Drought Water Rights Allocation Tool: Eel River Model Update and pyWRAT Application

By

JEFFERSON LAIRD
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

2018

Table of Contents

Figures

Tables

Equations

Abstract

California’s dual system of riparian and appropriative water rights was tested in the state’s dry 2014 and 2015 water years. The Drought Water Rights Allocation Tool (DWRAT) was developed to estimate water rights allocations in drought conditions by turning the riparian and appropriative doctrines into linear programs. In this thesis, DWRAT’s application to the Eel River was examined for the conditions in the 2014 and 2015 drought years as well as for curtailment thresholds. Future research into the new cannabis water rights is discussed. A new software for the model was developed in the Python coding language (pyWRAT) and some of its applications are explored in the Sacramento River Basin.

Acknowledgements

I would like to thank the members of my committee and the countless other counselors, mentors, and friends in the UC Davis (and UC Merced) faculty and staff for their guidance and support. I would also like to thank all of my colleagues in the water systems research group for inspiring me to be curious, broad-thinking, and diligent in the pursuit of a better understanding of complex issues. I also want to thank my family for lifting me up when I needed it, and most of all my partner for keeping me disciplined, motivated, and sane.

Chapter 1: Introduction

California Water Management and Droughts

Managing water rights in California is complex in the variability of its water supply system, water demands, ecosystems, number and sizes of watersheds, and the diversity, variability, and historical precedents of water uses. This management complexity is exacerbated by a changing climate, which brings potentially longer and deeper periods of drought, changed precipitation and runoff patterns, and uncertainty in water supply and demand predictions. Major data gaps in water use, rights, and availability limit the California State Water Resources Control Board's ability to enforce water allocations in drought conditions. This thesis briefly discusses California's system of water rights, analyzes current data collection and modelling with respect to the Eel and Sacramento Rