions and water right and infrastructure operations.
Water Evaluation	Industry/	- Integrated, simulation based water resources

and Planning (WEAP) (SEI, 2017)	Academia	planning tool. Accounts for basin hydrology, operations, and water rights. Allocations are solved with linear programming. - Requires software license and significant training.
OASIS (Hydrologics, 2016)	Industry/ Academia	- River basin management model for water supply and hydropower operations. Operations decisions are solved with linear programming, with all rules defined as goals or constraints. - Requires knowledge of OCL computer language.

An allocation model that accounts for both riparian and appropriative rights, while also being free and open-source, has yet to be developed or documented. To meet this need, researchers at the UC Davis Center for Watershed Sciences have developed the Drought Water Rights Allocation Tool (DWRAT) (Lord, 2015; Whittington, 2016; Tweet, 2016; Lord et. al, 2017). DWRAT is an Excel spreadsheet model that incorporates water right uses, priorities, and statistical flow forecasts into a pair of linear programs, to suggest water allocations among all water right holders. In doing so, DWRAT represents the logic of California water rights law mathematically, providing a precise and transparent framework for the complicated and often controversial technical aspects of curtailing water rights use during drought. DWRAT includes a user-friendly interface and an open-source solver. Figure 3 provides an overview schematic of how DWRAT incorporates unimpaired streamflow, basin hydrology, and water user demand data into the riparian and appropriative linear programs to compute legally and hydrologically sound water allocation decisions.

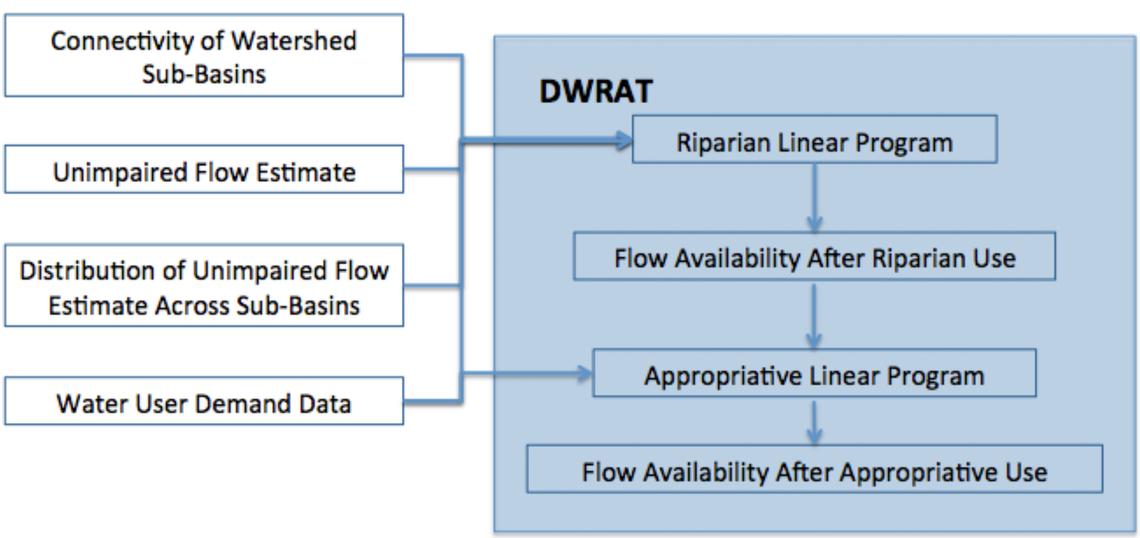

Figure 3. DWRAT Model Workflow

Hydrologic Connectivity

The first step in developing a DWRAT model is to delineate the basin (watershed) into smaller sub-basins. To account for spatial variability within a basin, DWRAT uses the USGS's Hydrologic Unit Code (HUC) system's smallest delineation level, HUC-12 basins, which typically range from 15-60 square miles. The HUC-12 system also allows for the straightforward creation of a connectivity matrix to inform DWRAT of the hydrologic connectivity of sub-basins. DWRAT requires the connectivity matrix to inform its linear programs to properly create and compute the mass balance and decision constraints given the sub-basin's upstream-downstream connectivity. The matrix is built as a binary table with each sub-basin listed as both a row and column. Figure 4 and **Table 2** show a small example basin, where a "1" in the table indicates the column sub-basin is upstream of the row sub-basin, while a "0" indicates the column sub-basin is downstream of the row sub-basin.

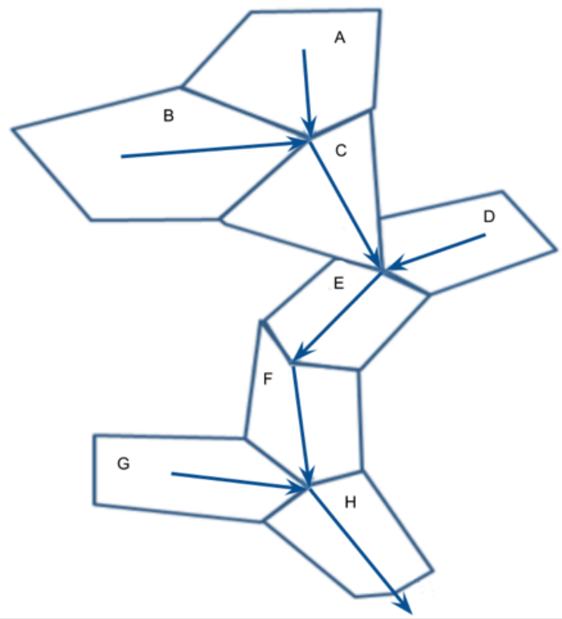

Figure 4. Example Basin with 8 sub-basins (A-H)

Table 2. Connectivity Matrix of example basin shown in Figure 4

Downstream	**Upstream**							
	A	B	C	D	E	F	G	H
A	1	0	0	0	0	0	0	0
B	0	1	0	0	0	0	0	0
C	1	1	1	0	0	0	0	0
D	0	0	0	1	0	0	0	0
E	1	1	1	1	1	0	0	0
F	1	1	1	1	1	1	0	0
G	0	0	0	0	0	0	1	0
H	1	1	1	1	1	1	1	1

In **Table 2**, rows A, B, D, and G only have a single "1" because they are the most upstream sub-basins. Likewise, row H has a "1" in each cell because it is downstream of all other sub-basins. In this sense, a "1" indicates that the column sub-basin and the row sub-basin are hydrologically connected and water from the column sub-basin is available to the row sub-basin. This establishes the foundation on which water right user priorities in these sub-basins must be followed.

Estimating Unimpaired Flow

The next step in the development of a DWRAT model is the creation of the statistical flow forecasts. Since streamflow is not measured in most HUC-12 basins, DWRAT's flow model estimates the unimpaired flow available in each HUC-12 by scaling flow estimates at discrete unimpaired flow reference gage locations. The statistical model, originally developed by the USGS, combines 20 hydrologic and geographic indicators with historical streamflow data to develop monthly unimpaired flow estimates for each HUC-12 from 1950-2011 (Grantham & Fleenor, 2014; Falcone, 2011; Moriasi, 2007). The monthly unimpaired flow estimates for each HUC-12 are used to create a monthly flow ratio between the HUC of interest and the gaged HUC. To estimate the HUC's outlet flow, a second ratio of the gaged HUC's drainage area to the gage location's drainage area is computed. The product of these two ratios and the unimpaired flow gage data produces an estimate of the outlet flow for each individual HUC-12 for each date of interest. Equation 1 details the flow scaling equation, where STA is the reference gage station, Q is the unimpaired flow estimate (for the reference gage and the historical flows), HUC is the discrete HUC-12, and DA is drainage area. For simplicity, DWRAT assumes that each user in a HUC-12 has access to the HUC's outlet flow.

$$Q_{HUC} = \frac{Q_{monthly,HUC}}{Q_{monthly,STA,HUC}} \times \frac{DA_{STA,HUC}}{DA_{STA}} \times Q_{STA} \quad (1)$$

Alternative flow predictions could easily be implemented into DWRAT, provided they are produced at the HUC-12 level.

Water User Demand and Priority

The last dataset needed for DWRAT are users' demand quantities and priorities. Currently these data are from the SWRCB's Water Right User Database System (WRUDS). WRUDS provides average monthly user demand based on reported use for 2010-2013. This dataset provides a useful sample period as 2010 was an average precipitation year, 2011 was exceptionally wet, and 2012 and 2013 were dry. The demand is likely somewhat over-estimated as many users might implement conservation measures to reduce their use in dry years even if their right is not curtailed. WRUDS also provides user priorities as reported in the Board's water right database, eWRIMS (SWRCB, 2017a), as well as the HUC-12 where each right is located. Direct diversions by hydropower users (not including diversions to storage) are considered non-consumptive in WRUDS, so such diversions do not add to a hydropower user's overall demand. Unfortunately, WRUDS does not currently include releases (return flows) of non-consumptive uses back to streams that augment water availability; such augmentations (mostly in summer) are currently omitted from the model.

Accurate and comprehensive reporting of surface water diversions has been cited as a major shortcoming to effectively account and manage California's surface water supplies (Escriva-Bou, et. al., 2016). Prior to 2009, riparian and pre-1914 appropriative users were not required to report their use. Legislation passed in 2009 initiated some expansion to reporting requirements, however significant improvements were achieved with the Board's 2015 Informational Order (SWRCB, 2015b) and the passage of SB 88 in 2016. SB 88 requires all users with an annual use exceeding 10 acre-feet, regardless of right, to submit an annual report. The bill also implements additional accuracy and frequency reporting requirements dependent on the size and type of diversion. The data obtained through this regulation will significantly improve water accounting in California and improve the accuracy of results and analysis produced by DWRAT. Although some user demand data are available for 2014 and 2015, for simplicity and consistency, the current San Joaquin DWRAT model uses the 2010-2013 average monthly demand listed in WRUDS. When more accurate user data becomes available, DWRAT's framework allows for a quick and simple update of user demand and quantities.

Riparian and Appropriative Linear Programs

The computational "engines" of DWRAT are its pair of linear programs. A linear program is a mathematical model that optimizes a linear objective function, subject to a set of linear constraints that define a feasible region of solutions. As such, each of the riparian and appropriative water right systems requires their own linear program (LP) to calculate optimal water allocations under the legal requirements of each doctrine. A goal of each linear program (LP) is to minimize shortage at every time step. However, the two water right systems approach shortage and allocations differently. The riparian LP is run first to comply with the seniority of riparian users over appropriative users. Upon completion of the riparian LP, the remaining water is then allocated to appropriative users with the appropriative LP. This report provides a brief explanation of the functions and constraints for each LP. Previous reports provide more detailed explanations of the riparian and appropriative mathematics (Lord, 2015; Whittington, 2016, Lord et. al, 2017).

Since riparian water right holders have equal priority among themselves, water shortage must be shared by each user in a sub-basin as an equal proportion of their normal use. The goal of the riparian objective function, shown in Equation 2, is to minimize total shortage across the basin, where the decision variable is the proportion (P_k) of normal use allocated to users in each sub-basin k. $\propto$ is a weighting factor needed to equalize proportions across the entire basin, while w_k is a weighting penalty needed to enforce proportional allocations from upstream to downstream.

$$Min\ z = \propto \sum_k w_k P_k - \sum_i A_i \qquad (2)$$

Accordingly, the objective function seeks to minimize the difference between the sum of the weighted allocation proportions and the sum of each individual (i) user's allocation A_i. The riparian LP is subject to eight constraints, summarized in **Table 3.**

Table 3. Riparian LP Constraints

Constraint Equation	Purpose
(1) $A_i = P_k u_i, \forall\, i, i \in k$	Each user's allocation is defined as the product of the user's demand (u_i) and the proportional allocation for the user's sub-basin.
(2) $P_j \leq P_k, \forall\, k, j \in k$	Ensures that the proportion of water allocated to an upstream sub-basin *j* does not exceed the proportion to a downstream sub-basin *k*. Without this constraint, upstream sub-basins would receive disproportionately large allocations.
(3) $\sum_{i \in k} A_i \leq v_k - e_k - b_k, \forall\, k$	Ensures mass balance in each sub-basin by constraining the allocations upstream of and in a sub-basin to be less than or equal to the water available at the basin's outlet. Water available equals the inflow to the sub-basin (v_k) minus any environmental flow (e_k) and buffer flow (b_k) requirements.
(4) $0 \leq P_k \leq 1, \forall\, k$	Constrains the proportion for each sub-basin to be between 0 and 1.
(5) $A_i \geq 0, \forall\, i$	Maintains allocations to each user to be non-negative.
(6) $A_i \geq d_i, \forall\, i$	Individual user allocations must exceed any public health and safety requirement (d_i) assigned to the user's demand.
(7) $w_k = \frac{n_k}{n_{k,system\ outlet}}$	Weighting penalty to enforce proportional allocations from upstream to downstream. Defined as the number of sub-basins upstream of sub-basin *k,* divided by the number of sub-basins upstream of the basin outlet.
(8) $\propto < \min\left(\frac{w_k}{u_k}\right), \forall\, k$	Weighting term to enforce equal shortage across the watershed, while maximizing total user allocations.

The appropriative priority system has a less complex objective function and constraint equations. The appropriative objective function, shown in Equation 3, minimizes the total weighted water shortage across the whole basin, where the decision variable is DWRAT's allocation to each individual user (A_i). Each appropriative user is assigned a shortage penalty (p_i), with the most senior user having the largest penalty, while the most junior user has the smallest penalty. Shortage penalties are determined by subtracting a user's priority number from the total number of users in a basin. For example, the 2nd most senior user in a basin of 10 total users would have a shortage penalty of 8.

$$Min\ z = \sum_i p_i (u_i - A_i) \quad (3)$$

Each user's shortage penalty is multiplied by the difference between their use (u_i) and allocation (A_i). Since shortage penalties increase with water right priority, the objective function motivates shorting junior users first. The appropriative linear program is subject to four constraints, summarized in **Table 4**.

Table 4. Appropriative LP Constraints

Constraint Equation	Purpose
(1) $\sum_{i \in k} A_i \leq v_k - e_k - b_k - \sum_{i \in k} A_R$, $\forall\ k$	Ensures mass balance by requiring that all appropriative allocations upstream of and within a sub-basin k do not exceed the water available at the outlet of that sub-basin after environmental flows, buffer flows, and upstream riparian diversions are accounted for.
(2) $A_i \leq u_i$, $\forall\ i$	Individual user allocations cannot exceed user demand.
(3) $A_i \geq 0$, $\forall\ i$	Individual user allocations must be greater than or equal to 0.
(4) $A_i \geq d_i$, $\forall\ i$	Individual user allocations must be greater than or equal to the public health and safety requirement (d_i) assigned to the user's demand.

To solve the linear programs, DWRAT uses an open-source optimization software package called SolverStudio. SolverStudio is written in Visual Basic for Applications (VBA), but conducts the optimization calculations outside of Excel with the user's choice of 11 different solvers (Mason, 2013). DWRAT uses the Python-based package called PuLP with SolverStudio. SolverStudio does not limit the number of decision variables and allows for a much quicker and efficient solution of the linear programs compared to Excel's native solver.

DWRAT Applications

DWRAT's design allows for straightforward operation and easy to understand results. Environmental flow requirements and/or buffer flows can easily be input in DWRAT to constrain the amount of water available for allocation. DWRAT also can be used to assess water right reliability and the potential for new appropriations over a range of hydrologic conditions. DWRAT's framework allows for the development of a model for any basin in California with available unimpaired flow and water right user data. To date, DWRAT models have been developed for four river basins in California. The Eel River DWRAT was developed first and provided the initial DWRAT framework (Lord, 2015; Lord et. al., 2017). Development of the Russian River DWRAT required the inclusion of an additional linear program for Lake Mendocino Reservation rights, as well as accounting for inflows from the Potter Valley Project (Whittington, 2016). The development of the Sacramento River DWRAT addressed many issues facing the analysis of large basins, including the need to account for water user return flows (Tweet, 2016). The remainder of this thesis details the development and analysis of the San Joaquin River basin DWRAT model.

Chapter 2 – San Joaquin River Basin DWRAT

At 366 miles long, the San Joaquin River is the second longest river in California. The river begins near the 14,000-foot crest of the Sierra Nevada, and flows in a westerly direction off the slope of the Sierras. Upon reaching the Central Valley floor, the river turns to the north, and eventually flows into the Sacramento-San Joaquin Delta. Along the way it picks up several tributaries that drain the western slope of the Sierra, including the Fresno, Chowchilla, Merced, Tuolumne, Stanislaus, Calaveras, Mokelumne, and Cosumnes Rivers. The basin is bounded on the east by the Sierra Nevada and on the west by the Diablo Range coastal mountains, and drains an area of over 15,800 mi^2. The climate in the basin is similar to much of California, with hot, dry summers and cool, mild winters. While the lower elevation rivers in the basin are rain-fed, the Mokelumne, Stanislaus, Tuolumne, Merced Rivers, along with the headwaters of the San Joaquin all drain from high elevation areas of the Sierra Nevada. As such, flow in these rivers is predominantly from snowmelt, which typically sustains streamflow year-round, and supplies significant surface water storage. As is typical in California, the region is also prone to high variability and dramatic shifts in precipitation from year to year. Actual versus unimpaired annual flow and the range of annual variability for the San Joaquin River at Vernalis (entrance to the Delta) and for the Eastside streams (Cosumnes, Mokelumne, Calaveras) are shown in **Table 5** (USGS 2017; CDEC 2017). Differences between the unimpaired and actual flow values are significant, especially for the San Joaquin River at Vernalis.

Table 5. Actual and Unimpaired Flow for San Joaquin Rivers

	Actual Flow		**Unimpaired Flow**	
Gage Location	**Mean Annual* (MAF)**	**Observed Range* (MAF)**	**Mean Annual** (MAF)**	**Calculated Range** (MAF)**
San Joaquin at Vernalis	3.1	0.41 - 15.4	5.6	1.1 - 15.1
Eastside Streams	1.1	0.2 - 3.5	1.3	0.17- 3.9

*For water years 1924 – 2016; **Estimated for water years 1908-2016
Key: MAF = million acre-feet

To counteract the drought-flood variability and to meet the large demands of agricultural users in the San Joaquin Valley, every major stream draining the western slope of the Sierra, except the Cosumnes River, has been dammed to create sizable surface water storage. Several of these dams are part of the Federal Central Valley Project (CVP), which supplies water to farmers in both the San Joaquin and Tulare basins (DWR, 2014; Hanak, et. al., 2017). The CVP diverts so much water from the San Joaquin River at Friant Dam that several reaches of the river often dry up before the river reaches its confluence with the Merced River. To satisfy the demands of right holders on these dry stretches of the San Joaquin River, the CVP's Delta-Mendota Canal releases water into the San Joaquin at Mendota Pool (DWR, 2014). East Bay Municipal

Utility District (EBMUD) and San Francisco Public Utilities Commission (SFPUC) also export large volumes of water from the Mokelumne and Tuolumne Rivers for urban use in the San Francisco Bay Area, respectively. Many water rights supplying federal and local projects are held by the agencies themselves (e.g. Bureau of Reclamation, irrigation districts) and are delivered to their users under individual contracts and priorities (Hanak, et. al., 2017). Figure 5 provides an overview map of the San Joaquin River Basin.

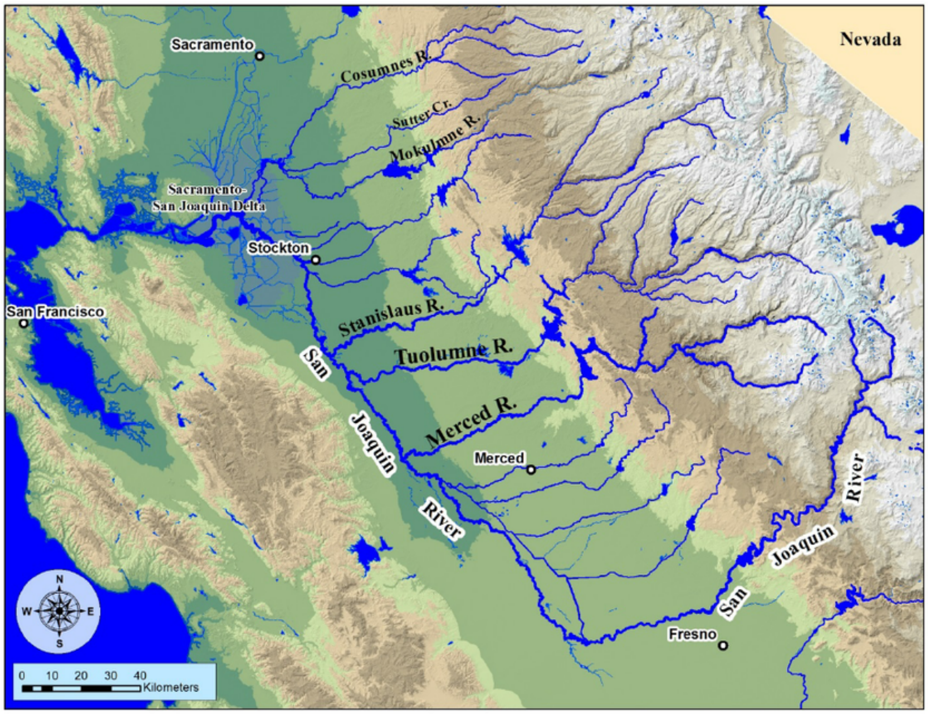

Figure 5. San Joaquin River Basin (Stringfellow, 2014)

The San Joaquin basin's valley floor has been dominated by agriculture since the late 19th century. The basin and the Tulare Lake hydrologic region to the south combine to form California's largest agricultural region, producing about half of California's total agricultural output, while generating $37 billion in farm related revenue for the region as a whole (Hanak, et. al., 2017). Agricultural production in the San Joaquin basin serves state, national, and international demands, and is an important economic driver of the region.

However, large agricultural and growing urban demands have continued to increase water stress and controversy in the region. Shifts from annual to permanent crops have hardened agricultural water demands, and cutbacks in Delta exports to the region over the last 20 years have limited CVP and State Water Project (SWP) deliveries. The Sustainable Groundwater Management Act (Nelson, et. al., 2016) and the SWRCB plan to increase environmental flows on the Merced, Tuolumne, and Stanislaus Rivers (SWRCB, 2016c) will also further increase the demand for surface water supplies (Hanak, et. al., 2017). As such, the most recent drought has made it apparent that a precise and transparent tool is needed to assist with the administration of surface water right curtailments during times of shortage. The San Joaquin DWRAT model was developed for this need.

Unimpaired Flow Data

The San Joaquin DWRAT model uses seven reference stream gage locations for unimpaired flow estimates. Data for the six "valley rim" locations are available from CA DWR's California Data Exchange Center (CDEC), while flow estimates at Vernalis (the basin outlet) are available from the California Nevada River Forecast Center (CNRFC). Unimpaired flow estimates for Vernalis are essentially a sum of the flow estimates for the Upper San Joaquin, Merced, Tuolumne, and Stanislaus Rivers. The data available from CDEC are calculated monthly unimpaired flow, however DWR also publishes April-July forecast flows for some of these points as part of its Bulletin 120 (DWR, 2017). Daily, monthly, and seasonal ensemble unimpaired flow forecasts are produced by CNRFC (CNRFC, 2017). Reference gage locations used by CNRFC mostly have the same locations as CDEC gages. This simplifies comparison between the different flow values, but slight differences require the use of two different flow forecast models for DWRAT analyses, one with CDEC gages for historical analyses, and one with CNRFC gages for historical and forecast analyses. Forecast simulation runs can be useful for planning, so water right holders and agencies can be better prepared for potential curtailment actions.

Figure 6 shows the seven unimpaired flow reference gage locations. The flow in each HUC-12 within the San Joaquin basin is scaled using unimpaired flow data from the reference gage point within each major watershed. For the San Joaquin DWRAT model, each region is largely divided along the major tributary drainage boundaries. HUCs in drainage basins without a reference gage (Calaveras, Fresno, and Chowchilla Rivers or westside HUCs) and HUCs on the Lower San Joaquin River are all scaled from the unimpaired flow reference gage at Vernalis. Further hydrologic analysis could be completed to assign HUCs to different unimpaired flow gages, however this is beyond the scope of this report. **Table 6** summarizes the number of HUC-12s and user statistics (2010-2013 WRUDS use demands) for each reference gage in the basin. For some basins, annual demand is greater or nearly equal to annual estimated unimpaired flow.

Table 6. Unimpaired Flow Reference Gage HUC Statistics

Unimpaired Flow Gage	# of HUCs	# of Riparian Users	# of Appropriative Users	Annual Demand (TAF)	Unimpaired Mean-Annual Flow* (TAF)
Cosumnes - Michigan Bar	29	116	257	78.7	362.6
Mokelumne - Mokelumne Hill	40	205	249	610.5	731.6
Stanislaus - Goodwin Dam	34	125	186	1528.4	1119.2
Tuolumne - La Grange	57	80	195	1230	1836.8
Merced - Merced Falls	37	95	124	866.8	953.9
Upper San Joaquin - Friant	56	61	115	14.5	1727.3
San Joaquin - Vernalis	190	319	696	2404.4	5636.7

*Estimated for water years 1908-2016 (CDEC, 2017)
Key: TAF = thousand acre-feet

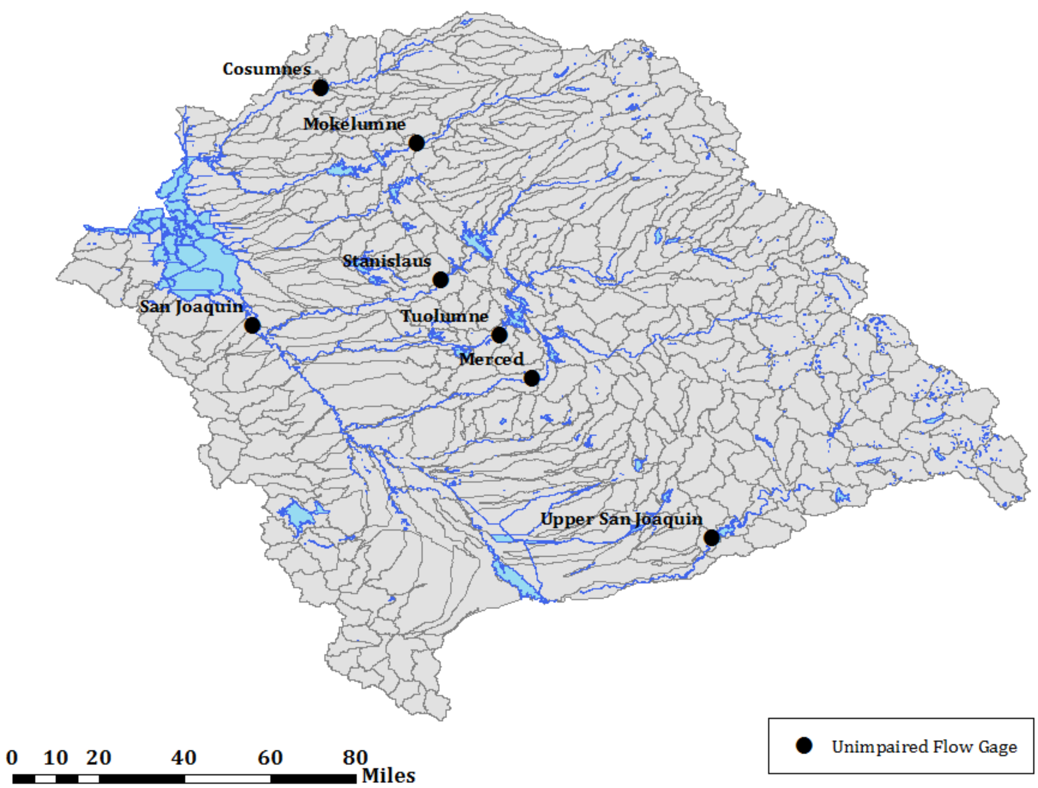

Figure 6. San Joaquin Basin Unimpaired Flow Gage Locations

California DWR produces estimated monthly unimpaired flow volumes for each of the noted gage locations from 1907 to the present. As can be seen in Figure 7, water years 2014 and 2015 were significantly drier than average. Water year 2015 was especially dry during the peak runoff months of March through June, as 2015 had the lowest snowpack in recorded history.

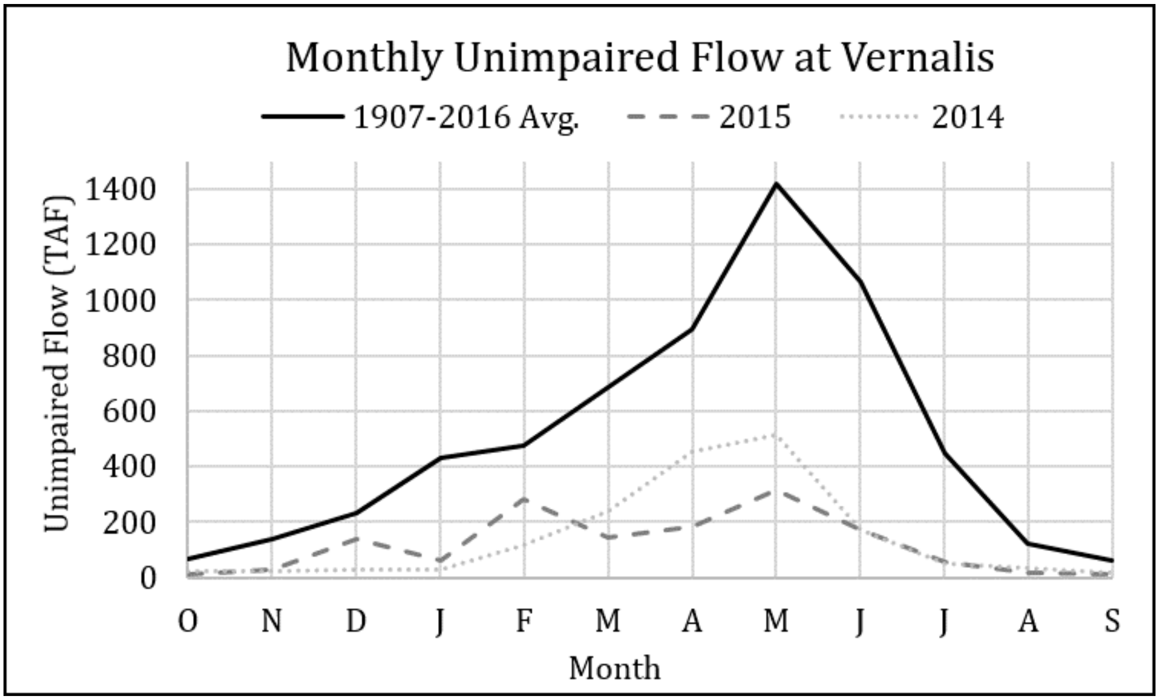

Figure 7. Average Monthly Unimpaired Flow of the San Joaquin River at Vernalis

Water Right User Demand Data

Water right user data for the San Joaquin DWRAT are from the SWRCB's WRUDS database. Users are considered "active" if they have a listed, non-zero use per data available from the 2010-2013 user reports. Using the water right use provides a more realistic representation of water demand for drought management, as DWRAT would likely over-curtail use if water right face values were used. Quantities and statistics of water rights in the basin are summarized in **Table 7**, while Figure 8 shows total riparian and appropriative demands by month. Annual and monthly total riparian demands are much smaller than total appropriative demands. Pre-1914 demands are also less than post-1914 use. As a whole, a small percentage of riparian users are active, while a much greater percentage of appropriative users are active. Despite a small spike in appropriative demand during December for diversions to storage, total demands are largest from March through June, as would be expected for the irrigation season.

Table 7. San Joaquin Basin User Data per WRUDS 2010-2013 Demand

Right Type	Total Users	% of Total Users	Active Users	% of Users Active	% of Total Active	% of Total Volume
Riparian	1001	35.5%	101	10.1%	10.5%	11.3%
Pre-1914 Appropriative	137	4.9%	90	65.7%	9.4%	19.2%
Post-1914 Appropriative	1685	59.7%	770	45.7%	80.1%	69.5%
Total Appropriative	1822	64.5%	860	47.2%	89.5%	88.7%
Total Users	2823	100%	961	34.0%	100%	100%

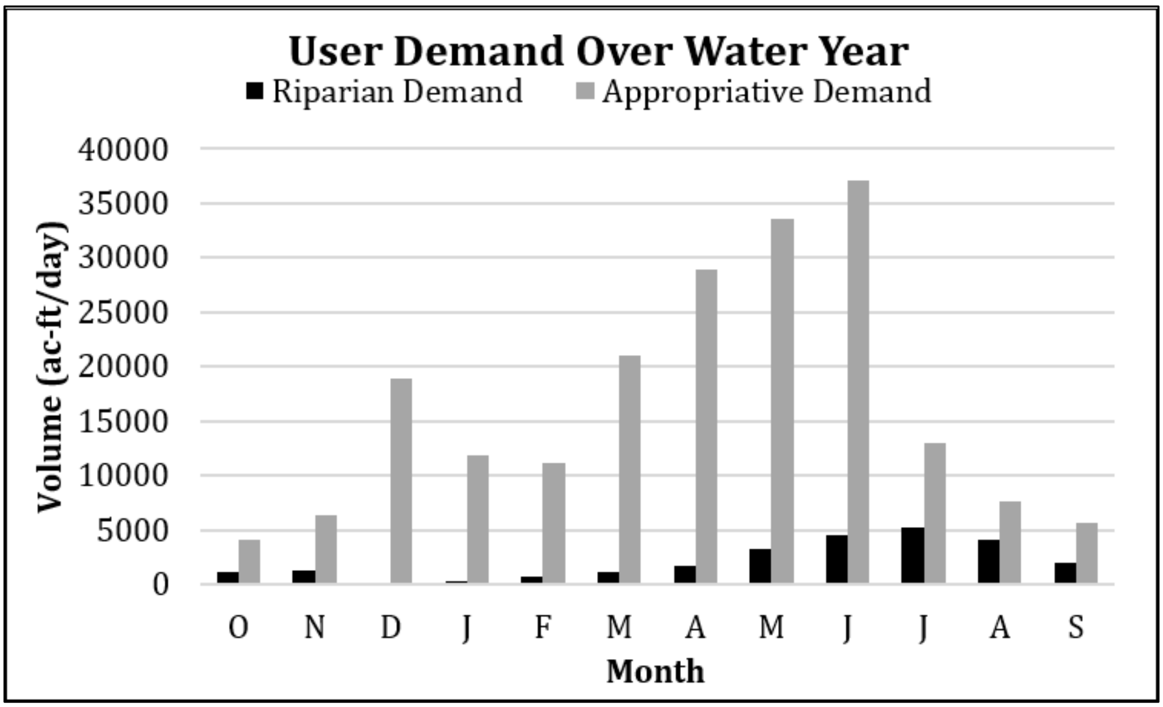

Figure 8. San Joaquin Basin Monthly User Demand by right from WRUDS 2010-2013 Demands

Modeling Issues for Large Basins

DWRAT models of larger basins (e.g., Sacramento or San Joaquin) face several challenges that are of less concern in smaller basins (e.g., Eel or Russian). The most concerning challenges are hydrologic error, computation speed, and consideration of return flows.

Although larger basins typically have additional unimpaired flow gage locations available for use in the hydrologic model, errors from differences in hydrologic and climatic variation are unavoidable. The larger size means in some cases that flow in a HUC-12 is estimated from a gage more than 100 miles away from the HUC-12. While the hydrologic model has been designed and improved to limit such error, model estimates are imperfect and some error will always be present. Furthermore, the significant number and size of reservoirs, diversions, interactions with groundwater, and tributaries complicates estimation of unimpaired flow and water availability. Changes to any of these variables and missing or incorrect data will affect the accuracy of unimpaired flow and water availability estimates, which adds additional error into DWRAT's hydrologic representation.

Larger basins have more HUC-12s and more individual water rights, both of which significantly increase the computation and time to solve each linear program. The San Joaquin basin has 443 HUC-12s, 1001 riparian users, and over 1800 appropriative users. These elements combine to create a significant number of decision variables for the linear programs to solve, leading to computation times of 2.5 and 1.5 minutes (using a desktop PC) each for the riparian and appropriative linear programs, respectively. DWRAT studies requiring the analysis of multiple days or repeat runs of different conditions will require an extended computation time, compared to smaller DWRAT models like the Eel River or Russian River, which require less than 30 seconds to compute each riparian and appropriative linear program.

Lastly, most water uses are not fully consumptive. Some percentage of their original diversion (demand) will return to the watercourse as a return flow and be available for further use in the basin. In large basins, return flows have more opportunity to re-enter the system, accumulate to a meaningful volume, and be available for use by other water right holders. Without considering return flows, DWRAT is more likely to over-curtail water use in a large basin.

Return Flows

Initial DWRAT models assumed each water user consumed the full portion of their demand (gross use). For smaller basins, such as the Eel or Russian River, this assumption produces little error in estimates of water availability. However, for large basins, such as the Sacramento or San Joaquin, return flows can add significant water volumes available for use, particularly in the downstream HUCs of the basin.

Tweet (2016) identified four methods to consider return flows in DWRAT. **Table 8** summarizes the benefits and drawbacks of each method. To consider return flows, DWRAT must first assign a return flow factor to each user based on their beneficial use as defined in WRUDS. Flow factors for users with multiple beneficial uses are set by averaging the factors of each use. Once this is complete, the reduced consumptive use method is straightforward to implement, as a user's demand is simply scaled to be their consumptive demand. Consequently, DWRAT assumes the user's return flow is immediately available to meet other user's demands within the same HUC-12. Conversely, the explicitly return flows downstream method calculates the volume of each water user's return flow and returns the water into the system at the next downstream sub-basin. This method requires an additional linear program to maintain water right priorities given the changes in water availability (Israel & Lund, 1999). The "precisely represent return flows" functions similarly, except the return flow is returned to the system at a discrete sub-basin downstream. This method is currently unrealistic to implement given its intense data and user information requirements. Tweet (2016) subsequently evaluated the "consumptive use diversions" and "explicitly return flows downstream" methods for implementation into the DWRAT framework.

Table 8. DWRAT Return Flow Methods

Return Flow Method	Benefits	Drawbacks
Assume Fully Consumptive Use	- Simplest	- Over-curtails
Consumptive Use Diversions	- Simple to implement - Creates upper bound	- Under-curtails
Explicitly Return Flows Downstream	- Increases water availability accuracy - Creates lower bound	- Over-curtails - Requires additional linear program
Precisely Represent Return Flows	- Most accurate	- Most complicated to implement - Requires point of return data and additional linear program - Time consuming

Tweet (2016) found that the consumptive use diversions method tends to under-curtail water right holders, while the explicitly return flows downstream method tends to over-curtail use. Using both methods provides an upper and lower bound of curtailment requirements, bounding an appropriate decision space. However, additional analysis demonstrated that for surface water return flow factors less than 0.2, the two methods produce nearly identical results. Since most users have surface water return flow factors less than 0.2, the simplicity of the consumptive use diversions method was recommended for current use in DWRAT.

Accordingly, the consumptive use diversions method was incorporated into the San Joaquin DWRAT. Return flow factors for each use were established in a similar manner as detailed by Tweet (2016). 19 possible beneficial uses are identified by the SWRCB, and each user in WRUDS has identified the beneficial use(s) of each water right. These uses include: irrigation, stock watering, domestic, power generation, recreation, mining, milling, aquaculture, fish and wildlife, and snowmaking. Each use is assigned a return flow factor between 0 and 1. Since diversions for the CVP are largely exported out of the basin, the return factors are considered to be 0 for these rights, as they are essentially fully consumptive. **Table 9** summarizes the beneficial uses of San Joaquin basin water rights. Note that many rights serve multiple beneficial uses, so this table allows double counting of water volume leading to total percentages greater than 100%. Figure 9 displays the range of return flow factors for water rights in the San Joaquin, with most water rights having return flow factors less than 0.2.

Table 9. Beneficial Use Statistics for San Joaquin Basin

Beneficial Use	# of Rights	% of Right Holders	Vol. of Water (ac-ft)	% of Total Water
Irrigation / Stockwatering / Aquaculture	1940	68.7%	5,281,591	78.4%
Milling / Mining / Industrial	46	1.6%	1,279,030	19.0%
Domestic / Municipal	367	13.0%	2,827,702	42.0%
Fish and Wildlife / Recreation	887	31.4%	2,161,261	32.1%
Partial Power	147	5.2%	2,612,628	38.8%
Other	402	14.2%	42,415	0.6%

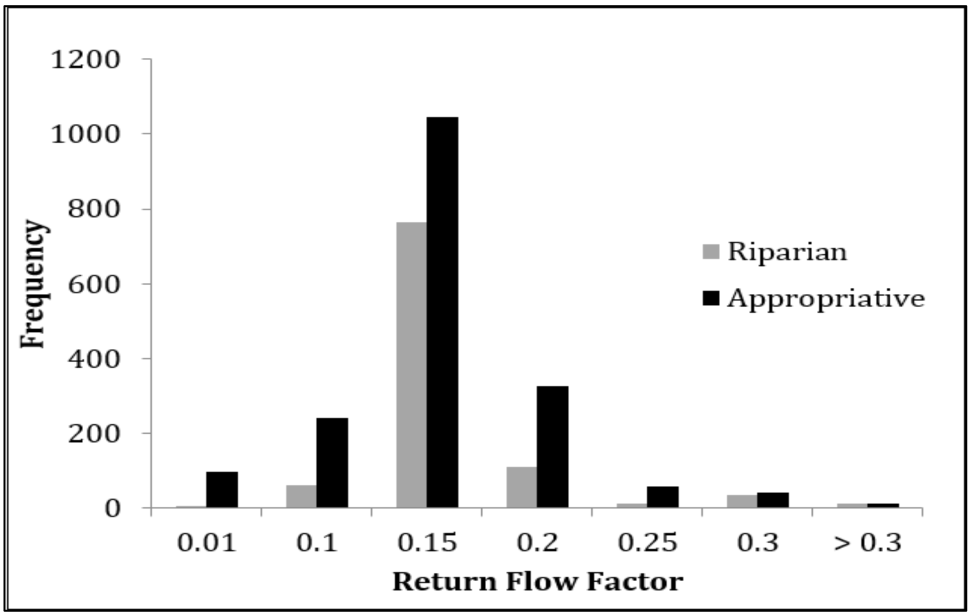

Figure 9. Distribution of Water Right Return Flow Factor for each Water Right

Flow Model – Scaling Ratio Analysis

DWRAT's unimpaired flow representation estimates available unimpaired flow throughout the basin with scaling ratios. The scaling ratio provides a simple, straightforward way to estimate flow, but includes some error. To limit this error, flows from similarly dry years or combinations of dry years can be used for the scaling ratio. Initial versions of DWRAT used water year 1977 unimpaired flow estimates for HUC-12 scaling ratios, as water year 1977 was the driest year on record for much of California. It was thought that 1977 provided an appropriate comparison for dry year flow estimates. However, no two dry years are alike, and even an extremely dry year overall will likely have relatively wet or average periods. Whittington (2016) demonstrated the usefulness of calculating "dry-year average" scaling ratios for the Russian River. Similar analysis completed in this report demonstrates the same usefulness of dry-year averages for the San Joaquin DWRAT.

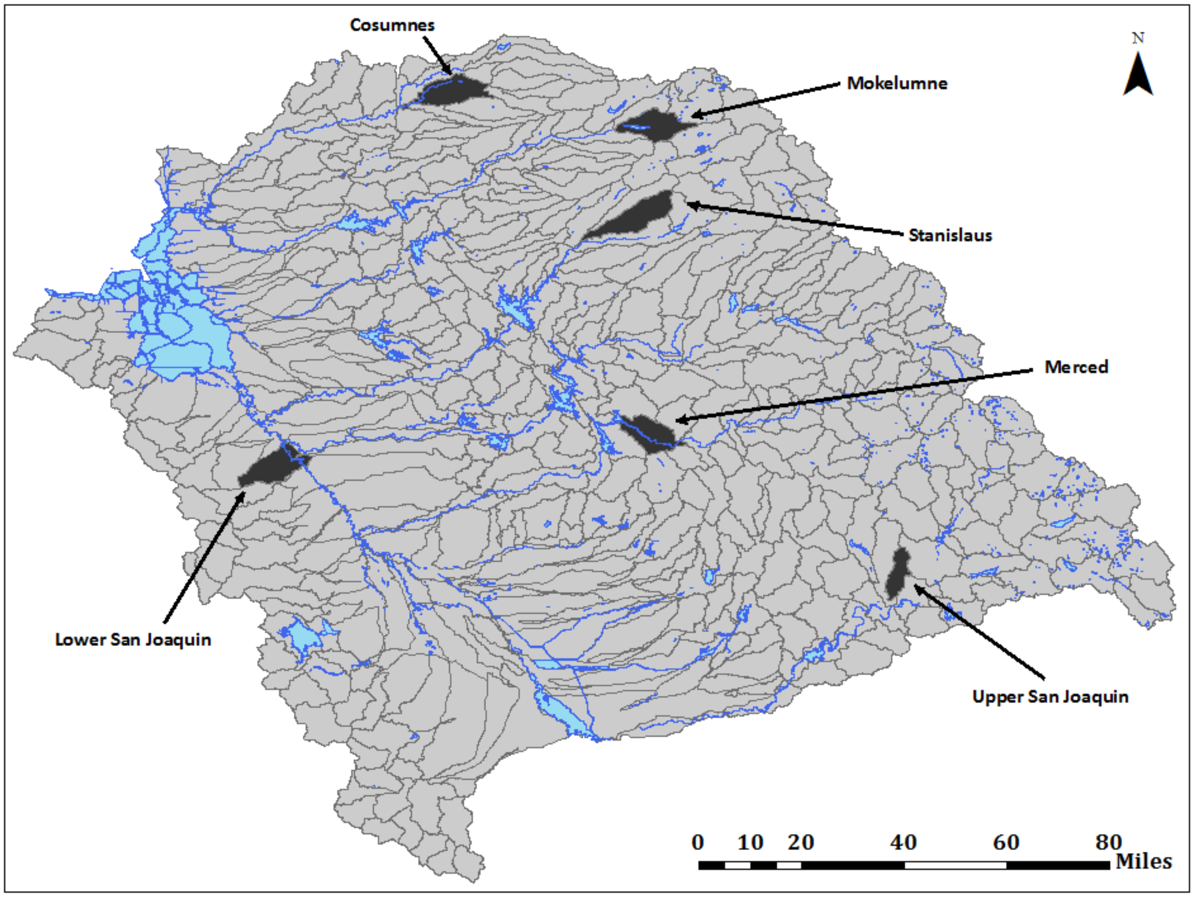

Figure 10. Shaded HUC-12's represent HUC's used in Figure 11 analysis

Figure 11 demonstrates the potential error from only using one year (e.g. 1977) in the scaling ratio equation. Flow ratios were calculated for the 13 driest years (between 1950-2011) in the San Joaquin River basin for each month, as the 13 driest years represent the bottom 20th percentile of precipitation totals for the water year. Six HUC-12s were chosen to demonstrate the variation seen relative to the HUC's location in the basin. The HUCs are identified in the plot by the tributary they reference, with mapped locations shown in Figure 10. For simplicity, only October, January, April, and July are shown to demonstrate seasonal variation.

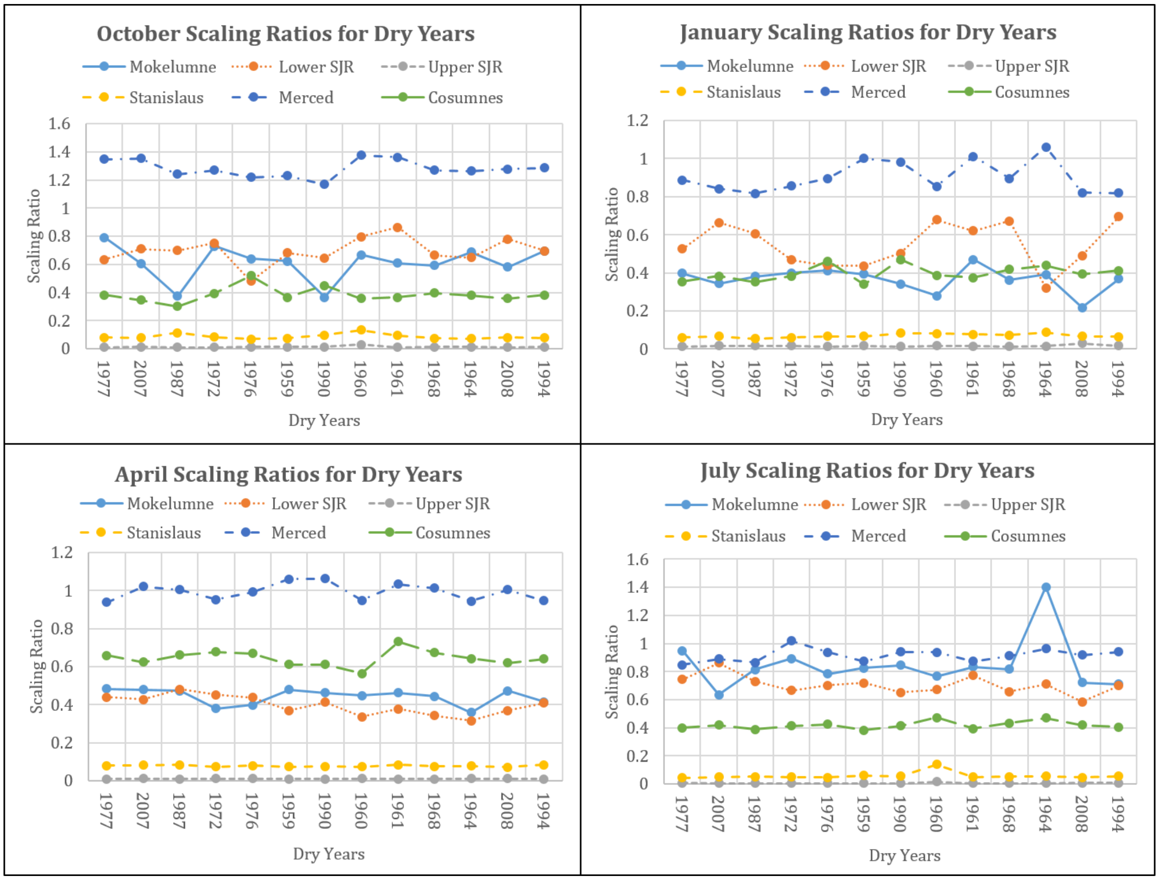

Figure 11. Scaling Ratio Variation of Dry Years for October, January, April, and May

Even among dry years there can be significant variation in the monthly scaling ratios, especially in HUCs with higher flows lower in the watershed (e.g. Lower San Joaquin and Merced). Likewise, HUCs further up in the watershed, not on the mainstem river (e.g. Stanislaus and Upper San Joaquin), have lower scaling ratios that are more consistent among years. The wetter months of October and January have the highest variation in scaling ratios among dry years, while April has less variability, likely because these rivers are largely snowmelt driven. No matter how dry the year has been, some snowpack accrued during winter, and some runoff will occur. July has very little variation, except for one year of the Mokelumne HUC. This HUC's location is on the mainstem river, but high in the watershed. Even as part of a dry year overall, enough snowpack or groundwater baseflow could have remained into the summer to produce this outlier.

Further analysis indicated that the distribution of scaling ratios for each HUC-12 over the dry years was largely symmetric, centered on the mean, and that all values fell within 3 standard deviations, indicating a roughly normal statistical distribution. As such, (similar to Whittington, 2016) using the average of the dry years as the input to the scaling ratio equation allows the flow model to produce more balanced and realistic flow estimates. However, error will remain in the scaling ratio representation. To further identify locations where errors are more likely, the normalized standard deviation (or coefficient of variation) was calculated for each HUC-12 and for each month of the year. The coefficient of variation is calculated by dividing the monthly standard deviation by the monthly average. This calculation allows for direct comparison of one sub-basin to another and from one month to another. Again, only values for October, January, April, and July are shown.

HUC-12 coefficient of variation values are similar to other HUCs within four specific regions of the basin for each month. For the San Joaquin basin, HUCs along the "mainstem" (the San Joaquin and all gaged tributaries), in the upper locations of the watershed, in the valley floor and foothill areas, and the westside of the basin have similar coefficient of variation values similar to HUCs within that region. Figure 12 summarizes these results as a set of box and whisker plots. The boxes indicate the middle 50% of values in the basin, while the whiskers indicate the upper and lower extents of computed values.

Across all months, coefficient of variation values are lowest in HUCs along the "mainstem" of each major river. Whittington (2016) noted similar results for the Russian River, as unimpaired flow estimates closest to gage locations were the most accurate predictions. Values in October are somewhat more variable in all locations, as winter storms begin affecting California. Values in January have the highest coefficient of variation values across the basin. January is one of the wettest months across California, which would produce a significant amount of variation in hydrologic conditions, even in dry years. Low levels of variation are seen in the upper watersheds in April, while the westside and valley/foothill areas have significant levels of variation. Flow in April in the upper watershed will be sustained by snowmelt, even in dry years, while flow in the westside and valley HUCs largely depends on how wet or dry April is. As noted by Whittington (2016), the standard deviation of flow ratios decreases in summer, as the lack of summer precipitation in California's climate means less variation among dry years. The lowest overall coefficient of variation values in the basin occurs in July.

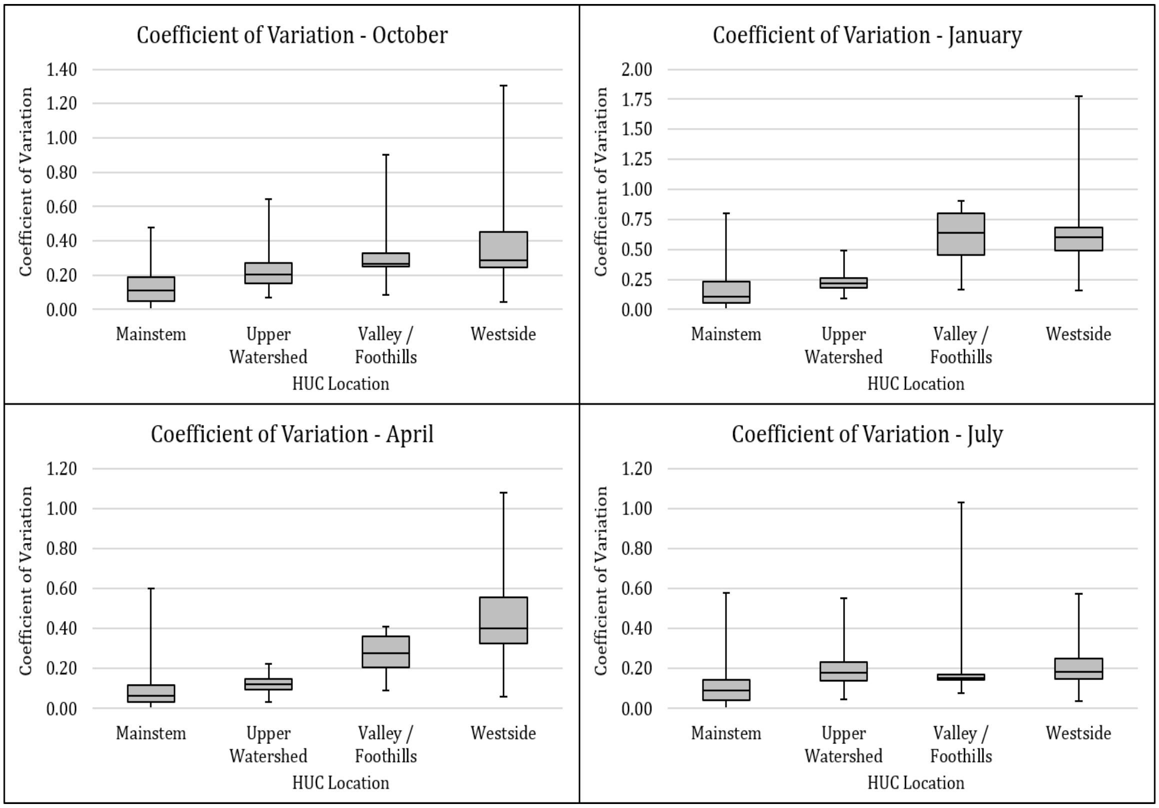

Figure 12. Coefficient of Variation by HUC location for all dry years

For the most part, the largest coefficient of variation and the widest distribution of values in each month are in the westside HUCs and the HUCs of the ungagged foothill rivers (Calaveras, Fresno, and Chowchilla Rivers). Areas or streams with consistently large coefficients of variation indicate locations where additional unimpaired flow estimates could be useful. Adding unimpaired flow estimates for the Calaveras, Fresno, and Chowchilla Rivers would likely reduce potential for error in the unimpaired flow forecasts for these areas.

As noted, using the dry-year average scaling ratio produces a more consistent estimate of dry-year hydrologic conditions. However, it might not be the best option for all locations in the watershed, especially given the spatial variability in large basins like the San Joaquin. Tweet (2016) suggested using past years' scaling ratios that best resemble current drought conditions, and even using different reference ratios for different locations in the basin. This would require additional calibration, as different years or combinations of years could be used for different locations in the watershed. Unfortunately, such work is beyond the scope of this thesis. However, research to improve the hydrologic model has been completed and detailed in a report by Magnusson-Skeels (2016).

Chapter 3 – San Joaquin DWRAT Results

DWRAT suggests water shortage and curtailment decisions for a diverse set of water right holders, scattered over a large basin, at an average daily or monthly timestep. Historical hydrology and user demand can be input to analyze past dry periods, or forecast hydrology and expected user demands can be input to prepare for future drought conditions. Although not noted in the results that follow, DWRAT curtailments do distinguish between physical shortage (water availability) and administrative curtailments (water right priority).

To demonstrate DWRAT's results for the most recent drought and for forecast decisions, the San Joaquin DWRAT model was run with observed data for water years 2014 and 2015, and with forecast unimpaired flow data for the 2016 summer season. For each analysis, unimpaired flow and user demand data were available at a monthly timestep. As such, results available in each analysis are for a single representative day in each month. Actual daily modeling would require hydrologic routing to account for flow lag and travel time in a large basin. The 2014 and 2015 DWRAT results were then compared to SWRCB water shortage actions in both years. In both years, DWRAT typically shorts a greater percent of users and total use in the basin compared to the Board's actions. Further analysis of this comparison demonstrates the differences between the Board's aggregated watershed approach and DWRAT's spatially disaggregated approach to calculating water availability and shortages. 2015 results including return flows also were calculated to demonstrate the effects of return flows on water availability and user shortage.

Additionally, a range of forecast unimpaired flows for the 2016 summer season was input to demonstrate DWRAT's ability to generate forecast curtailment decisions. Forecast model runs can be useful for water rights administrators and water right holders to make management decisions given potential flow conditions. However, as the results demonstrate, forecasting unimpaired flow can be very difficult, even in California's dry summer months.

2014 Results

Hydrology at reference gages for water year 2014 was obtained from CDEC and input to DWRAT to suggest optimal shortage decisions. HUC-12 scaling ratios were based on the dry-year average scaling ratio calculation, as detailed in Chapter 2. Figure 13 shows the percent of users (a) and percent of normal use (b) shorted by DWRAT for both riparian and appropriative users for a representative day in each month during water year 2014. The basin outlet flow in each month is included to contrast overall water availability against the percent of users and normal use shorted by DWRAT. Water year 2014 was exceptionally dry in the San Joaquin basin, particularly in the early winter months. December through February flows were significantly less than normal, and the reduced snowpack resulted in lower volumes of snowmelt runoff in March, April, and May. The reduced snowpack also meant that flows were much lower in the summer than normal, as most snowpack had already melted. As such, DWRAT shorted a significant percentage of appropriative users throughout the year, with the percent of users shorted exceeding 70% in each month except February through April, and over 90% in October and from July through September. The percent of appropriative use shorted followed a similar trend, except from February to May, when flows were somewhat higher and several large appropriative rights were allowed to divert. DWRAT also shorts nearly 100% of normal demand from July through September.

Since the riparian doctrine requires shortage to be shared proportionally among all users, riparian users are only shorted their full demand if no water is available in their basin. However, DWRAT considers a user shorted if any percentage of their use is shorted. This can be misleading if one only considers the percent of users shorted. For example, in August and September, the percent of riparians shorted jumps from 53% to 86% but the percent of use shorted actually drops from 72% to 69%. In this case, water availability and location of demands dictate that a greater percentage of active users must share shortage in September, even though the percent of use shorted is smaller. Most riparian rights are small, and riparian demands as a whole are small during the winter and early spring. Accordingly, DWRAT shorts a small percent of riparian users and volume in the winter and early spring of 2014, mostly in the upper tributaries. However, dry conditions in the fall and summer required DWRAT to short more than half of riparian demand in October, November, and from July through September.

2014 was the third year of California's most recent drought, and was also when the effects of the drought became especially acute. In response, Governor Jerry Brown declared a drought state of emergency for all of California on January 17, 2014 (Brown, 2014). As part of this declaration, the governor directed the SWRCB to assess the need to direct water right holders to reduce or cease water diversions based on water shortages. The Board deemed that such action was necessary for multiple basins in California, and for the first year since 1977, the SWRCB issued notices of water unavailability. **Table 10** summarizes the Board's actions in the San Joaquin basin during 2014.

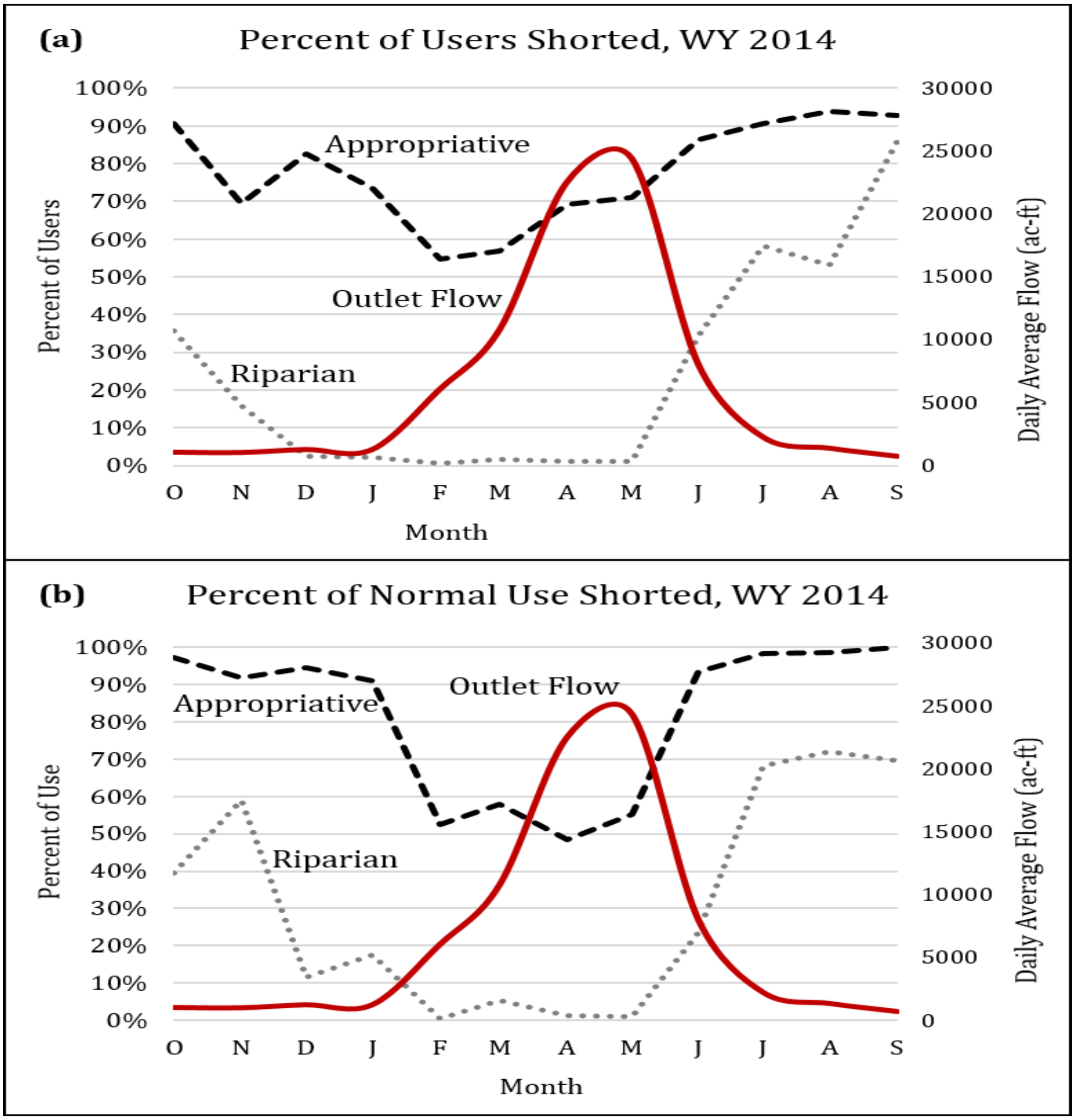

Figure 13. Percent of Users and Normal Use Shorted vs. Basin Outlet Flow for Water Year 2014

Table 10. Water Year 2014 – SWRCB Water Shortage Actions

Date	Notices Directed To:
5/27/2014	1914 and junior appropriative rights in San Joaquin basin received water shortage notice
10/31/2014	All appropriative rights received notice of temporary diversion opportunity
11/3/2014	1914 and junior appropriative rights in San Joaquin basin received water shortage notice
11/12/2014	All pre-1953 appropriative rights received notice of diversion opportunity
11/19/2014	All appropriative rights received notice of diversion opportunity

The shortage actions taken by the Board in 2014 were applied to the San Joaquin DWRAT user database, with 2010-2013 average demands. The results of these actions were then compared to the 2014 DWRAT results. Figure 14 shows the percent of users (a) and percent of normal use shorted (b) by DWRAT as compared to SWRCB actions. The Board's actions only apply to appropriative users in the basin, but DWRAT suggests some riparian shortage. While riparian use is a small percentage of total use in the basin in the winter and spring, the volume of riparian use in July through September is a much larger percentage of total demand, and can certainly affect water availability in drought conditions. Overall, DWRAT shorts 10-15% more appropriative users and 6-26% more percent of normal use than SWRCB actions from June through October. DWRAT shorts a significant number of appropriative users throughout water year 2014, while the Board's actions did not begin until the end of May. While some differences between DWRAT and SWRCB results can be from differences in water availability estimates, most of the difference in results is likely due to differences between the Board's aggregated watershed shortage approach and DWRAT's spatially disaggregated approach. Further analysis could be completed to compare DWRAT and SWRCB actions by inputting SWRCB water availability estimates into DWRAT's flow model.

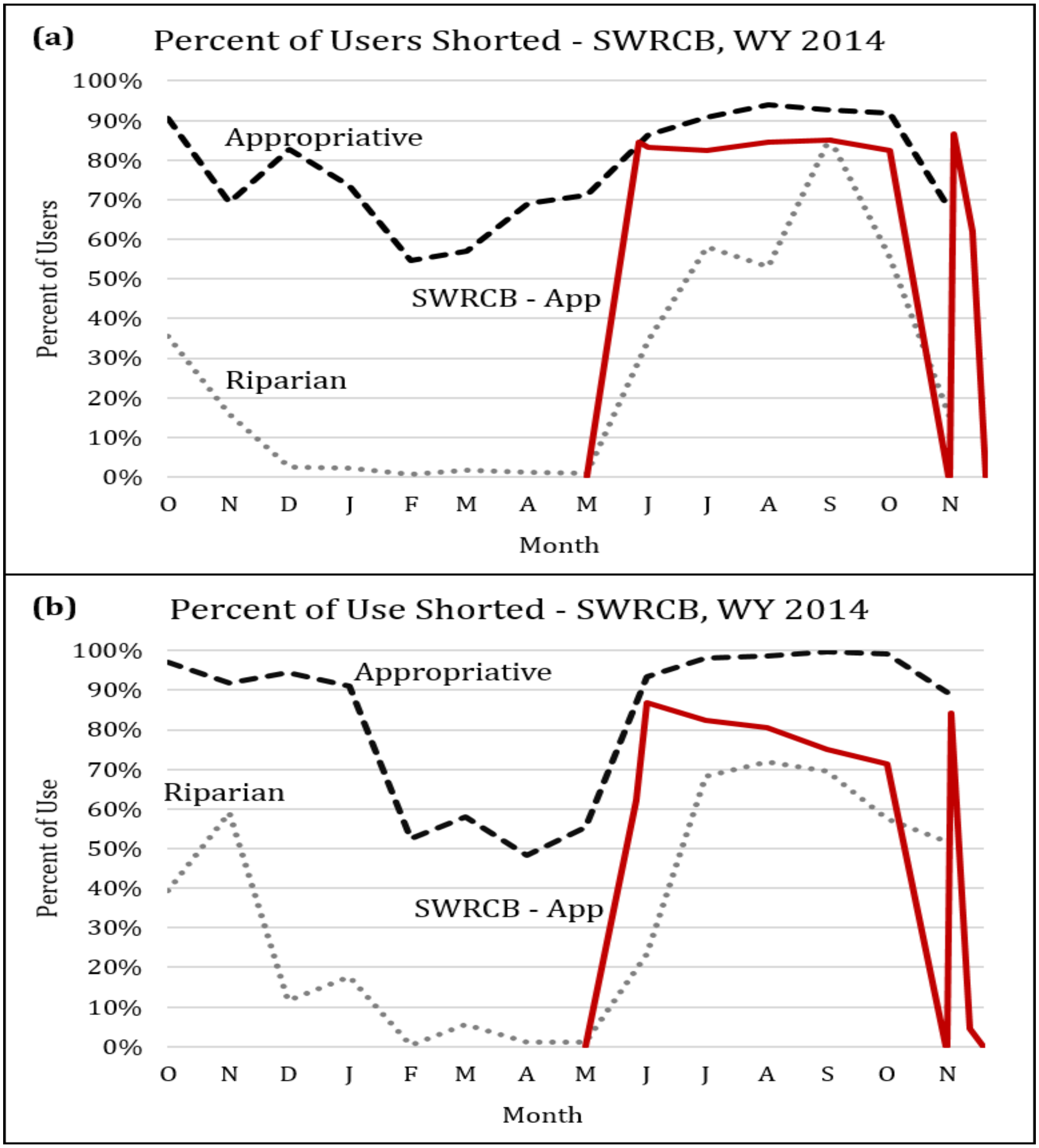

Figure 14. Percent of Users and Normal Use Shorted vs. SWRCB Actions for Water Year 2014. SWRCB curtailments apply only to appropriative users.

Figure 15 shows how user priority and location in the watershed affect DWRAT curtailment decisions in June 2014. In June, there are 397 active riparian users and 426 active appropriative users. Although all riparian users are equal in priority to each other and senior to appropriators, here they are ranked in "priority" by their percent of normal use shorted. Conversely, all appropriative users are ranked by their priority date. In Figure 15, user priority is plotted against percent of normal use shorted, where 0% means a user receives their full demand, and 100% means a user is shorted their full demand. Most riparian users are shorted a comparable percent of their normal use (between 10-20%), but a few users in downstream HUCs are shorted less than 10% and several users with large demands in upstream HUCs are shorted nearly 100%. For appropriative allocations, DWRAT's spatially disaggregated approach allows the model to account for local water availability by considering supply and demand at the HUC-12 scale. As such, DWRAT shorts a significant number of senior (pre-1914) users, while providing a full allocation to a considerable number of relatively junior users. All pre-1914 appropriative users shorted by DWRAT are in HUCs in the upper reaches of the watershed, most of which are users in the especially dry Cosumnes and Mokelumne basins. However, several other senior users were shorted simply by limited water availability and/or the need to satisfy demands of more senior downstream users. Likewise, the post-1914 appropriative users shorted 0% by DWRAT are mostly in downstream HUCs in the valley floor, where water availability is much higher. DWRAT allocated partial shortages to seven appropriative users in the basin. Six of these users are in upstream HUCs (2 on the Tuolumne, 1 each on the Cosumnes, Calaveras, Stanislaus, and Merced), which run out of water locally before being constrained by their right. One user (the most junior) is in a downstream HUC off of the mainstem San Joaquin. Results such as this indicate DWRAT is following the appropriative doctrine, while also considering spatial variability in demand and supply. DWRAT is requiring enough flow to remain instream in the upstream HUCs to satisfy more senior users' demands downstream.

Figure 15 also shows how DWRAT's spatially disaggregated approach to shortage compares to the Board's aggregated watershed approach. The dashed line for SWRCB action is at the most senior post-1914 appropriative user. By the Board's actions, that user and all users to the right of the line were shorted 100% of their demand, while all users to the left of line are shorted 0%. DWRAT's design and methods allow for a more detailed accounting of the spatial variability in demand and supply within the basin. Compared to the Board's actions, DWRAT's approach allows some junior users in downstream locations with greater water availability (group A) to receive their allocation, while some senior users in basins with limited availability (group B) are shorted.

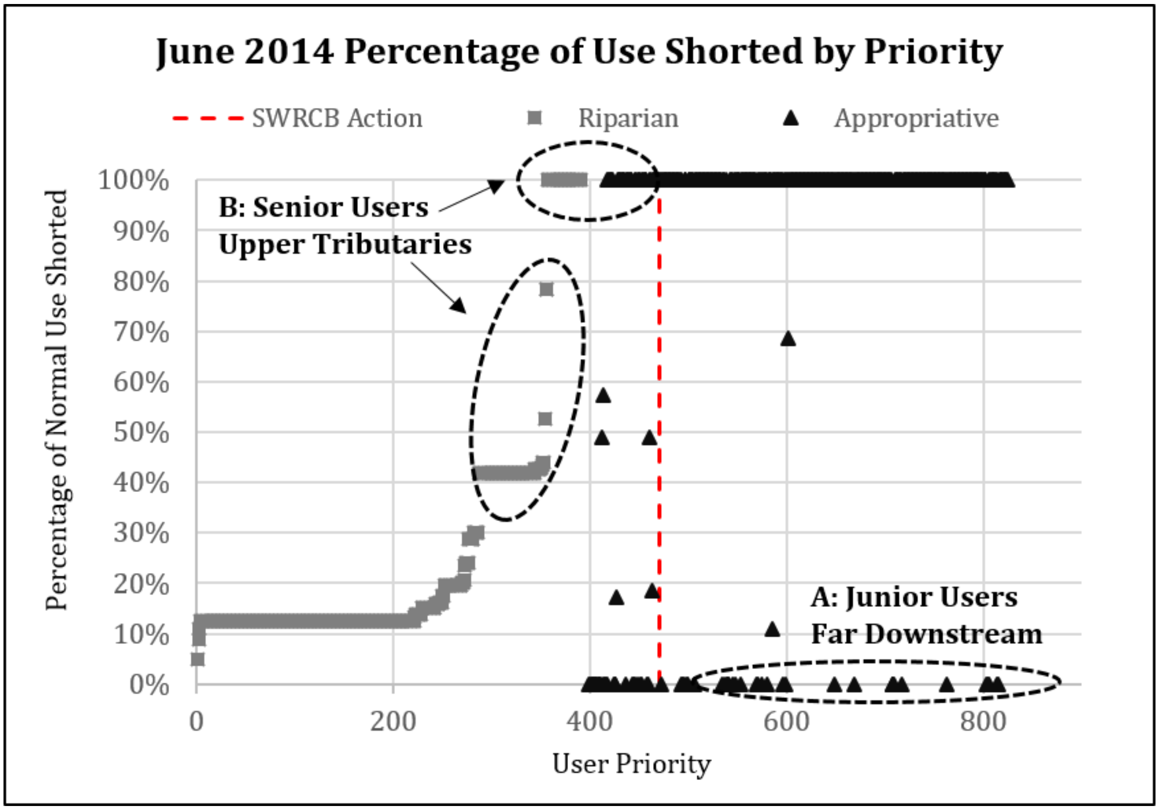

Figure 15. Percent of normal use shorted by DWRAT compared to SWRCB actions

2015 Results

The drought continued into Water Year 2015, and for much of the San Joaquin basin, conditions were even drier than 2014. The April 1st snowpack in the San Joaquin basin was 5% of normal, the lowest measured in the 75-year period of snow records (DWR, 2015). Hydrology at reference gages for water year 2015 was obtained from CDEC and input to DWRAT to suggest optimal shortage decisions. Figure 16 shows the percent of users (a) and percent of normal use (b) shorted by DWRAT for both riparian and appropriative users for a representative day in each month during water year 2015. The basin outlet flow is included to contrast overall water availability against the percent of users and normal use shorted by DWRAT. Flow as a whole was even less in 2015 than 2014, with peak flow occurring in March. The dismal snowpack led to minimal spring snowmelt runoff, and unimpaired flows at gage locations throughout the basin approached zero by the end of the summer. Small storms in December and February provided some relief from shortages, as DWRAT shorted a small percent of total use in February. However, DWRAT shorted some percent of riparian use in every month except December and February, and in August shorted over 90% of riparian users. The percent of appropriative users and percent of normal appropriative use shorted by DWRAT was over 70% in every month except February, and extremely low flows in August and September forced DWRAT to short 99% of normal appropriative demand. DWRAT's actions are not surprising, as estimated unimpaired flow at the gage location for the Mokelumne River was zero in August and September, zero for the Stanislaus River in September, and near zero for the Cosumnes River in September.

The continued dry conditions led the SWRCB to again issue water shortage notices to all post-1914 appropriative rights in the San Joaquin basin beginning on April 23, 2015. Further notices of water unavailability affecting more senior users were issued throughout the summer. The Board's actions for 2015 are summarized in **Table 11.**

Table 11. Water Year 2015 – SWRCB Water Shortage Actions

Date	Notices Directed To:
4/23/2015	1914 and junior appropriative rights in San Joaquin basin received water shortage notices
6/12/2015	1903 and junior appropriative rights in San Joaquin basin received water shortage notices
6/26/2015	All Upper San Joaquin appropriative rights, 1858 and junior appropriative rights on the Merced, several City & County of San Francisco appropriative rights on the Tuolumne received water shortage notices
10/27/2015	All pre-1914 appropriative rights received notice of diversion opportunity
11/2/2015	All appropriative rights received notice of diversion opportunity

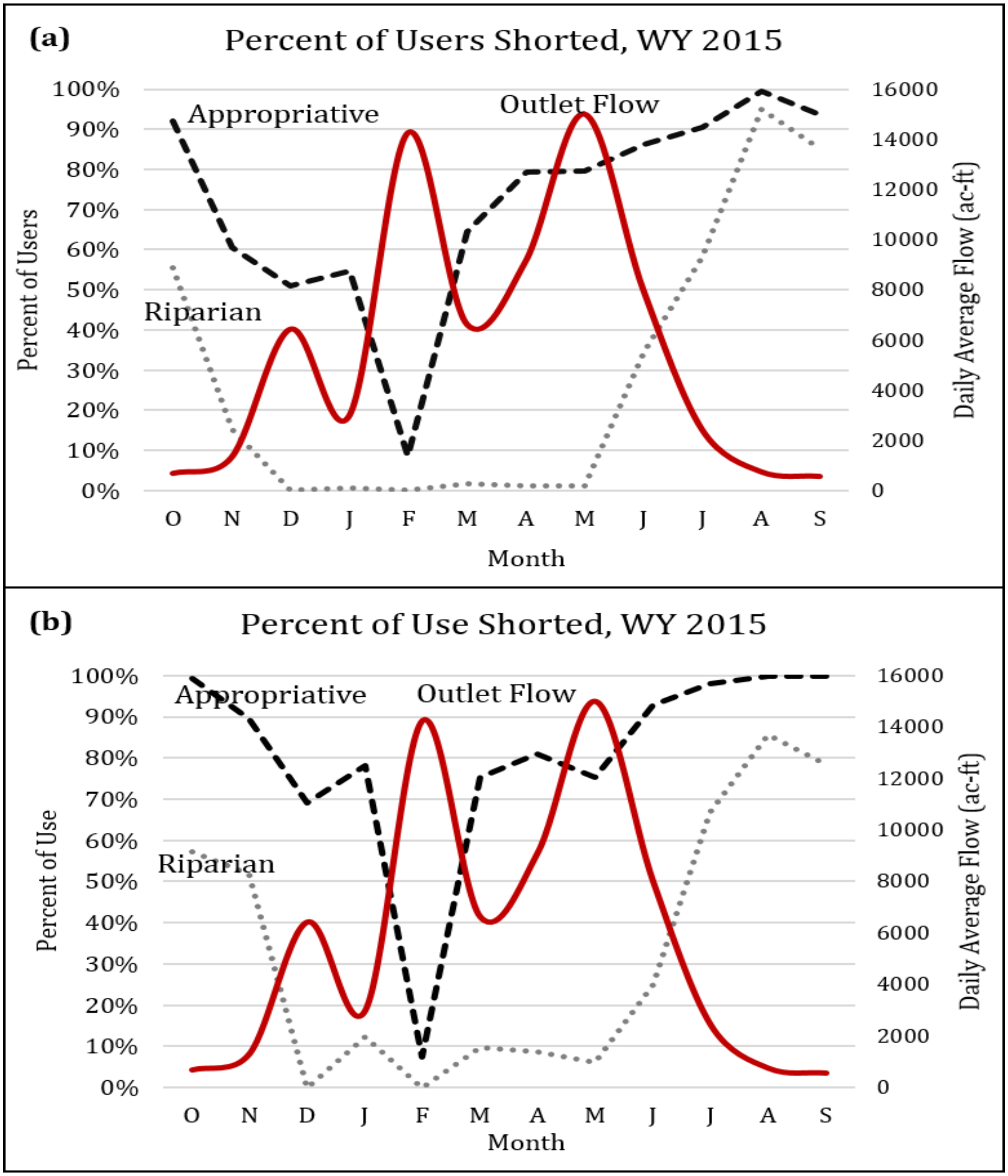

Figure 16. Percent of Users and Normal Use Shorted vs. Basin Outlet Flow for Water Year 2015

The shortage actions taken by the Board in 2015 were also applied to the San Joaquin DWRAT user database, with 2010-2013 average demands. The results of these actions were then compared to the 2015 DWRAT results. Figure 17 shows the percent of users (a) and percent of normal use (b) shorted by DWRAT as compared to SWRCB actions. Again, SWRCB actions only applied to appropriative users, and the Board did not begin to issue water shortage notices until April 23rd. Conversely, DWRAT shorts both riparian and appropriative users and shorts appropriative use throughout the year. Differences between DWRAT and SWRCB actions are similar to 2014 results, although the differences between results of the two approaches are less in 2015. The Board shorts a larger percent of appropriative users in April, May, and November. However, April and November SWRCB actions did not apply for the whole month as DWRAT's actions do. For June through October, differences between the percent of normal use shorted hovers around 15%. DWRAT continues to short a greater percent of users and a greater percent of normal use, likely due to DWRAT's spatially disaggregated approach. However, in reality some senior users might have physically run out of water before being administratively shorted by SWRCB actions.

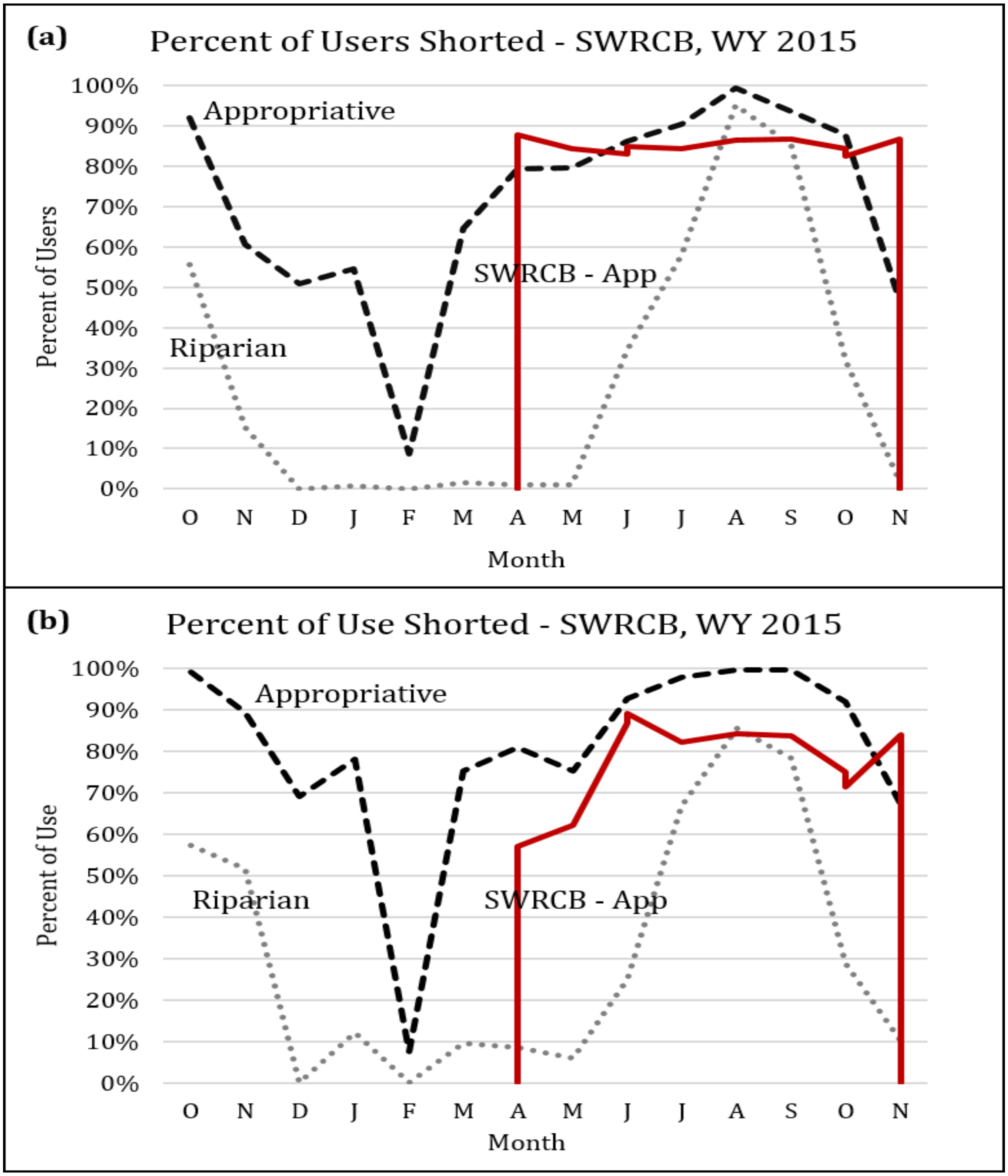

Figure 17. Percent of Users and Normal Use Shorted vs. SWRCB Actions for Water Year 2015.

Figure 16 demonstrates the percent of normal use shorted by DWRAT by user priority, compared to the Board's actions on June 12, 2015. The results for June 2015 are very similar to the June 2014 results. For 2015, the dashed line indicates the priority of an appropriative user with a priority date of 1903. This user and all lower priority appropriative users (to the right of the line in Figure 18) were shorted 100% of their demand by the Board. Conversely, DWRAT again shorts several users more senior than the 1903 priority date, but does not short several other users more junior than 1903. The post-1914 appropriative users shorted 0% by DWRAT (group A) are mostly located in downstream HUCs in the valley floor. Likewise, the more senior users shorted by DWRAT (group B) are again in upstream HUCs, most of which are users in the especially dry Cosumnes and Mokelumne watersheds. However several other senior users were shorted simply by limited water availability and/or the need to satisfy demands of even more senior downstream users. Five of the seven appropriative users that received a partial allocation in June 2014 are the same users that received a partial allocation in June 2015, but all seven users are in the same tributaries as the 2014 results. Figure 18 again shows the differences in shortage decisions between DWRAT's spatially disaggregated approach versus the Board's aggregated watershed approach.

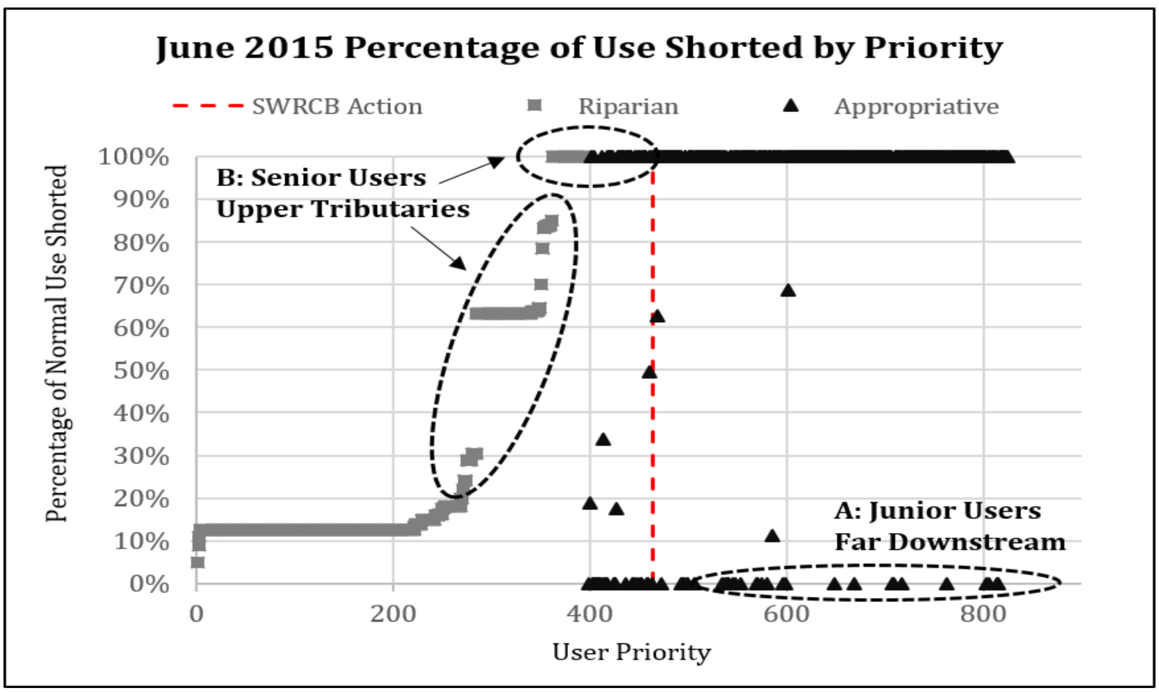

Figure 18. Percent of normal use shorted by DWRAT compared to SWRCB actions on June 12, 2015

2015 Results with Return Flows

In large basins such as the San Joaquin, the inclusion of user return flows can significantly affect the volume of water available, especially in drought conditions. As such, the Consumptive Use Diversions return flow method was incorporated into the San Joaquin DWRAT model, as discussed in Chapter 2. DWRAT results with and without return flows for water year 2015 were compared to demonstrate differences in shortage decisions. Results were also compared to 2015 SWRCB actions. Figure 19 shows the percent of riparian users (a) and the percent of normal use (b) shorted by DWRAT in water year 2015, for DWRAT runs with and without return flows.

The inclusion of return flows does not reduce the number of riparian users curtailed by DWRAT. Since riparian right holders share shortage equally, the additional water available from return flows does not release any users from curtailment. The inclusion of return flows does reduce the total volume of riparian shortage. However, relative to the volume that demand is reduced, the percent of normal shorted is only reduced by about 1% each month. The inclusion of return flows also has minimal effects on several large riparian rights in upstream HUCs, which in turn minimizes the effects to the basin as a whole. When riparians are shorted, there is little upstream use to provide return flows. Furthermore, in most months the percent of riparian users shorted is less than the percent of normal use shorted. Riparians are shorted proportionally across the basin and most are small uses, so it would be expected that the percent of users shorted would be greater than the percent of normal use shorted. However, the demands of these large upstream riparian rights are a large percent of riparian use in the basin, and the hydrologic availability in the basin is rarely enough in dry years to meet their full demand.

DWRAT results for appropriative users with return flows tell a similar story, as shown in Figure 20. The inclusion of return flows reduces the percent of appropriative users (a) shorted in every month, but only by 0.2 to 4.2%. Including return flows brings the percent of users shorted in slightly better agreement with the Board's actions. The difference in percent of normal use (b) shorted between DWRAT with and without return flows is similarly consistent across all months. Including return flows reduces the percent of use shorted between 1.6 and 5.6% each month. The results indicate that reducing demand to consumptive use increases water availability so DWRAT can reduce shortage to some small appropriative users. The percent of normal use shorted by DWRAT with return flows also becomes more consistent with SWRCB actions, although it is still about 13% larger.

Figure 19. Percent of Riparian Users and Use Shorted for Water Year 2015, with and without return flows

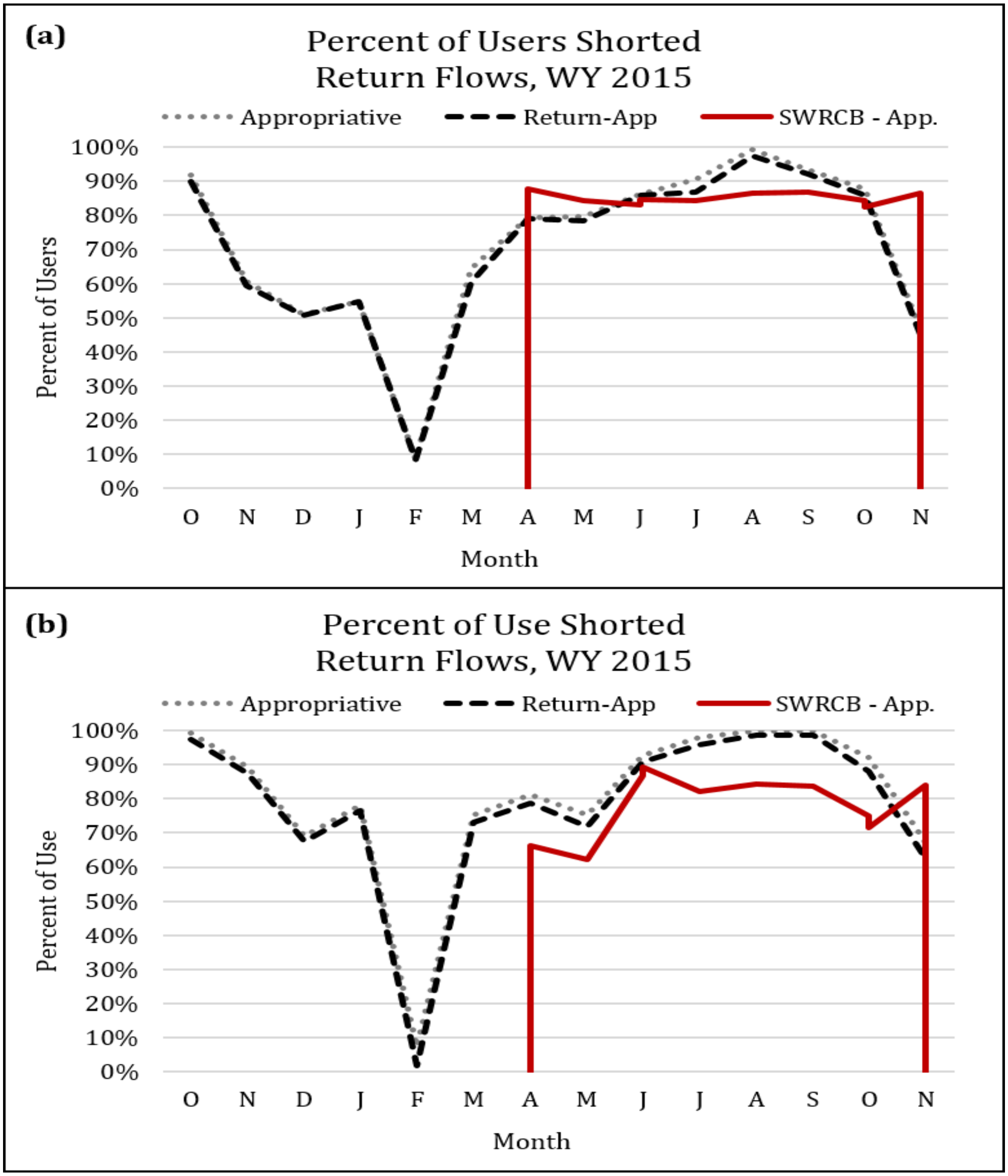

Figure 20. Percent of Appropriative Users and Use Shorted for Water Year 2015, with and without return flows as compared to SWRCB actions

Forecast Flow Analysis

DWRAT can be used with forecast unimpaired flow forecasts to suggest future shortage decisions. For each unimpaired flow gage in the San Joaquin River basin (and for river locations throughout California) the CNRFC produces daily unimpaired flow volume forecasts and monthly volume forecasts (updated daily) for the remainder of the water year (CNRFC, 2017). Monthly volume forecasts are produced for the 90, 75, 50, 25, and 10% exceedance probability levels. Each of these forecasts can be input to

DWRAT to produce five different exceedance level shortage forecasts. Monthly volume forecasts from May 1, 2016 for the remainder of water year 2016 were input to DWRAT to demonstrate the use of these forecasts. Although most water users would likely make water supply decisions earlier in the season, this forecast is used to show the inherent difficulty in water availability forecasts. Figure 21 displays the flow at the basin outlet for a representative day in each month for each exceedance level. The actual unimpaired flow for May was included to demonstrate the antecedent conditions in the basin, and for June through October to demonstrate the accuracy of the forecast. Although CNRFC updates these forecast flows daily, these results only use the monthly forecast flows produced on May 1, 2016. While model runs with data such as this would not be used to make long-term curtailment decisions, they provide a useful planning outlook for water right users and administrators. Figure 21 also shows how difficult long-term forecasting for hydrologic conditions in California can be, even for low flows in the dry summer months.

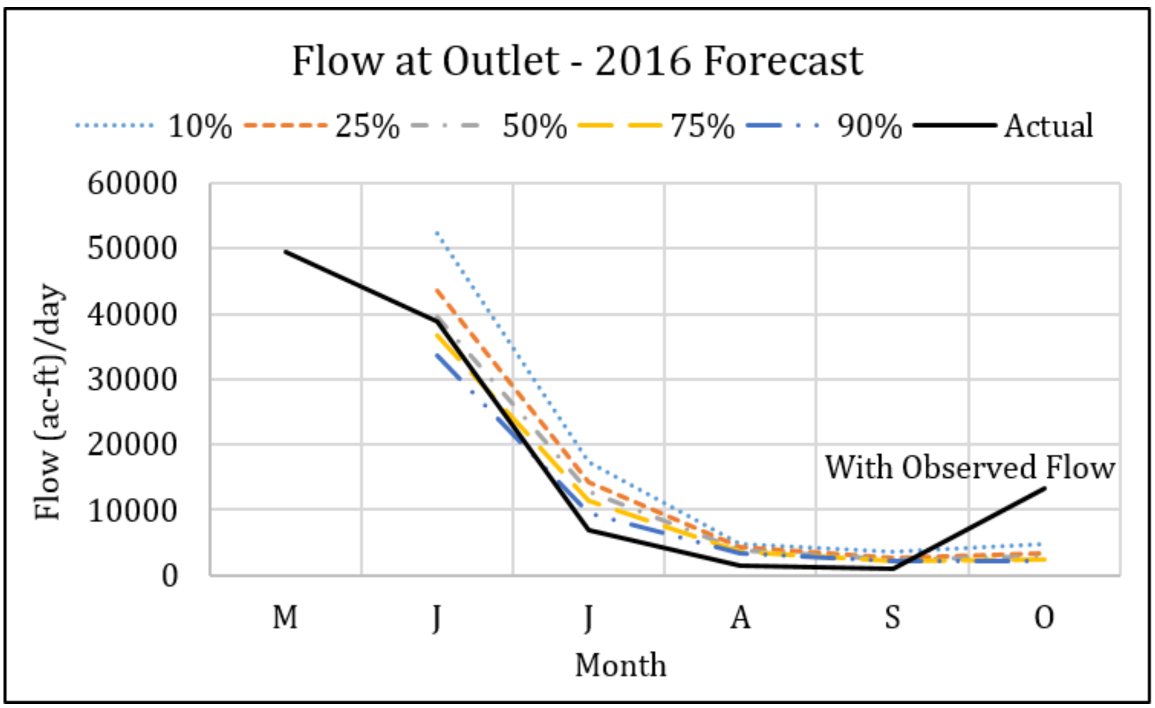

Figure 21. Freshwater flow at San Joaquin basin outlet with CNRFC forecast flows higher in June and October, but lower in July-September than observed flow

Hydrologic conditions in the San Joaquin during water year 2016 significantly improved over 2014 and 2015, with total basinwide runoff near 90% of normal. However, conditions varied significantly between the northern and southern parts of the basin, and above average temperatures in spring led to an early melt of the snowpack. The April 1st snowpack measurement for the region was 90% of normal, however this reflected slightly above normal conditions in the northern watersheds (Cosumnes, Mokelumne, and Stanislaus Rivers) and below normal in the southern watersheds (Tuolumne, Merced, and Upper San Joaquin) (DWR, 2016). The actual basin outlet flow volume in May was above average, as shown in Figure 21, and the actual flow in June was at about the 30% flow exceedance level from the May 1st forecast. Flow conditions in May and June largely reflected the above average spring temperatures in the basin, which produced an early and accelerated snowmelt. Conversely, the early and accelerated snowmelt led to reduced flow volumes in July, August, and September that were below even the 90% exceedance forecast. Flow in October was well above average, which reflected the beginning of a record-breaking hydrologic year in California.

Hydrology for each exceedance forecast value was input to DWRAT to produce a range of shortage decisions. The percent of users shorted (a) and the percent of normal use shorted (b) for riparian users in each exceedance flow forecast is shown in Figure 22. As expected, August and September have the smallest variation between results, since August and September have the lowest hydrologic variation of any months. Actual conditions were dry enough in June for 1% of riparian users to be curtailed, which agreed with the 90% exceedance forecast. However, conditions quickly dried out, and July saw 33% of users shorted, well above even the 90% exceedance forecast. Similar results continued through the summer, but ended in October when zero users were shorted. The actual flow results for riparian users in September further show the effects of shared riparian shortage. The number of users does not decrease substantially from August to September, despite total demand being halved. Although the percent of normal use shorted drops in September, the percent of users shorted increases dramatically. Some of this increase is a product of the dry conditions on the Cosumnes and Mokelumne Rivers, where unimpaired flow was zero at each reference location in September.

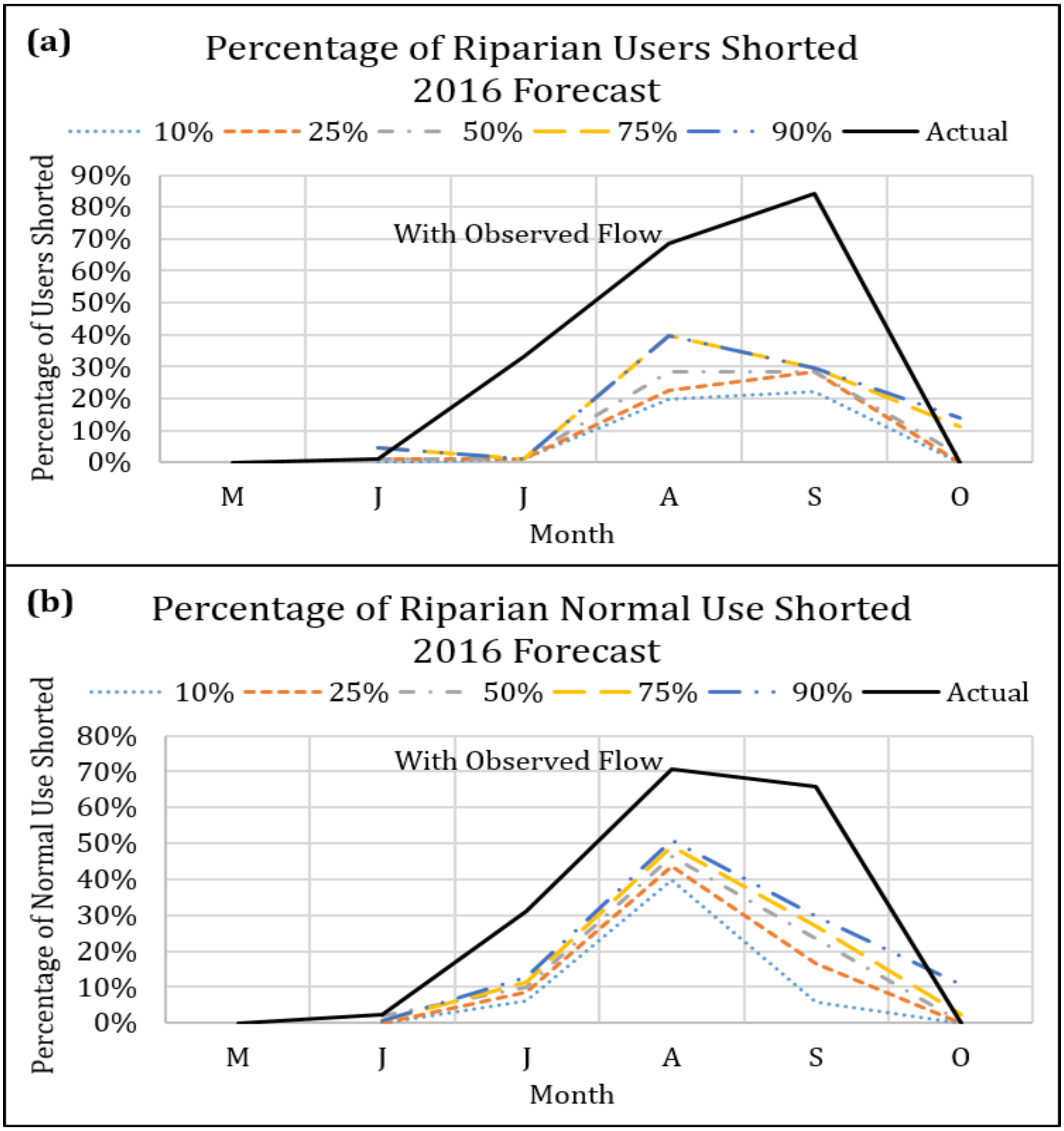

Figure 22. Percent of Users and Percent of Normal Use Shorted for Riparian Users with 2016 forecast flows mostly lower than observed flow.

Results for appropriative users in the basin follow a similar trend as riparian users for the 2016 forecast runs. The percent of users and percent of normal use shorted by DWRAT for appropriative users is shown in Figure 23. Differences between each exceedance forecast are relatively small, especially in August and September. However, there is a smaller difference between the percent of users shorted versus the percent of normal use shorted. For June and July, the difference in percent of users shorted is relatively small between each forecast, at most 15% between the 10 and 90% exceedance flows. Conversely, the difference between the percent of normal use shorted ranges from 22% in June to 40% in July. Several large appropriative rights are active in June and July, whereas most rights in August and September are small. As such, the increase in the number of users shorted in August or September produces a smaller reduction in the percent of normal use shorted as compared to May or June.

However, actual results differed significantly from the forecast values. The total percent of normal use shorted by DWRAT in May was only 10%. The percent of normal use shorted steadily increased to 45% in June, 86% in July, 98% in August, and 99% in September. In each run of the observed data, DWRAT shorts a greater percent of normal use than even the 90% exceedance forecast. Given the low flows observed in August and September, this is somewhat expected. Again, the results only reflect the forecast flows issued on May 1st. Forecasts made later in the summer would more accurately reflect changes in hydrologic conditions and availability.

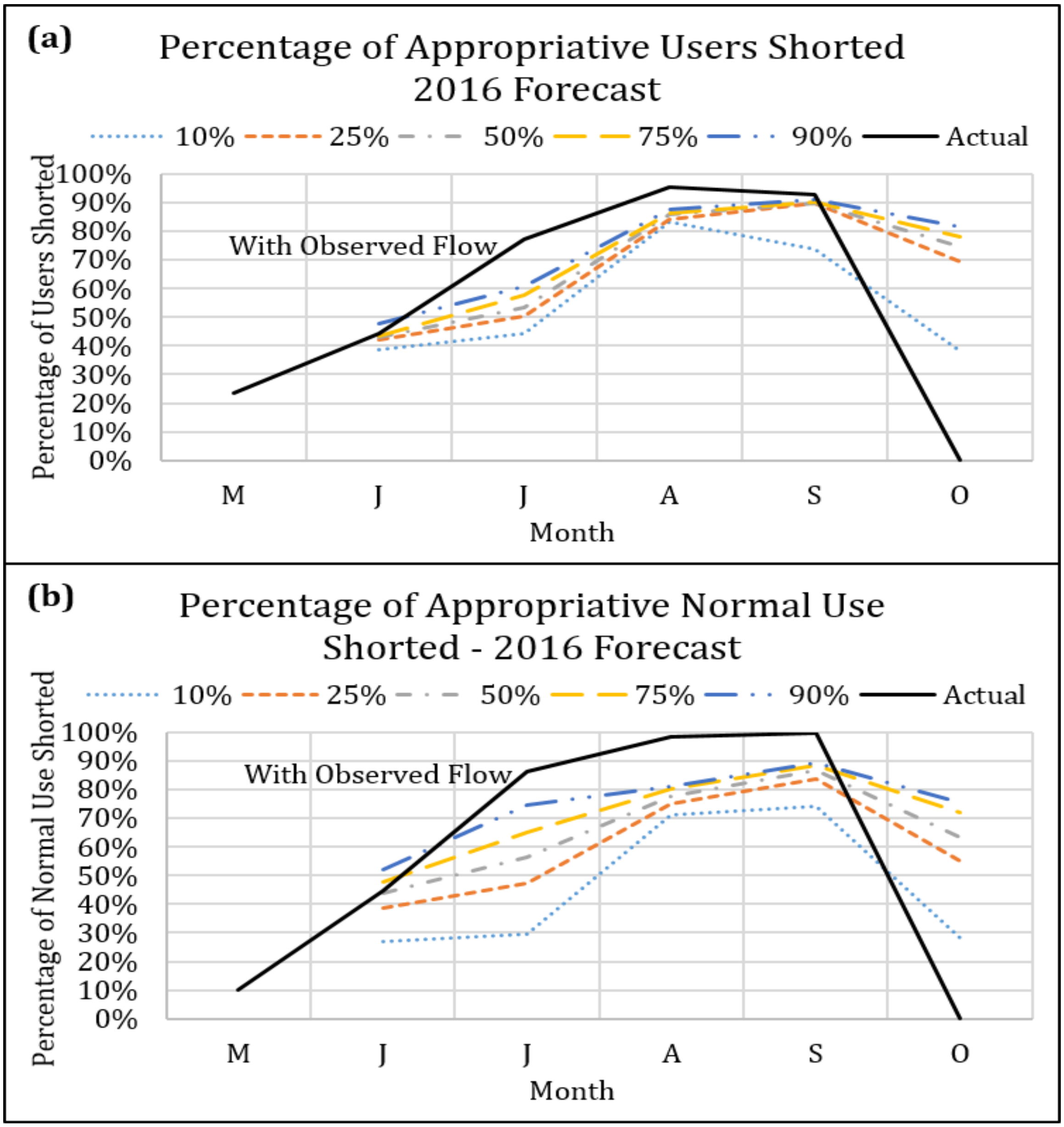

Figure 23. Percent of Users and Percent of Normal Use Shorted for Appropriative Users with 2016 forecast flows mostly lower than observed flow.

The Board did not issue water shortage notices during water year 2016, but DWRAT's results suggest notices might have been reasonable, especially in August and September. The use of forecast flows such as these can provide daily, monthly, and seasonal outlooks for water right users and water rights administrators. Administrators can warn users of potential shortages in the future, and water right holders can plan appropriately to limit the effects of surface water shortages. As updated flow forecasts are released, shortage forecasts and decisions can be revised. The accuracy of user demand will also affect forecast model run results. In some western states, it's common for appropriative users (especially senior right holders) to call in their use to water rights administrators (Escriva-Bou, et. al, 2016). If appropriative users in California were required to call in their use, a much more accurate estimate of demand could be input to the forecast DWRAT runs.

The use of DWRAT for forecast decisions also could be improved with the use of buffer flows. As seen in the forecast analysis, actual flow and even user demand can significantly differ from forecasts. Forecast flow error can lead to false curtailments, where a user is shorted when flow was available for diversion, or false promises, where a user is not shorted but sufficient flow is not actually available for diversion. DWRAT's structure allows for the addition of a buffer flow to artificially reduce or increase water availability. For example, higher buffer flows will lead to additional increased false curtailments, but fewer false allocations. Although overall shortage will increase, higher buffer flows ensure that sufficient water will be available for more senior users and/or environmental flows. Ultimately, the level of buffer flow is up to the basin administrator, and will be a function of the administrator's desire to limit total shortage or to limit total falsities. Lord, et. al. (2017) provide additional detail on the use of buffer flows in DWRAT to limit the amount of false curtailments and false allocations. Buffer flow analysis has not yet been completed for the San Joaquin basin. However, analysis is underway and will be summarized in a future report.

Chapter 4 – Water Right Reliability and Error Analysis

Water resources simulation and optimization models are often used to evaluate and compare the performance of alternative solutions to a particular problem (Loucks, 2005). Although model results can help to generate operational rules, estimate performance, and provide additional information for decision-making, operations of water projects often face significant uncertainty in model inputs, related to both natural conditions and human inputs. By not accounting for uncertainty, model results are less insightful and realistic, which could lead to additional model and decision-making error. To limit potential error from uncertainty, model results can be produced over the range of possible alternatives and model input conditions. The results of these diverse model runs can be further used to develop operations decisions.

Implicit stochastic optimization (ISO) and Monte Carlo analysis are two approaches that can be used to account for some of the uncertainty in DWRAT model inputs. Both approaches can produce user shortage probabilities, which can be used to develop curtailment rules and thresholds for all users in the basin. Analyses such as these are especially useful in large basins like the San Joaquin, as a user's shortage probability is a function of their basin location and priority. The results produced by ISO and Monte Carlo analysis can also assist water right administrators with analysis for permitting new water rights and quantifying availability in stream adjudications.

While no model is perfect, quantifying and reducing error can help reduce model uncertainty. One approach to evaluate model error is by comparing model results to observed data. For DWRAT, shortage results are most sensitive to the predictions made by DWRAT's water availability estimates. Later in this chapter, observed gage flow for several locations in the San Joaquin basin is compared to DWRAT predicted flows in 2015, to assess the accuracy of DWRAT's water availability estimates and to suggest ways to improve their accuracy.

Implicit Stochastic Optimization (ISO) Applied to DWRAT

DWRAT is a deterministic optimization model that estimates optimal water right shortage decisions given a set of unimpaired inflows and user demands. DWRAT results are produced with a level of uncertainty, as the unimpaired flow estimates and user demands input to DWRAT are prone to error. Attempting to account for this uncertainty can be complex and computationally intensive. Implicit stochastic optimization (ISO) can account for some of the uncertainty in unimpaired flow estimates by producing DWRAT results over a representative range of model input parameters (Lord, 2014 & Lord et. al., 2017). To apply ISO to DWRAT, synthetic flow sequences are fed into the model, and a set of shortage decisions is produced for each set of flows. By conducting probabilistic analysis of the shortage decisions, the reliability of a water right, or probability of shortage, can be estimated for each user in the basin. After completing this analysis over a range of input parameters, water rights administrators can develop "look-up" tables to assist with making optimal curtailment decisions based on current or forecasted conditions, without the need for additional model runs.

To estimate water right reliability in DWRAT with ISO, the following steps were completed (Whittington, 2016):

1. A synthetic range of inflows (Q_n) at a reference location is developed based on historical hydrology.
2. DWRAT is run for each inflow to suggest a set of optimal shortage decisions (C_n) for each run, where each user *j* has a binary shortage decision C_j.
3. By stepping through the range of inflows, each user's "shorted threshold flow rate" (Q_{Tj}) can be found as the minimum flow for which $C_j = 0$.
4. Each user's probability of shortage is defined as the probability that Q_n is less than or equal to Q_{Tj}.
5. Monthly curtailment rules are constructed from water right reliability and shortage results.

Estimating Shortage Probabilities and Curtailment Rules for the San Joaquin DWRAT

ISO was applied to the San Joaquin DWRAT to calculate the probability of shortage for each right holder and to develop curtailment rules for July, given reported user demands and historic monthly flow statistical distributions. As such, the shortage probabilities and curtailment thresholds apply only to July. July was chosen to demonstrate a month with significant demands and typically dry conditions. However, such analysis could easily be completed for any month.

A range of Q_n values were input to DWRAT, as flow at Vernalis from 1 to 21,000 ac-ft/day by 100 ac-ft increments. For each flow, C_n was calculated to determine each user's Q_{Tj}. Figure 24 shows the relationship between the daily flow rate at Vernalis and the number of users shorted for a representative day in July. As outlet flow increases, more flow becomes available throughout the basin and fewer users are shorted. Several "steps" in the number of users shorted occur as flow is increased. These steps correspond to plateaus where sufficient water becomes available at some location in the system to release a group of users from curtailment. Most plateaus are dominated by the demand of a single, large user.

For example, the circled step A in Figure 24 corresponds to the release from curtailment for two large groups of users. The first group is several riparian users on the mainstem San Joaquin River, mostly in the downstream reaches. Sufficient water becomes available in their HUC-12 to release all of these users, as well as some appropriative users in the same HUC-12. The second group is several appropriative users, both pre-1914 and post-1914. The pre-1914 users are in the upper reaches of the tributary watersheds, and as flow reaches 6600 ac-ft/day at Vernalis, DWRAT's flow model forecasts enough flow available in their HUCs to meet full demands. The post-1914 users are mostly in HUCs in the lower reaches of the tributary watersheds and on the mainstem San Joaquin. These users are shorted administratively because of a relatively senior post-1914 appropriative right (permit date 9/26/1924) on the Lower San Joaquin River with a rather large demand (40.4 ac-ft/day). When flow reaches 6700 ac-ft/day at Vernalis, enough water is available to satisfy this user's demand, which then releases the more junior upstream users.

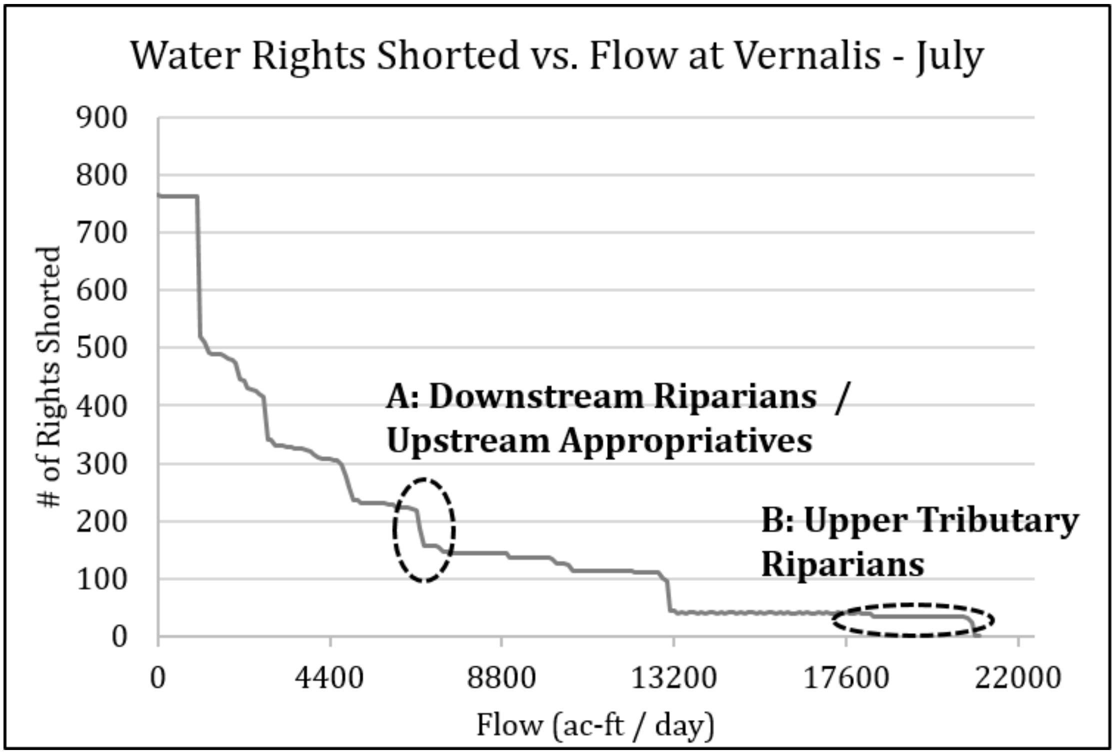

Figure 24. Total Number of Water Right Shortages vs. Flow at Vernalis in July

Although the total number of water right shortages decreases in steps as flow increases at Vernalis, total shortage in the watershed declines steadily as flow is increased. The decline corresponds to reduced partial curtailments as flow is increased, especially for riparian users. Figure 25 shows how total volume shorted decreases as flow at Vernalis increases. As flow is initially increased, shortage is reduced at a high level. Although there are slight changes to the slope of the line as flow increases, a noticeable decrease in the slope occurs at 13,100 ac-ft/day. At this flow level, 52 water rights are released from curtailment. As flow increases, shortage continues to be reduced, but only 1 additional right is released from curtailment until the flow at Vernalis reaches 18,000 ac-ft/day. Here, the slope of the line flattens, as more "surplus" water (water that will be unused downstream) is needed to satisfy several large upstream demands. At this flow rate, several large riparian rights in the Valley floor, but off the mainstem San Joaquin, are finally released from curtailment (also circled step B, Figure 24).

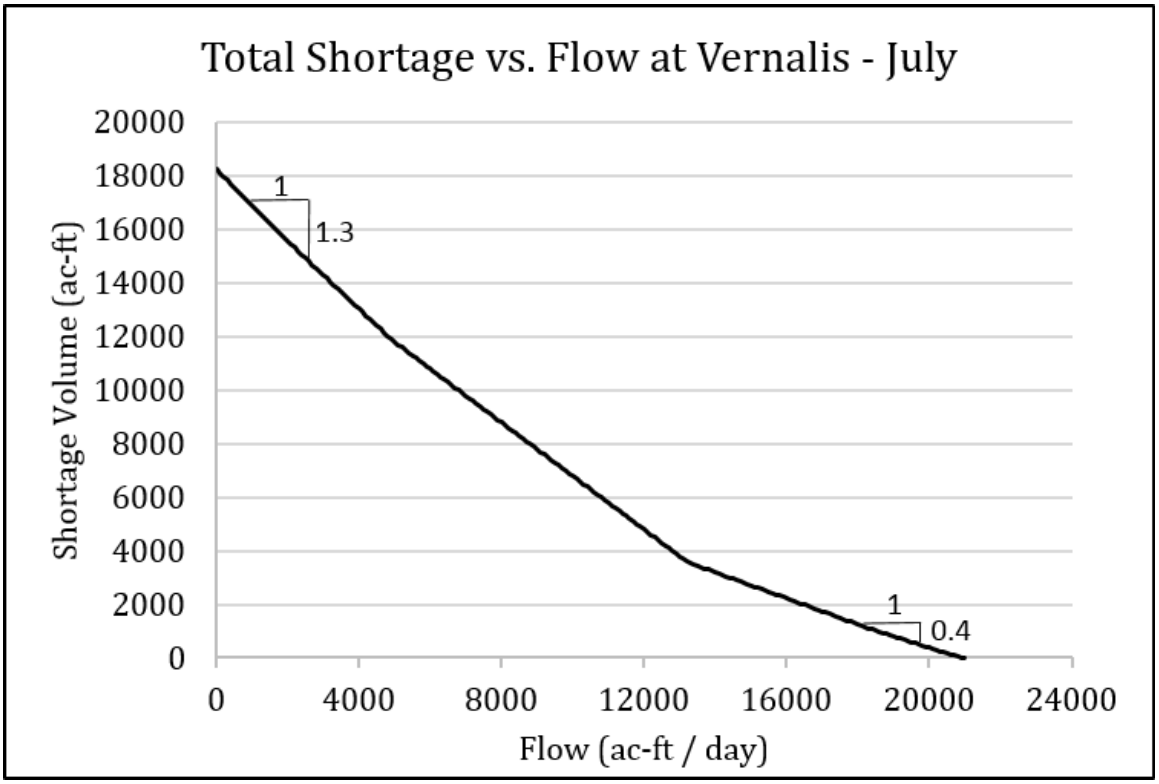

Figure 25. Total Volume Shorted vs. Flow at Vernalis in July

By determining each user's curtailment threshold (Q_{Tj}), a user's probability of curtailment can be determined by calculating the cumulative probability that Q_j is less than or equal to Q_{Tj}. For the analysis completed, every user references the unimpaired flow at Vernalis, which has estimated monthly unimpaired flow available from October 1907 to the present. For July, flow is log-normally distributed, with a mean of 14,351 ac-ft/day and a standard deviation of 13,194 ac-ft/day. Cumulative probabilities were calculated using Equation 4, where μ is log-mean flow (Equation 6), σ is log-standard deviation flow (Equation 7), m is the population mean, v is the population variance, and erf is the Gaussian error function (Equation 5).

$$F(Q|\mu,\sigma) = 0.5 + 0.5[\mathrm{erf}\left(\frac{\ln x - \mu}{\sqrt{2}\sigma}\right) \quad (4)$$

$$\mathrm{erf}(Q) = \frac{2}{\sqrt{\pi}}\int_0^Q e^{-t^2}dt \quad (5)$$

$$\mu = \ln\left(\frac{m}{\sqrt{1+\frac{v}{m^2}}}\right) \quad (6)$$

$$\sigma = \sqrt{\ln\left(1+\frac{v}{m^2}\right)} \quad (7)$$

By calculating the CDF of each user's shortage threshold, we can estimate a user's shortage probability. For example, the cumulative probability that average daily flow at Vernalis will be 10,000 ac-ft is 46%. This means flow will not exceed 10,000 ac-ft in 46% of average days in July. As such, users with curtailment thresholds of 10,000 ac-ft/day have a 46% probability of being shorted. Based on this principle, probabilities of shortage were calculated for each user in the basin for July, as shown in Figure 26.

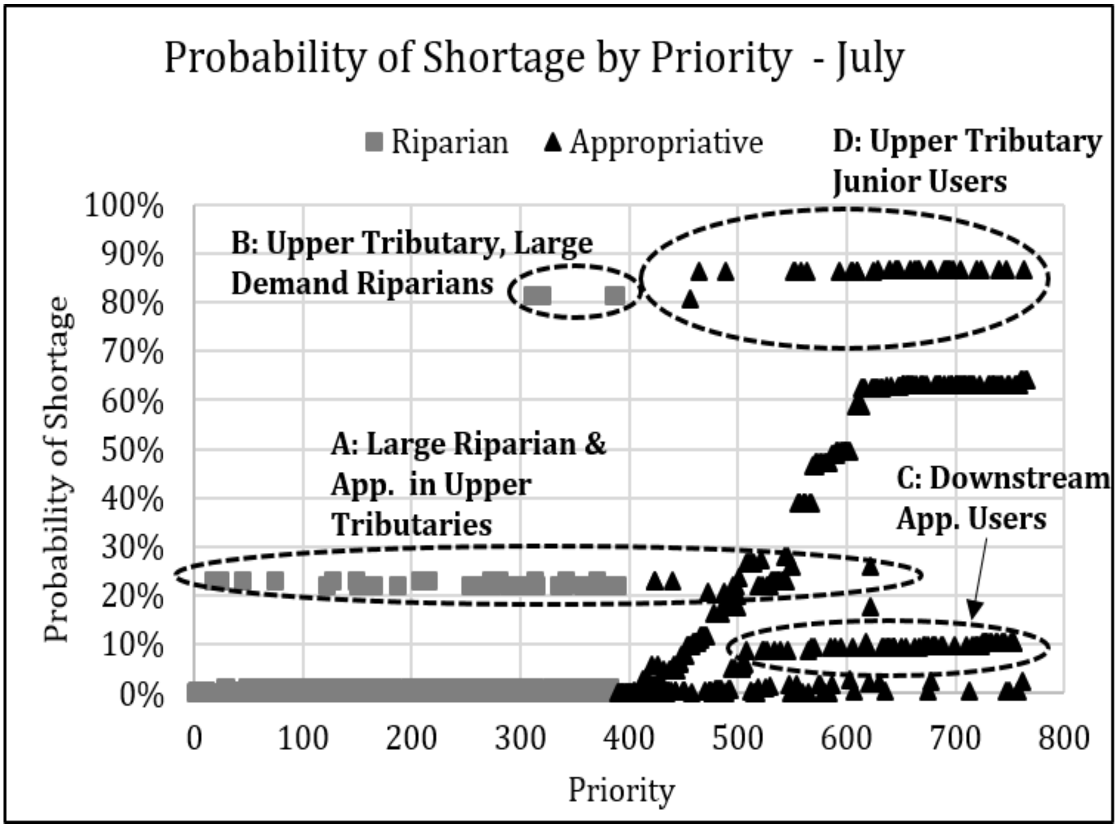

Figure 26. User Shortage Probability by Priority for July

A user's probability of shortage is a function of user priority and location within the watershed. Most riparian users in Figure 26 a low probability of shortage. However, because of their location in the watershed, several users have higher probabilities of shortage. The riparian users inside oval A are the same tributary riparian users in the discussed in Figure 24. One relatively large riparian right with a higher shortage threshold forces all of these hydrologically connected users to share shortage. Likewise, the riparian users with shortage probabilities over 80% (oval B) are the previously mentioned users from users in Figure 24 in the valley floor, but off the mainstem. These three users have large demands for July, but are consistently shorted by water availability, not by administrative curtailments. Furthermore, they have no users upstream of them, but are in a HUC off of the mainstem with limited local water availability. While these users do have high probabilities of shortage, the riparian principle of shared shortage means that their shortage is always a proportion of their demand, and they would likely never be completely shorted.

Appropriative probability of shortage is largely correlated with priority, however location can have a major effect on shortage probability. Lower priority users with low probabilities of shortage are exclusively located in the Lower San Joaquin River and Delta. For these users, sufficient water will almost always be available for diversion. Conversely, some users' shortage probability is affected by their location, both in terms of water availability and by more senior downstream users. For example, the users in oval C are led by a pre-1914 user on the Lower San Joaquin. As this user receives their water, increasingly junior users on the Stanislaus and Merced are released from shortage, while at the same time non-hydrologically connected users on Mokelumne and Cosumnes Rivers now have sufficient water to release them from curtailment. Appropriative users in oval A are the previously discussed users from Figure 24, who were also limited by a senior user with a large demand located on the Lower San Joaquin. In general, curtailment probabilities steadily decrease as user priority increases. However, a large group of appropriative rights (circle D) have shortage probabilities over 80%, including three fairly senior users. These three users are on the Stanislaus, Upper San Joaquin, and Fresno Rivers, respectively. As they all have fairly large demands and are higher in the watershed, they are often shorted by limited local water availability. The more junior users with similar shortage probabilities are located in the same watersheds, but have much smaller rights. As the senior users are released from curtailment, a small amount of additional water is needed to release the junior users from curtailment.

As a deterministic model, DWRAT produces a set of optimal curtailment decisions given a particular inflow sequence and set of user demands. Assuming perfect foreknowledge of unimpaired streamflow and user demands, DWRAT's optimal shortage decisions can be used to produce curtailment rules. Each user's shortage threshold determined through ISO (in this example, flow relative to Vernalis) can be used to suggest curtailment rules. For example, if unimpaired flow was forecast to be 7500 ac-ft/day next week, all users in the basin with a shortage threshold greater than 7500 should expect to be shorted. Development of multiple analyses such as this, with different user demand datasets, could allow for the development of curtailment look-up tables. Users and administrators would not need to run DWRAT, as potential shortage decisions could be made based on forecasted flow volumes. Figure 27 shows each user in the basin's shortage threshold relative to flow at Vernalis for July. To give a slightly different perspective, user priority is plotted on the y-axis and shortage threshold is plotted on the x-axis. Users appear in similar groups in this plot. The riparian users with a very high shortage threshold in oval A, are the same upper tributary, large demand users off of the mainstem. The appropriative users in ovals B are on the Tuolumne, Merced, Stanislaus, and Chowchilla Rivers. For these users, higher priority means lower shortage threshold. Conversely, the appropriative users in oval C have low priorities, but all have small demands and are downstream, near the Delta.

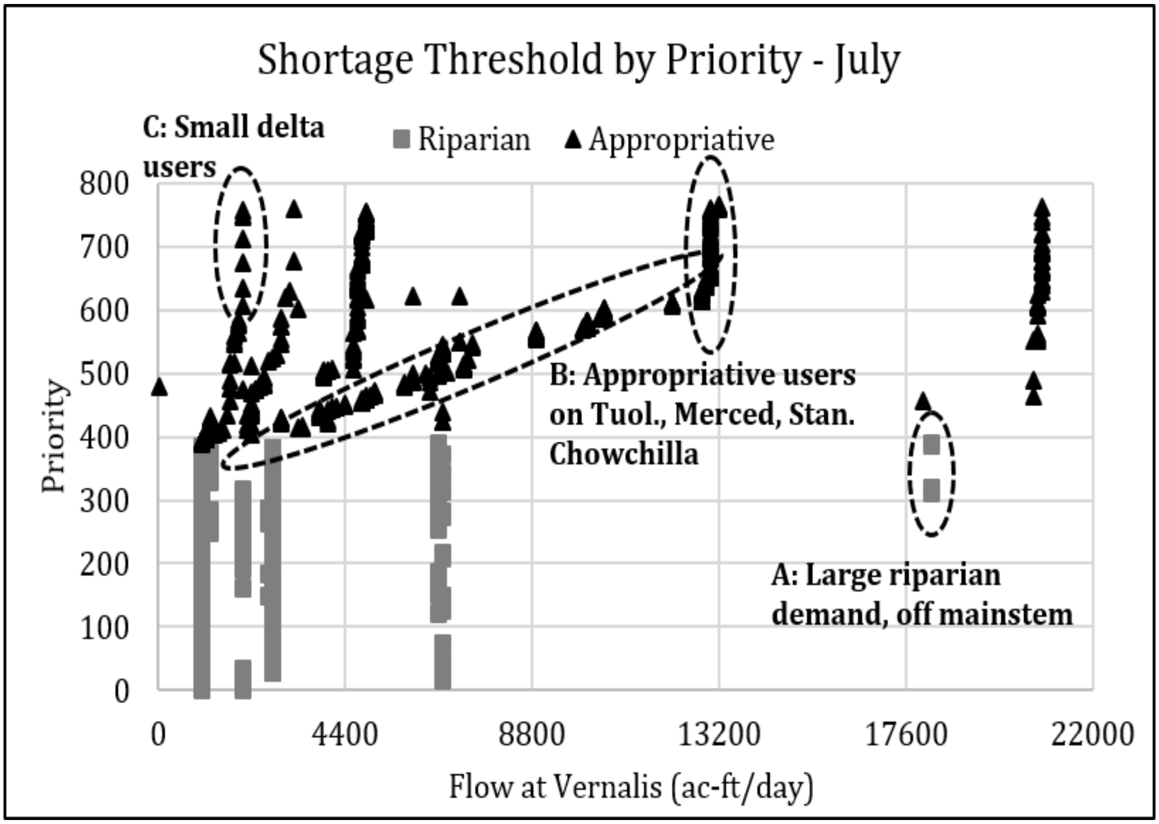

Figure 27. Shortage Threshold by Priority for July

To better quantify spatial variation relative to shortage probabilities, separate shortage probability charts for individual HUC-12s can be produced to more easily evaluate local shortage probabilities for individual water right holders. Shortage threshold charts can also be generated for individual HUC-12s to develop local curtailment rules. Figure 28 shows shortage thresholds (a) and shortage probabilities (b) for riparian and post-1914 users in HUC-12 180400020405 (on the San Joaquin mainstem, just upstream of the Tuolumne River confluence). Given this HUC's location in the watershed and the minimal flow required to satisfy riparian demands, none of these riparian users are likely to ever be shorted by water unavailability or shared shortage from downstream hydrologically connected riparian users. As such, their shortage threshold is 1000 ac-ft/day (flow at Vernalis) and shortage probability is near 0%. Conversely, the increasing shortage threshold and probabilities of the appropriative rights follow the appropriative priority system. The most senior user has a priority date of 8/27/1920. However, this user's fairly large demand and the demands of more senior downstream appropriators combine to produce a shortage probability of 20.6%. Although the other appropriative users have small demands, their increasing priority, relative to this HUC and other users in the basin, corresponds to an increase in shortage probability and curtailment threshold.

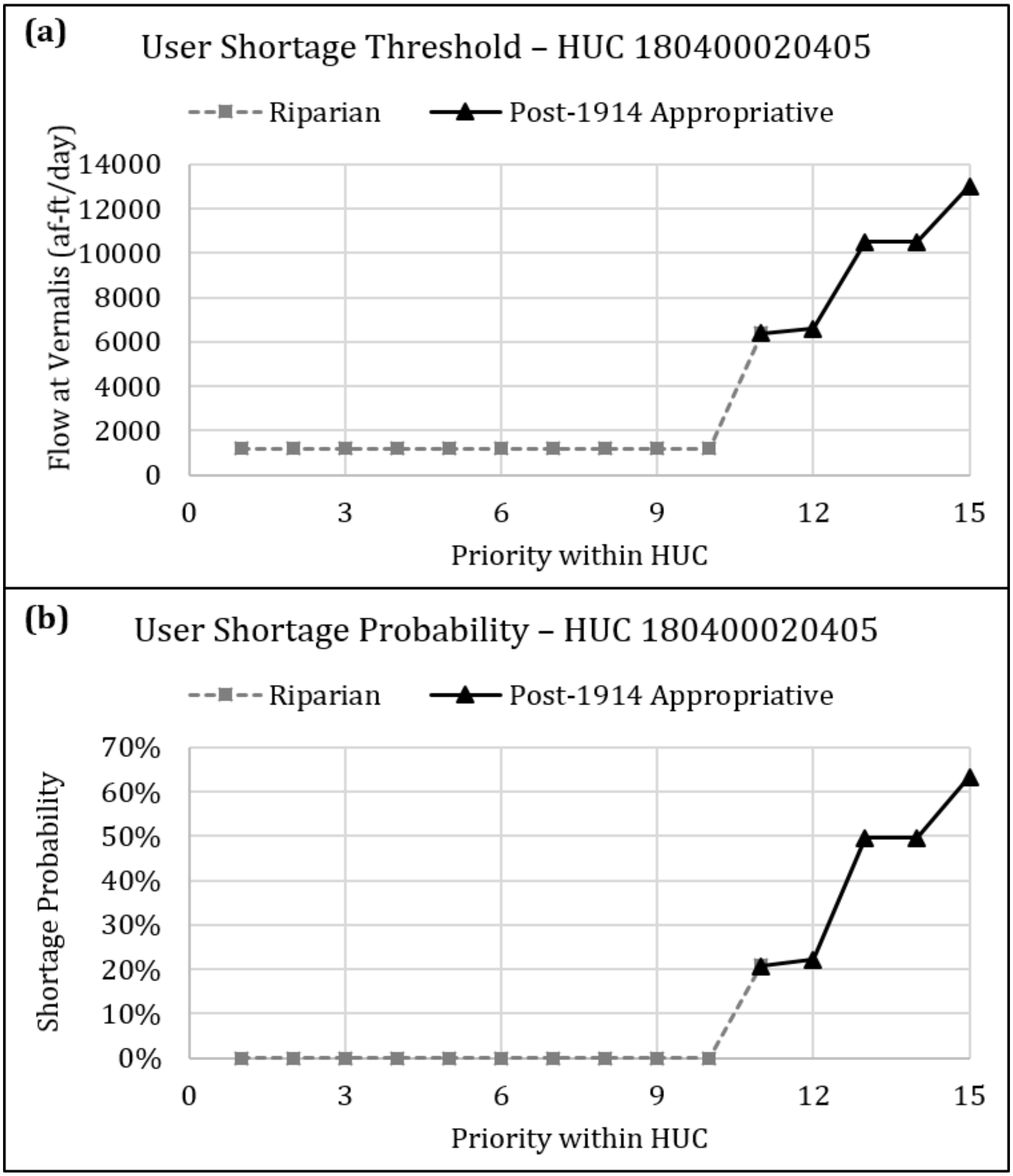

Figure 28. Shortage Probability and Threshold for Users in HUC 180400020405 in July

For simplicity, unimpaired flow in this analysis was scaled from only one point in the basin, Vernalis. Monthly flow volume in July at the other unimpaired flow gage locations in the San Joaquin basin are highly correlated to flow at Vernalis in as shown in **Table 12.** The correlation between Vernalis and the other flow reference points could be used to create a flow regression to better inform basin hydrology in future studies. While the regression approach still maintains flow throughout the basin as a function of flow at Vernalis, it allows for more accurate unimpaired flow predictions. ISO could also be completed at the individual watershed level, to develop more watershed specific curtailment rules. This would allow users who reference a particular reference gage (Tuolumne, Merced, etc.) to use flow at that gage to reference their shortage probability or water right reliability.

Table 12. Unimpaired Flow Gage Linear Regression to Vernalis in July

Unimpaired Flow Gage	Linear Regression	R-squared
Cosumnes - Michigan Bar	88.41x + 62230.6	0.746
Mokelumne - Mokelumne Hill	10.36x + 113441.4	0.915
Stanislaus - Goodwin Dam	7.17x + 18558.2	0.968
Tuolumne - La Grange	3.07x + 24537.3	0.995
Merced - Merced Falls	6.23x + 51881.3	0.978
Upper San Joaquin - Friant	2.57x - 33585.2	0.987

Water reliability and shortage decisions are predicated on the accuracy of DWRAT's flow-forecasting estimates. Shortage decision rules such as those in Figure 27 and Figure 28 are sensitive to the accuracy of DWRAT's predicted flows in each HUC-12. Unfortunately, uncertainty exists for all parameters input to DWRAT, not just unimpaired flow. Monte Carlo analysis is one approach that can account for some of this additional uncertainty.

Monte Carlo Analysis for Shortage Probability

In Monte Carlo analysis, model parameters are sampled from a probability distribution. The sampled parameters are input to the model, and the output is recorded. This process is completed many times to sample a large range of possible input values with realistic relative frequencies of occurrence. Frequency analysis of the model results is then used to estimate the likelihood of some result over the range of possible input values (Lund et. al., 2014).

DWRAT results and analyses are sensitive to the accuracy of DWRAT's water availability estimates, and can be affected by the uncertainty in unimpaired flow estimates and scaling ratio values. To account for this uncertainty and limit potential error, Monte Carlo analysis can be used to extend user shortage probability analysis completed with ISO (Lord et. al., 2017). The following steps were completed with DWRAT to develop user shortage probabilities with Monte Carlo analysis (Whittington, 2016). This analysis was again completed for July, but easily could be extended to other months.

1. A random sample distribution of unimpaired flow values for each reference gage was produced. Each flow is log-normally distributed.
2. A random sample distribution of each HUC-12's scaling ratio was produced. Scaling ratios are normally distributed, with monthly means and standard

deviations estimated from model runs by Grantham & Fleenor (2014). Scaling ratios are not correlated with reference gage unimpaired flows.

3. DWRAT is run with the sample distribution of unimpaired flows and scaling ratios (Q_H). A set of binary curtailment decisions (C_n) is produced for each run.
4. Frequency analysis over all sets of (C_n) informs the probability of shortage for each user.

The Monte Carlo approach was applied to the San Joaquin DWRAT model to estimate shortage probabilities for all users in the basin, based on 2010-2013 average reported use. To account for uncertainty in the flow model, randomly generated scaling ratios and monthly unimpaired flows at Vernalis were produced given their historical statistical distribution. Producing a stochastic streamflow sequence for multiple, serially correlated, gage locations is inherently difficult (Urica, 2015). For this analysis, the flow correlations detailed in **Table 12** were used to inform flow at the other reference gages from flow at Vernalis. Given the time and computational requirements of the San Joaquin DWRAT model, 100 flow and scaling ratio combinations (Q_H) were input to the model. The frequency at which each user was shorted over Q_H was determined to be the user's shortage probability. Figure 29 shows user shortage probabilities versus priority as found with Monte Carlo analysis. By accounting for additional uncertainty, most users in the basin have a higher shortage probability with Monte Carlo analysis than ISO, and no users have a lower probability. Such results are largely expected, as the additional uncertainty in scaling ratios produces a much wider range of predicted unimpaired flow, particularly in HUC-12s with large standard deviations. Results are also likely different due to the inflow method chosen, as this Monte Carlo analysis used unimpaired flow correlated to Vernalis, while the ISO analysis only used flow scaled from Vernalis.

The Monte Carlo results suggest a more realistic view of shortage probabilities, especially for riparian users. For riparian users in Figure 29, users on the same "line" (shortage probability) are located in the same HUC, and users within similar probabilities +/- 3% are in the same watershed. For example, the users in oval A are all in the Fresno or Mokelumne watersheds. Riparian users in HUCs lower in the basin tend to have lower shortage probabilities, while users in upper watershed HUCs have higher probabilities. For appropriative users, Monte Carlo analysis also suggests more realistic shortage probabilities. The users in oval B are a mix of junior and senior rights with shortage probabilities around 85%. The more senior users are all on upper tributaries, and have higher shortage probabilities because of the high probability that water will not be locally available. The more junior users are mostly on the upper and middle San Joaquin, but have high shortage probabilities because of the need to satisfy more senior downstream demands. Likewise, the users in oval C, while very junior, are all in lower San Joaquin and Delta HUCs and mostly have small demands.

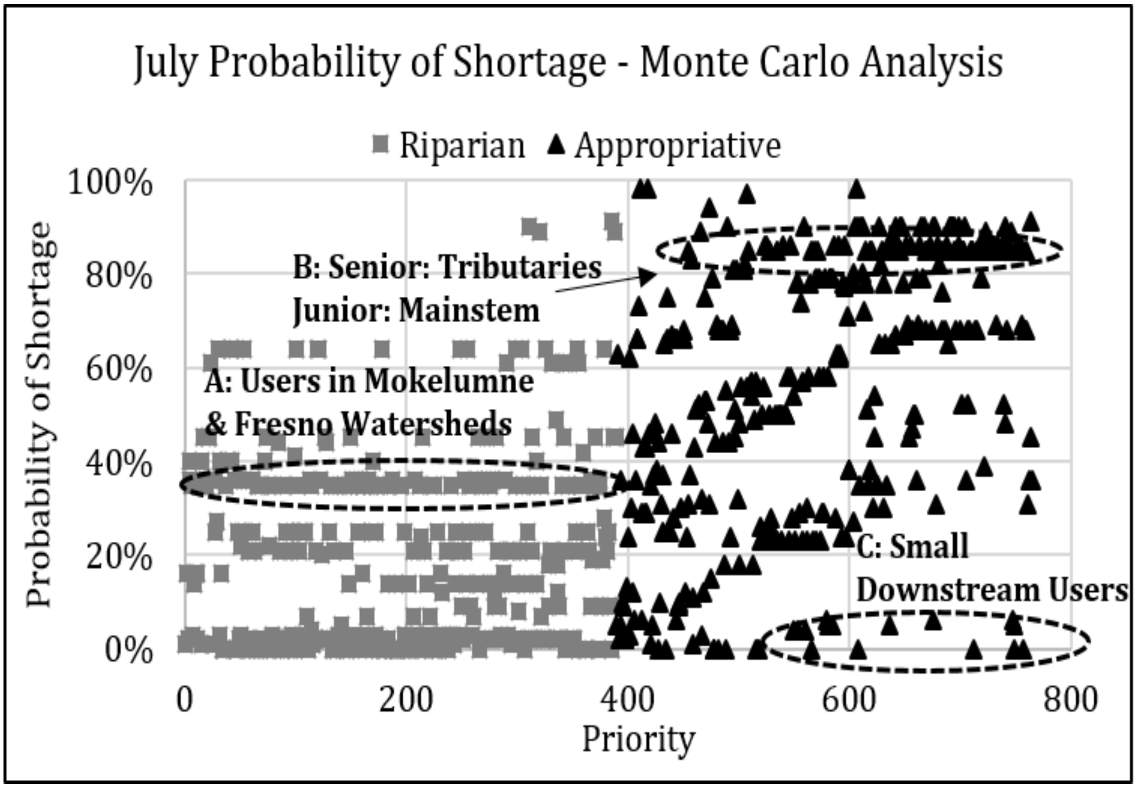

Figure 29. User Shortage Probability with Monte Carlo Analysis by Priority

Figure 30 shows the difference in shortage probability for each user between Monte Carlo results and ISO results. No user in the basin had a lower shortage probability with Monte Carlo analysis, although some users (mostly riparian users in the Calaveras watershed and some fairly junior appropriative users) had no change. Large increases in shortage probability were largely confined to users in the upper watersheds. The riparian users in oval A are all in the Cosumnes watershed, and have an increase in shortage probability over 60%. The appropriative users in circle B are primarily in the Cosumnes and Mokelumne watersheds, and all have an increase in shortage probability over 60%. Conversely, a large set of users (oval C), all in the Calaveras, Stanislaus, and Delta watersheds, has little to no increase in shortage probability. These changes reflect more realistic shortage probabilities for users based on annual variability in their respective watersheds, especially for the Cosumnes and Mokelumne watersheds. Monte Carlo analysis certainly seems to produce more realistic results for all riparian users, but the inclusion of flow correlation appears to also produce more realistic shortage probabilities for particular locations in the San Joaquin basin.

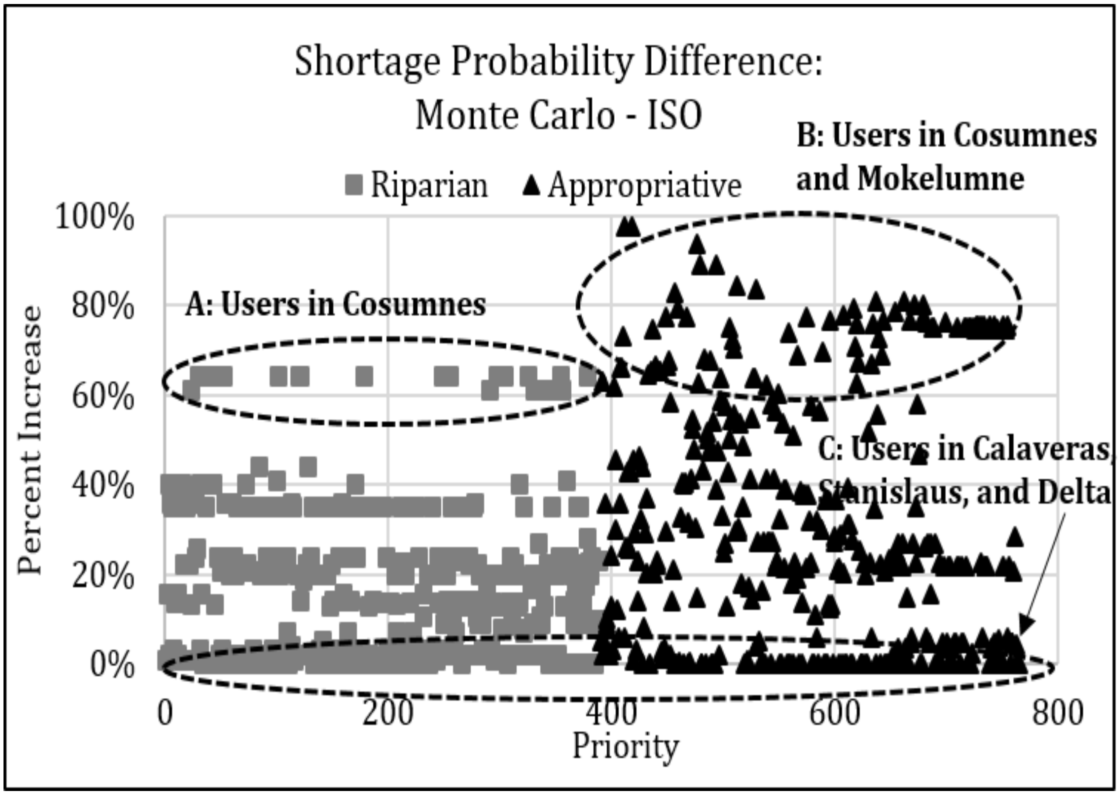

Figure 30. Shortage Probability Difference, Monte Carlo vs. ISO by Priority

Results Without Flow Correlation

Monte Carlo analysis was also completed with randomly generated flow for each unimpaired flow reference gage. By omitting correlation between flow at Vernalis and the other unimpaired flow gages, some of the produced flow combinations were not physically possible (i.e. flow at Vernalis was less than the combination of the Merced, Tuolumne, and Stanislaus and vice-versa). Nonetheless, model results provide an extreme, but interesting view of water shortage probabilities. In addition, two different cases were analyzed.

The first, shown in Figure 31, considers the dry-year statistical distribution of July scaling ratios. The second case, shown in Figure 32, uses the full historical distribution of July scaling ratios. Similar to the results from previous analyses, user shortage probability is a function of location and priority. Riparian users are mostly grouped geographically, given that users in the same HUC share the same proportion of shortage. For example, users in oval A at 30% shortage probability are in one HUC on the Merced River, while the users at 32% shortage probability are in one HUC on the Mokelumne River. Conversely, shortage probability increases for most appropriative users as priority decreases. However, users in oval B (all located in Delta HUCs) have significantly lower shortage probabilities than the more senior users in oval C (located on the Tuolumne, Merced, and Upper San Joaquin Rivers). The users in oval D, with nearly 100% shortage probability, face an uphill (literally!) battle since they are in the upper reaches of the watershed (Cosumnes and Upper San Joaquin) and have very low priority dates.

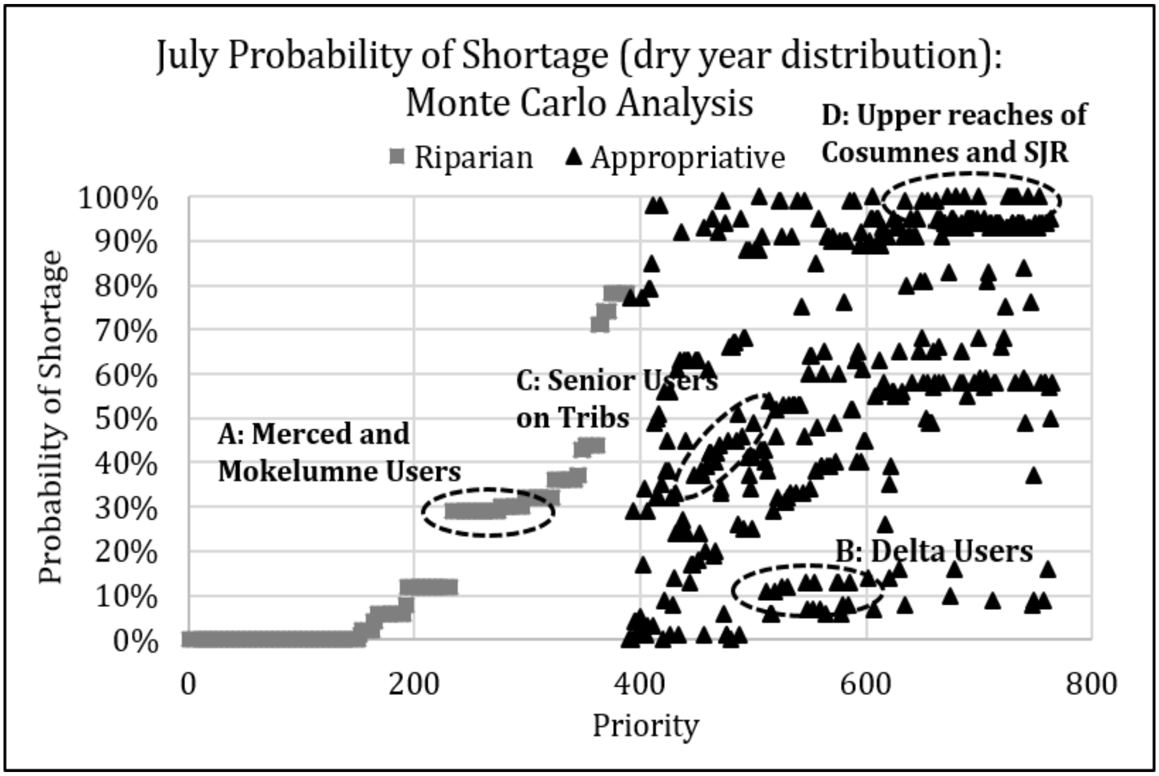

Figure 31. User Shortage with Monte Carlo Analysis with no spatial flow correlation and historical dry-year scaling ratio distribution

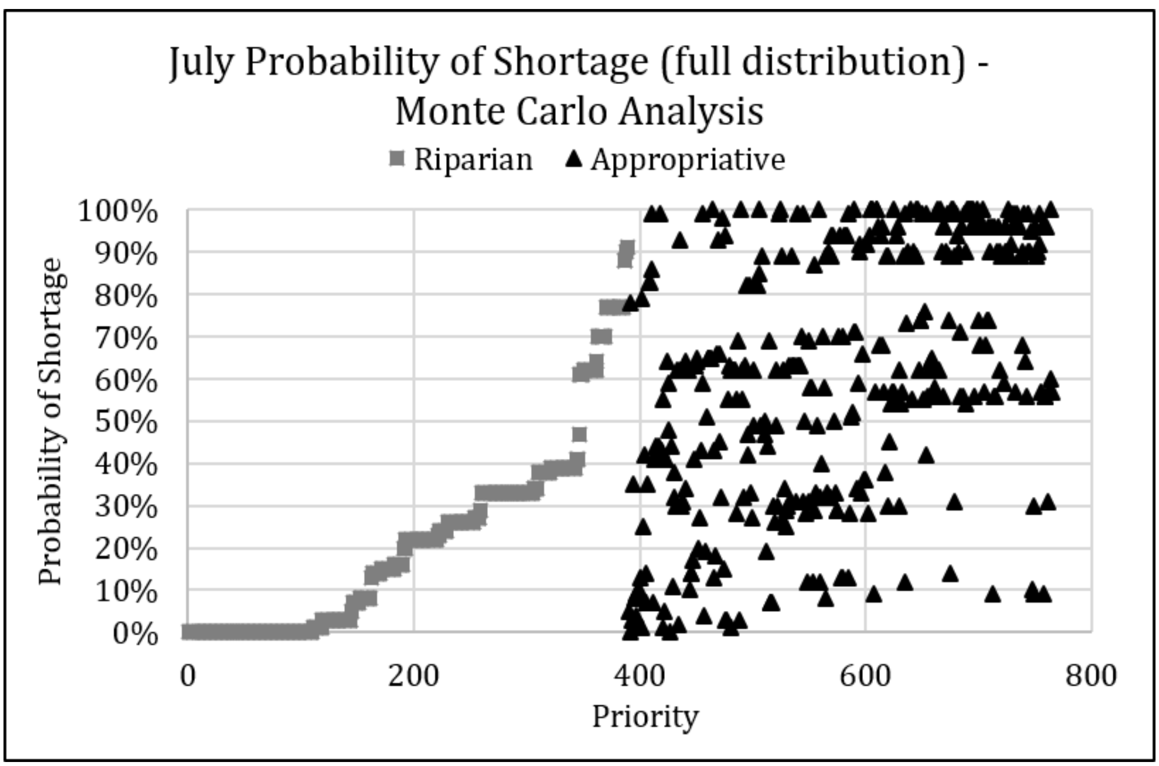

Figure 32. User Shortage with Monte Carlo Analysis with no spatial flow correlation and full historical scaling ratio distribution

The results for the analysis with the full historical scaling ratio distribution produced somewhat surprising results. Of the 765 active users in July, 312 had their shortage probability increase by more than 3%, while only 85 had their shortage probability decrease by more that 3%. Given that use of the dry year distribution biases DWRAT's flow model to dry conditions, it was expected that use of the full distribution would produce wetter conditions overall. However, the difference between flow in July in a dry versus a wet year is small, and the scaling ratios of many HUCs in the basin, especially mainstem and downstream HUCs, have larger standard deviations over the full distribution than over the dry year distribution. While the full distribution can produce wetter flow predictions, it can also produce even drier conditions than those produced with the dry-year distribution. Figure 33 shows the difference in shortage probability between using the full distribution and using the dry year distribution. User priority has little effect on the difference between the results. Users with reduced shortage probabilities are mostly located higher in the watershed on the Mokelumne, Tuolumne, and Merced Rivers (oval A). Whereas users with increased shortage probabilities are largely in mainstem HUCs, mostly downstream in the basin (oval B).

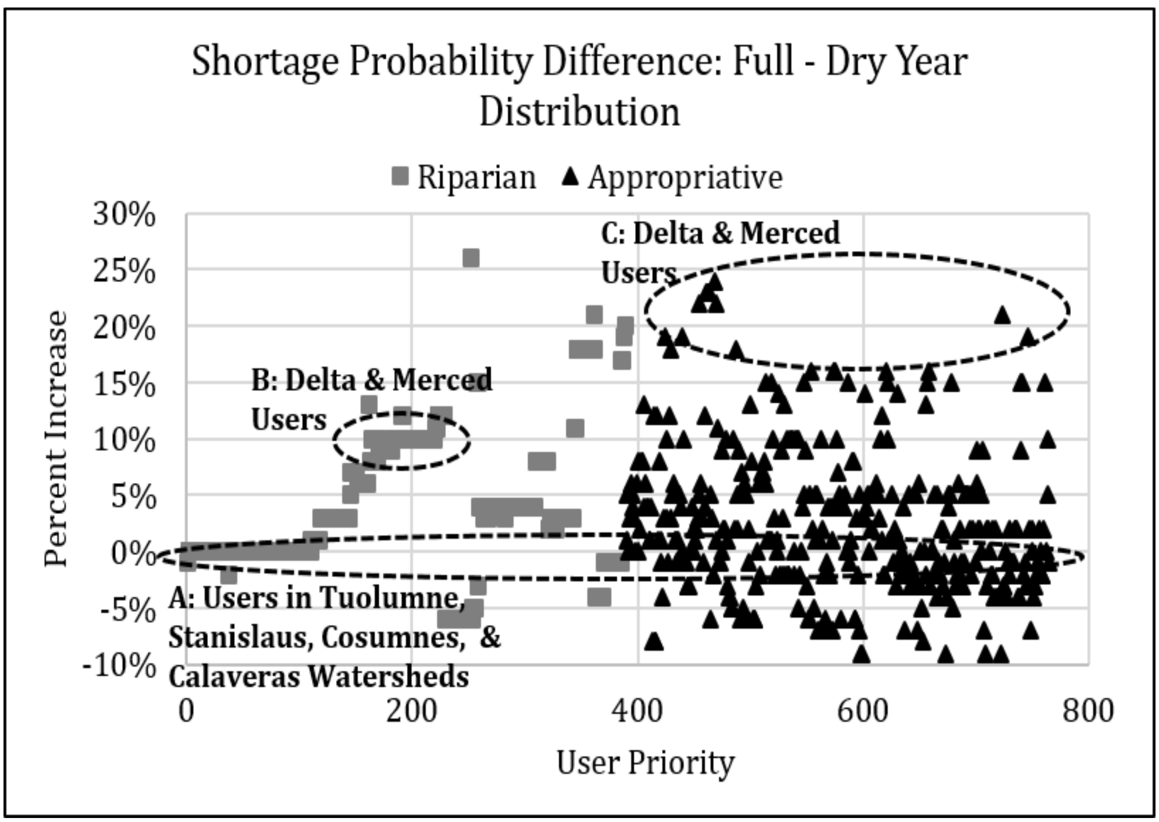

Figure 33. Shortage Probability Difference between Full and Dry-Year Distributions without spatial flow correlation

Ultimately, the analyses completed with stochastic flows are biased to produce excessive shortage, as it sometimes produces unrealistically low basin water availability. To truly develop user shortage probabilities, some degree of flow correlation (as used in the first Monte Carlo analysis) or advanced stochastic flow generation process would be required to develop more realistic inflow sequences.

Given additional computation power and time, it would also be advantageous to produce additional model runs to improve the frequency analysis. The full daily results of Grantham's (2014) unimpaired flow model could be run directly through DWRAT to produce overall shortage probabilities and curtailment rules. Nonetheless, the comparison of the results from the two different distributions highlights the sensitivity of DWRAT's flow estimates and the importance of selecting the appropriate input parameters. This analysis also demonstrates locations in the watershed (typically the upper reaches) where more flow error is probable.

Monte Carlo analysis allows DWRAT results to better account for uncertainty and reduce error in model results. It also produces more refined user shortage probabilities. However, Monte Carlo analysis does not allow for the development of curtailment decision rules. By considering scaling ratio uncertainty, each user no longer has a constant curtailment threshold. Further analysis could suggest a shortage probability curtailment threshold for various flow levels. For example, if flow is 10,000 ac-ft/day at Vernalis, all users with a 75% shortage probability or greater would be curtailed. Furthermore, a Monte Carlo analysis set of results could be combined with flow probability distributions to generate ISO shortage/curtailment rules.

Flow Error Analysis

DWRAT relies on the accuracy of its statistical flow estimates to inform water availability. If flow estimates are inaccurate, DWRAT shortage decisions will be less accurate. Flow error analysis can be used to estimate the reliability of DWRAT's flow estimates, and as a way to calibrate and improve the flow model. Flow error analysis is also useful for large basins with many reservoirs (such as the San Joaquin), as it provides a method of water accounting for total user demands and available flow in DWRAT and demonstrates how reservoir releases could be included into DWRAT as a source for appropriative water right holders.

The following steps were followed to complete flow error analysis for DWRAT (Whittington, 2016):

1. Specify a date of interest on the DWRAT user interface.
2. Add reservoir releases into the system by increasing water availability in all HUCs downstream of a reservoir.
3. Manually allocate right holders their reported use for the specified date (do not run the linear programs).
4. Obtain the remaining flow in each HUC-12 by subtracting the user allocations from the water available. Completion of this step produces the DWRAT predicted "impaired flow".
5. Compare DWRAT predicted impaired flows to flows recorded by a USGS stream gage.
6. Repeat each step for additional dates of interest.
7. Compare statistical differences between DWRAT and model results.

To complete flow error analysis for the San Joaquin DWRAT, gage flow and reservoir data for 2015 was obtained for 18 USGS flow gages, 2 canal diversions (Friant-Kern and Madera), and 12 reservoirs in the basin. Figure 34 shows the locations of USGS gages and available reservoir data used in this analysis.

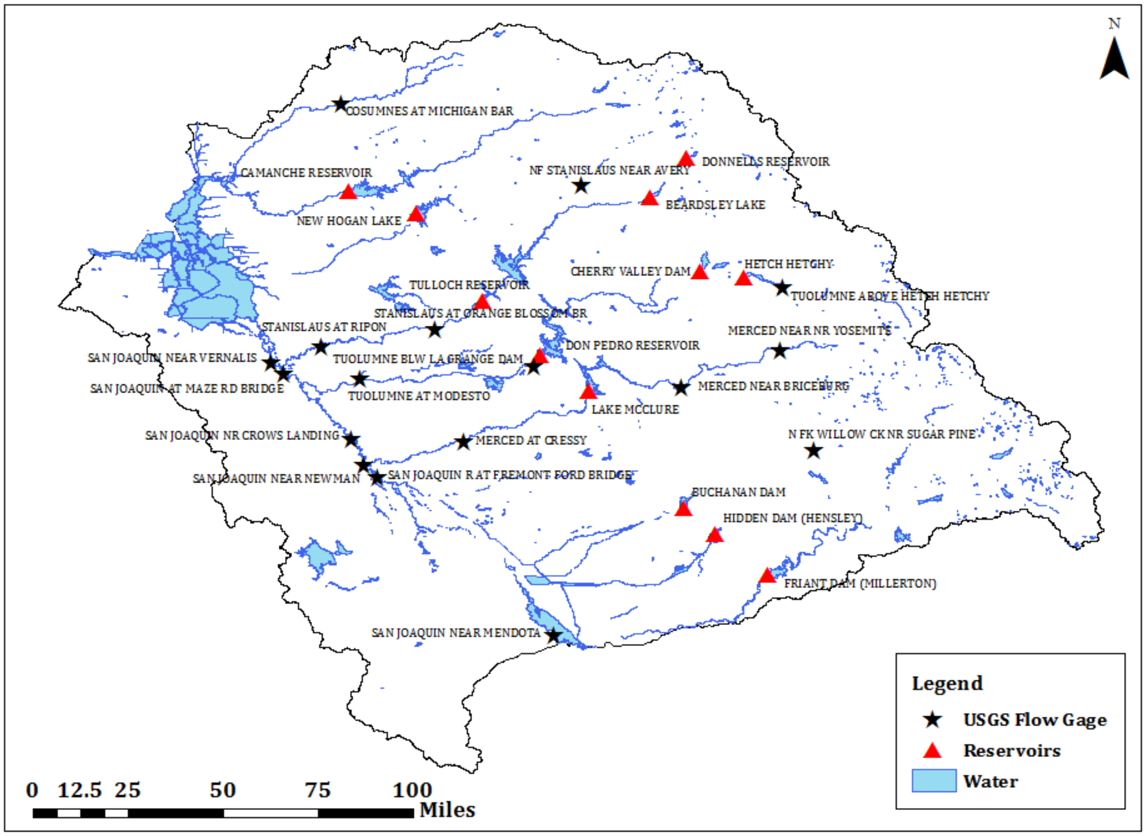

Figure 34. Flow Gage and Reservoir Data used for San Joaquin flow error analysis

Flow error analysis was completed for each day in 2015, with water right allocation decisions made manually based on the SWRCB's water shortage actions during the year. This analysis also assumes water right holder demands are the 2010-2013 average reported demands, and also includes return flows to improve water availability accuracy. DWRAT predicted impaired flows were then compared to the observed flows recorded at USGS gages by calculating the Normalized Root Mean Square Error (NRMSE). The Root Mean Square Error (RMSE) is calculated using Equation 8, and measures the average deviation between DWRAT predicted flows and gaged flows. The RMSE is normalized by using Equation 9, which allows for performance comparisons between different datasets. NRMSE is expressed as a percentage, where higher values indicate greater residual variance.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(Q_G - Q_D)^2}{n}} \tag{8}$$

$$NRMSE = \frac{RMSE}{Q_{G,max} - Q_{G,min}} \times 100\% \tag{9}$$

Figure 35 shows DWRAT predicted flow versus gage flow for 2015 at five flow locations not affected by reservoir regulation. DWRAT predicted flow at gages on the

Cosumnes, Merced, and Tuolumne Rivers is very good, with NRMSE values below 30%. Error is largest on the Tuolumne and North Fork Willow Creek (a tributary in the upper San Joaquin watershed). As both of these locations are upstream of the unimpaired gage locations, precipitation and runoff could have affected other regions in the watershed leading to over-estimated flow in these tributaries. Nonetheless, DWRAT predicted flow follows seasonal patterns and is within the same magnitude as gage flow. Flow prediction on the Cosumnes is exceptionally good. This gage is at the same location as the unimpaired reference gage, so results provide validation for unimpaired flow estimates and user demands upstream of this point on the Cosumnes. DWRAT predicted flow on the Cosumnes in the summer is slightly less than gaged flow. This could be a result of incorrect user demand estimates, or it could also demonstrate some groundwater-surface water interaction, which DWRAT's flow model does not currently include.

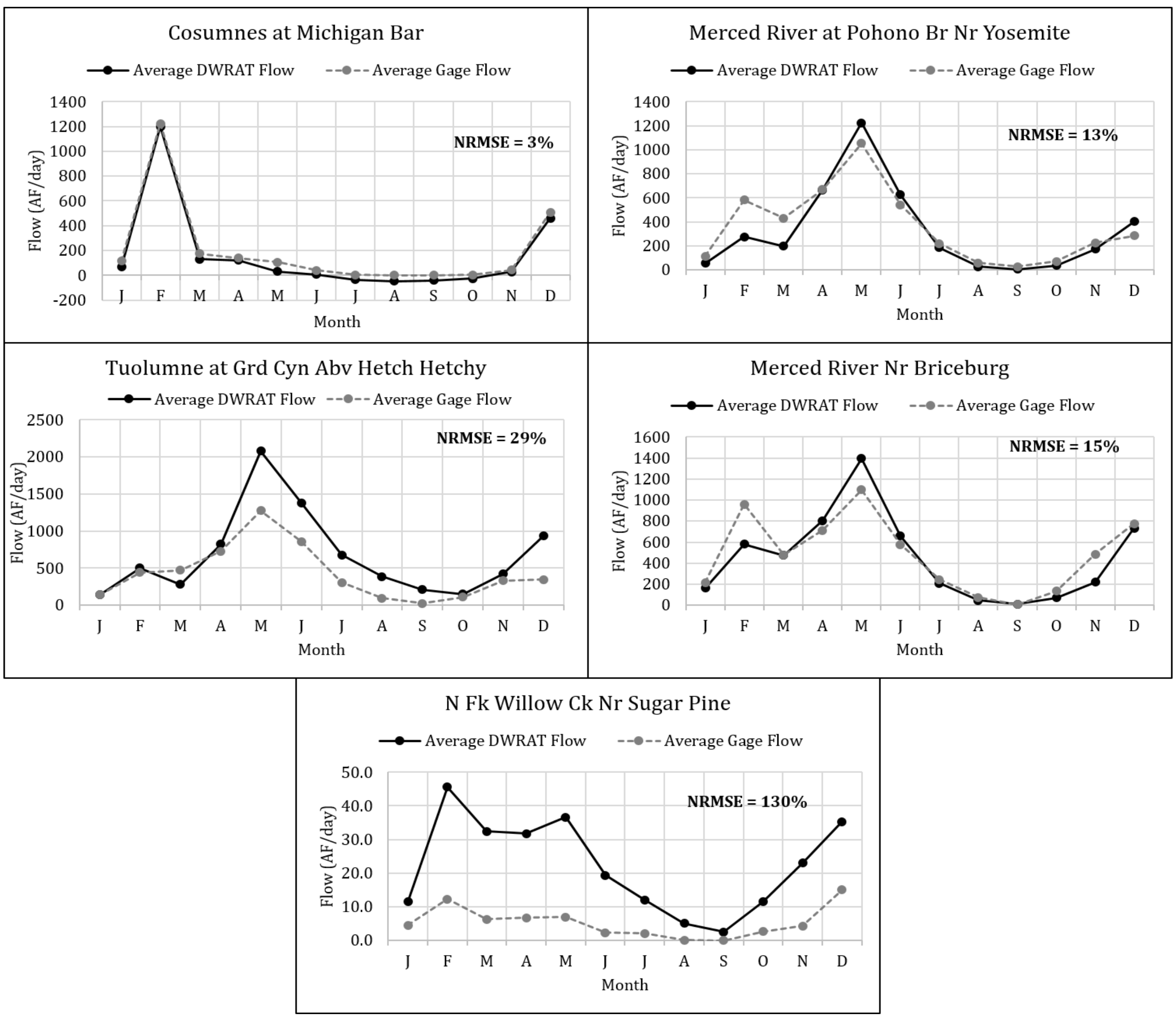

Figure 35. DWRAT predicted flow vs. gaged flow at unregulated gage locations for 2015

Figure 36 shows DWRAT predicted flow versus gaged flow for 2015 at six locations on the major tributaries affected by upstream reservoir regulation. Gage flow on the North Fork Stanislaus River is affected by several upstream hydropower reservoirs. Unfortunately, operations and release data for these reservoirs were not available for 2015. As such, DWRAT predicted flow is DWRAT's flow model minus user demand, while gage flow is reservoir releases minus user demand. Flow on the other five gages is affected by reservoir operations and canal diversions. DWRAT over-predicted impaired flow on the Stanislaus River in most months, while gage flow nearly mimics the minimum instream flow requirements for the lower Stanislaus River. New Melones is the last major dam on the Stanislaus River, and is part of the federal Central Valley Project. DWRAT's over-prediction is likely a result of missing federal project user demands, and that some reservoir releases were made to satisfy previously appropriated water, for which DWRAT does not account. DWRAT-predicted impaired flow on the Merced and Tuolumne Rivers is in fair agreement with gage flow for most of the year. However significant error exists in April and in the early summer. Error at these three gages is likely a result of erroneous user demands and missing diversion data.

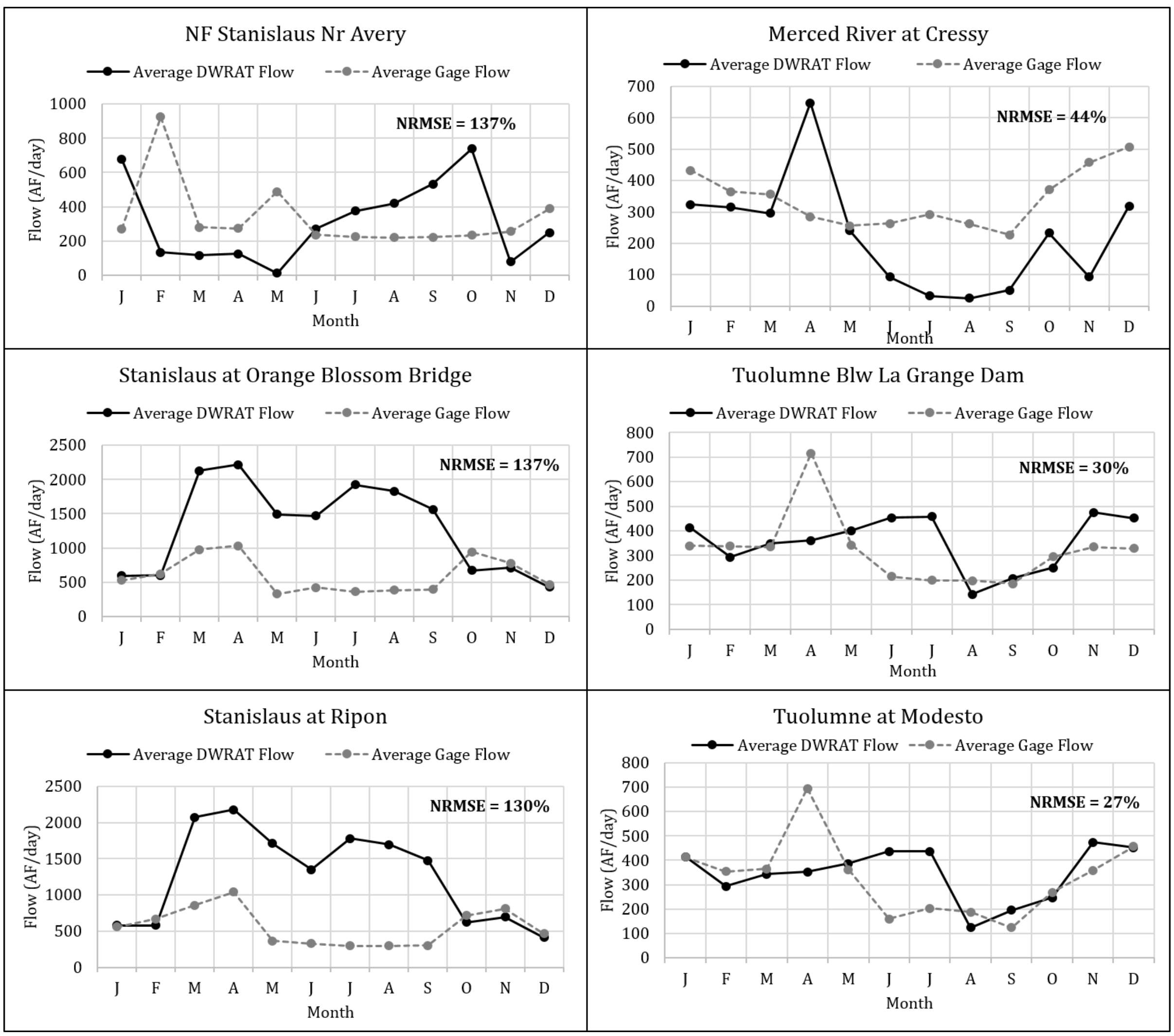

Figure 36. DWRAT predicted flow vs. gaged flow at regulated gage locations for 2015

Figure 37 shows DWRAT predicted flow versus gage flow for 2015 at six locations on the lower San Joaquin River. DWRAT predicted flow at all locations is acceptable from January through March and October through December. DWRAT flow prediction in all other months is poor, except at Vernalis. Most of the error for these gages is largely attributed to missing operations data for Mendota Pool. Particularly during the irrigation season, significant volumes of water are released from the Delta Mendota Canal into Mendota Pool and then into the San Joaquin River. By not accounting for this additional supply, DWRAT will under-predict available flow, as demonstrated by the negative flow rates in the summer. This is not surprising, as even with releases from Mendota Pool, the San Joaquin often goes dry in several locations up and downstream of Mendota Pool. Error in user demand is also likely affecting DWRAT predicted flow. Although DWRAT predicted impaired flow at Vernalis appears to be acceptable, this is more affected by luck and averaging than by accurate water accounting. DWRAT over-predicts flow on the Stanislaus, while under-predicting flow on the Lower San Joaquin by a similar magnitude. The error in these two locations balances out to give the appearance that flow prediction at Vernalis is more accurate.

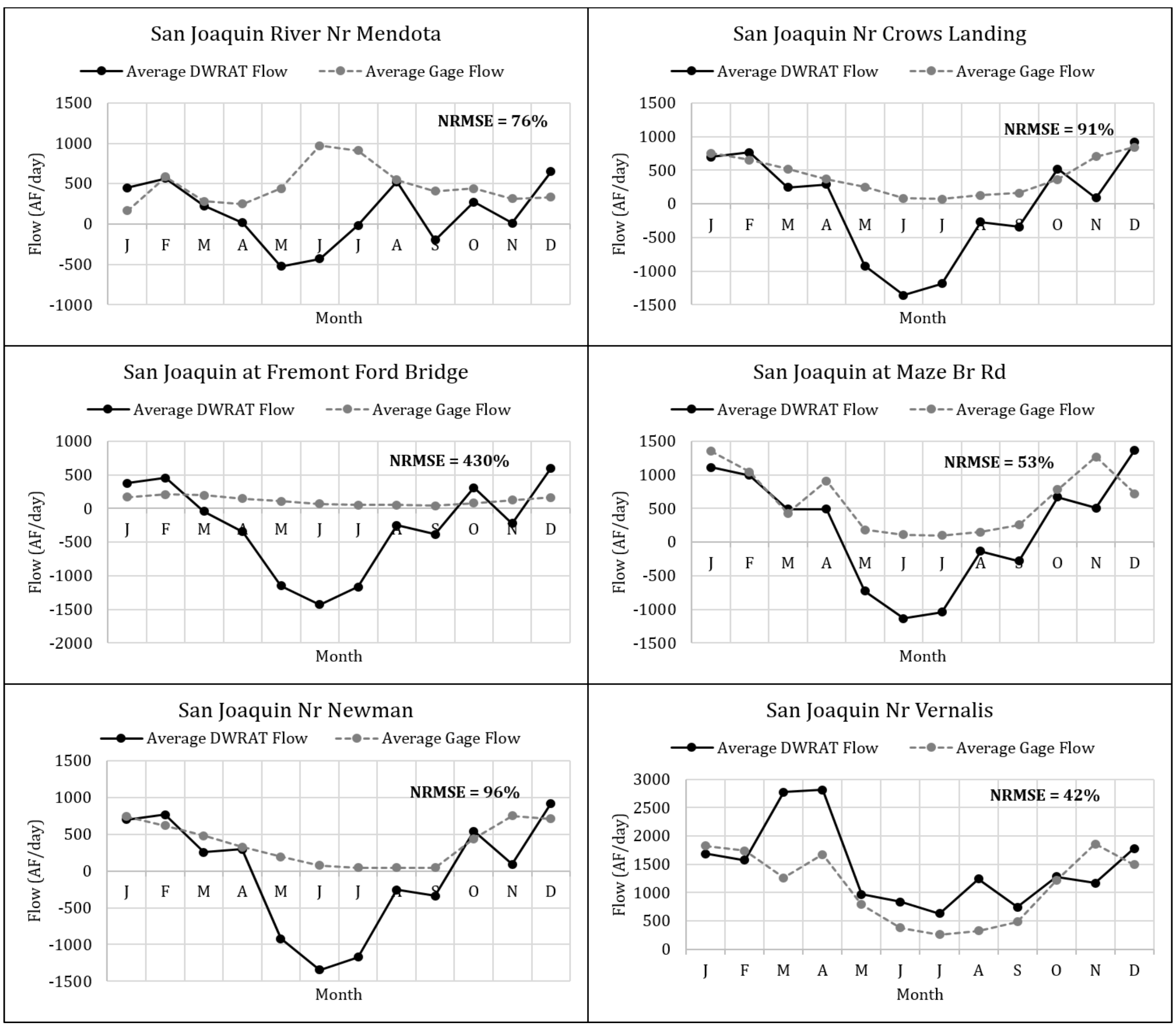

Figure 37. DWRAT predicted flow vs. gaged flow for Lower San Joaquin River for 2015

Unfortunately for this analysis, flow and reservoir release data was unavailable and/or unattainable for several areas in the watershed. Most notably, upstream hydropower operations, gage flow on the Mokelumne River (operated by EBMUD), and Mendota Pool operations were missing from this analysis. Without these data, a rigorous error analysis cannot be completed. Nonetheless, this analysis provides two important conclusions. First, error analysis for a large and complex basin requires extensive data and logistical information to complete a rigorous analysis. Data for all major inputs (federal project operations, uncontrolled reservoir releases) and outputs (canal diversions, federal project rights) must be accounted. This includes obtaining more accurate data on water right user demands, reservoir releases, and accounting for previously appropriated reservoir releases. Unfortunately for this analysis, updated user demands were unavailable, and in many cases the necessary operations data was simply unattainable. However, given additional access to agency resources this analysis could be completed appropriately.

Second, DWRAT predicted flow at the unregulated gage sites was acceptable, and at least for 2015, supports the decision to use the average dry-year scaling ratio. Additional calibration of the flow scaling ratios and additional unimpaired flow gage locations could further reduce error. Additional work is needed to account for groundwater-surface water interaction, and to continue to improve scaling ratios.

Conclusions

DWRAT model results are subject to uncertainty from many of its input parameters, including unimpaired flow estimates, scaling ratios, and user demands. DWRAT's water availability estimates are particularly sensitive to this uncertainty, and the input parameters chosen can significantly effect DWRAT's shortage and curtailment decisions. Implicit Stochastic Optimization and Monte Carlo analysis are two methods to account for some uncertainties. These methods also allow for creating curtailment and shortage probabilities and thresholds for all users in the basin. Such rules can inform shortage and curtailment decisions, without additional model runs. ISO and Monte Carlo analysis can also be used with DWRAT to estimate the reliability for new water rights, and to assist with stream adjudications. However, the results produced in this chapter demonstrate the importance of choosing the most appropriate probability distribution for each input parameter and considering input correlation.

The error analysis completed in this chapter demonstrated the accuracy of DWRAT's flow prediction model for unimpaired flow in HUCs not affected by reservoir operations or other flow regulation. For large basins, such as the San Joaquin, error analysis demonstrates the need to fully account for all major inputs, including federal project operations and user demands, reservoir releases, and canal diversions. For large basins where water availability is largely affected by reservoir and project operations, it is imperative to consider the impacts such infrastructure has on water supply. As more information and data is input to and becomes available to DWRAT, it should be possible to better represent water availability in DWRAT.

Chapter 5 – Conclusions and Future Work

Results of this report and of previous reports (Whittington, 2016; Tweet, 2016; Lord, et. al., 2017) demonstrate DWRAT's ability to suggest water allocation and shortage/curtailment decisions for users in a basin based on available supply and demand. By representing the logic of California water law mathematically, DWRAT can provide a precise and transparent framework for the complicated and controversial process of curtailing water rights during drought.

DWRAT shortage results for the San Joaquin basin in 2014 and 2015 were in fair agreement with SWRCB shortage actions. Differences in shortage decisions between DWRAT and the SWRCB can be largely attributed to the two different approaches taken. DWRAT makes allocation and shortage decisions from a spatially disaggregated approach, with user demands and water availability calculated at the HUC-12 level. While this approach is certainly not perfect, it can better account for spatial variability in supply and demand. Water availability estimates can also be improved by including return flows in DWRAT. The approach for including return flows recommended by Tweet (2016) and implemented in the San Joaquin basin is straightforward to build into the model and helps to reduce water availability error estimates in large basins.

The analysis completed with forecast flows demonstrates the inherent difficulty in forecasting flow in California, especially unimpaired flow. Forecast DWRAT decisions can be useful for water right administrators and users, but the potential error in these estimates should not be ignored. ISO and Monte Carlo analysis provide two approaches to account for some of the uncertainty and error. These approaches also can be used to estimate individual user shortage probabilities and new water right reliability. However, the analysis completed in Chapter 4 demonstrates the sensitivity of DWRAT's water availability estimates and the importance of choosing the most appropriate flow and scaling ratio distribution.

Tools such as DWRAT are becoming increasingly useful and necessary given the tightening state of water rights and water management in California. Surface water shortage is likely to occur more frequently as demands continue to harden and increase, climate and streamflow conditions become more variable, and environmental regulations become more stringent. With some additional calibration and improvement to its water availability model, DWRAT can provide a rigorous and transparent tool to address shortage decisions in future dry years.

Additional Data Needs and Future Work

Future improvements to DWRAT are largely related to calibration and improvements to DWRAT's water availability estimates. Using the current reference gage configuration, further analysis could better inform which HUC-12's should reference each unimpaired flow gage. Such analysis could also be extended to perform additional scaling ratio analysis to assess which year or combination of years provides the most appropriative input to the scaling ratio equation.

Improvements to the HUC-12 water availability estimates could also be achieved by completing a more rigorous flow error analysis, which would require obtaining additional flow gage data, reservoir release data, and user demand data. 2014 and 2015 DWRAT results run with the same water availability estimates used by the SWRCB could provide a more accurate comparison of the two method's results. These results should also be re-evaluated when updated and quality-controlled 2014 and 2015 user demands become available. Future DWRAT analyses (including real-time analysis) would benefit from the most accurate and up to date user demand data. California could also implement a system similar to other western states, where senior users make a 'call' on their demand. Hydropower use and demand must also be better accounted for in DWRAT. Currently demands that are entirely for hydropower are ignored by DWRAT. In reality, some of these demands are run of the river, while others are diversions to storage, and released at some point in the future. Including reservoir releases into DWRAT is one way to better account for these flows, and to better inform water availability for appropriative users.

Further work with ISO and Monte Carlo analysis at a finer spatial scale (watershed scale, e.g. Cosumnes basin) could provide a more specific set of rules for individual users in that basin. Monte Carlo analysis could also be re-evaluated with a more rigorous unimpaired flow gage correlation, extended with the flow values from Grantham's (2014) model, or applied to ISO results to generate more realistic shortage rules. Lastly, the use of buffer flows provides decision makers with a tool to limit the potential for false curtailments and false promises. Work is currently under way to analyze the sensitivity of the flow model and uncertainty inherent in the system, to best inform a decision maker of the value of buffer flows input to DWRAT given management objectives.

References

Brown, E.G. (2014). Proclamation of drought state of emergency. Retrieved from https://www.gov.ca.gov/news.php?id=18379

California Data Exchange Center (CDEC) (2017). Flow, Full Natural Stations. Retrieved June 1, 2017 from http://cdec.water.ca.gov/cgi-progs/staSearch?sta=&sensor_chk=on&sensor=65&dur=&active=&lon1=&lon2=&lat1=&lat2=&elev1=-5&elev2=99000&nearby=&basin=ALAMEDA+CR&hydro=CENTRAL+COAST&county=ALAMEDA&operator=%2B&display=sta

CA – Department of Water Resources (DWR) (2014). "San Joaquin River Hydrologic Region", *California Water Plan Update 2013.* Volume 2: Regional Reports.

CA – Department of Water Resources (DWR) (2015). "Sierra Nevada Snowpack is virtually gone; water content is only 5 percent of historic average, lowest since 1950", News Release. April 1, 2015. Retrieved from: http://www.water.ca.gov/news/newsreleases/2015/040115snowsurvey.pdf

CA - Department of Water Resources (DWR) (2016). "Estimates of Natural and Unimpaired Flows for the Central Valley of California: WY 1922-2014". Department of Water Resources, Bay-Delta Office.

CA – Department of Water Resources (DWR) (2017). "Water Conditions in California – DWR Bulletin 120", Retrieved from https://cdec.water.ca.gov/snow/bulletin120/index.html

California Nevada River Forecast Center (CNRFC) (2017). "Daily Water Resources Update" Retrieved from http://www.cnrfc.noaa.gov/water_resources_update.php

Carlisle, D.M., Falcone, J., Wolock, D.M., Meador, M.R., and Norris, R.H. (2010). Predicting the natural flow regime: models for assessing hydrological alteration in streams. River Research and Applications 26: 118-136.

Colorado (2016). "State of Colorado's Water Supply Model (StateMod) Version 15". Colorado Decision Support Systems, Department of Natural Resources.

Escriva-Bou, A., McCann, H., Blanco, E., Gray, B., Hanak, E., Lund, J., Magnuson-Skeels, B., Tweet, A. (2016). Accounting for California's water: Technical appendix. Retrieved from http://www.ppic.org/content/pubs/other/716EHR_appendix.pdf

Falcone, J. (2011). Gages-II: Geospatial attributes of gages for evaluating streamflow. Retrieved from http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml

Grantham, T. and Fleenor, W. (2014). California water rights model – Supply estimation. University of California, Davis. Center for Watershed Sciences.

Hanak, E., Lund, J., Arnold, B., Escriva-Bou, A., Gray, B., Green, S., Harter, T., Howitt, R., MacEwan, D., Medellín-Azuara, J., Moyle, P., & Seavy, N. (2017). Water Stress and a Changing San Joaquin Valley. *Public Policy Institute of California*.

Hydrologics (2016) "Oasis Software". Retrieved from http://www.hydrologics.net/oasis-software

Israel, M. & Lund, J., (1999). "Priority preserving unit penalties in network flow modeling", *Journal of Water Resources Planning and Management.* 125.4: 205-214.

Labadie, J. (2010). MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation. Department of Civil and Environmental Engineering, Colorado State University. Retrieved from: https://www.engr.colostate.edu/ens/tools/ajax/index.php?get_action=open_file&repository_id=549d154a3e649b2fce985fb92e82963b&file=%2FUserManual%2FMODSIMv8.1UserManual.pdf

Lexis-Legal (2016). "Parties In California Water Curtailment Case Want Hearing On Demurrers", Lexis Legal News. Retrieved April 12, 2017, from http://www.lexislegalnews.com/articles/7568/parties-in-california-water-curtailment-case-want-hearing-on-demurrers

Liebert, T. (2017) "A Research Guide to California Water Law". Loyola Law School, Los Angeles Legal Studies Research Paper No. 2017-09. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2921589

Littleworth, A.L. & Garner, E.L. (2007). California Water II. Solano Press Books. Point Arena, CA.

Lord, B. (2015). Water rights allocations for the California drought: Method and Eel River Application (Master's thesis). University of California, Davis – Center for Watershed Sciences.

Lord, B., Magnuson-Skeels, B., Tweet, A., Whittington, C., Adams, L., Thayer, R. & Lund, J. (2017). Drought water rights curtailment analysis in California. *In Press, Journal of Water Resources Planning and Management*

Loucks, D.P. & van Beek, E. (2005) *Water resources systems planning and management.* UNESCO: Paris. Delft Hydraulics.

Lund, J., Lord, B., Fleenor, W., & Willis, A. (2014). Drought Curtailment of Water Rights – Problems and Technical Solutions. Center for Watershed Sciences – University of California, Davis. Retrieved from https://watershed.ucdavis.edu/files/biblio/Water_right_curtailment_technical_ideas.pdf

Magnuson-Skeels, B. (2016). Using machine learning to statistically predict natural flow: The Sacramento Watershed under dry conditions (Master's thesis). University of California, Davis – Center for Watershed Sciences.
Mason A.J. (2013) SolverStudio: A new tool for better optimisation and simulation modelling in Excel. INFORMS Trans. Ed. 14(1):45–52.

Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R., and Veith, T. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50: 885-900.

Nelson, T., Chou, H., Zikalala, P., Lund, J., Hui, R., & Medellin-Azuara. J. (2016). "Economic and Water Supply Effects of Ending Groundwater Overdraft in California's Central Valley." San Francisco Estuary and Watershed Science. 14 (1).

Olenichak, T. (2015). "Concepts, Practices, and Procedures Used to Distribute Water Within Water District #1" Water District #1.

Stockholm Environment Institute (SEI) (2017). "History and Credits", Water Evaluation and Planning. Retrieved from http://www.weap21.org/index.asp?action=219

State Water Resources Control Board (2015a). "2015 Tuolumne R. To San Joaquin R. Supply/Demand Analysis". State Water Board Drought Year Water Actions. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/analysis/docs/sjprorated.pdf

State Water Resources Control Board (2015b). "Order WR 2015-0002-DWR" Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/2015sacsjinfoorder.pdf

State Water Resources Control Board (2016a). "Notices of Water Availability (Curtailment and Emergency Regulations)". State Water Board Drought Year Water Actions. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/water_availability.shtml

State Water Resources Control Board (2016b). "In the Matter of Administrative Civil Liability Complaint Against Byron-Bethany Irrigation District And In the Matter of Draft Cease and Desist Order Against The West Side Irrigation District ". Order WR 2016-0015.

State Water Resources Control Board (2016c). "Draft Revised Substitute Environmental Document in Support of Potential Changes to the Water Quality Control Plan for the Bay-Delta: San Joaquin River Flows and Southern Delta Water Quality".

State Water Resources Control Board. (2017a). eWRIMS – Electronic water rights information management system. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/ewrims/index.shtml

State Water Resources Control Board. (2017b). State Water Board – Measurement Regulation. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/

Stringfellow, W. & Camarillo, M. (2014). Synthesis of results from investigations of the causes of low dissolved oxygen in the San Joaquin River & Estuary in the context of the dissolved oxygen total maximum daily load (Report 7.1). *Ecological Engineering Research Program, School of Engineering & Computer Sciences, University of the Pacific.*

Tweet, A. (2016). Water Right Curtailment Analysis for California's Sacramento River: Effects of Return Flows (Master's thesis.) University of California, Davis - Center for Watershed Sciences.

Markovic, U., Plavsic, J., Ilich, N., & Ilic, S. (2015). Non-parametric stochastic generation of streamflow series at multiple locations. Water Resources Management, 29(13), 4787-4801. doi:http://dx.doi.org/10.1007/s11269-015-1090-z

U.S. Geological Survey (USGS) (2017). "USGS-11335000", "USGS- 11319500", "USGS-11303500". USGS Surface-Water Annual Statistics for the Nation. Retrieved from https://waterdata.usgs.gov/nwis

Whittington, C. (2016). Russian River DWRAT (Master's Thesis). University of California, Davis - Center for Watershed Sciences.

Wurbs, R. (2015). Water Rights Analysis Package (WRAP) Modeling System Users Manual. *Texas Water Resources Institute*. Technical Report No. 256. College Station, Texas.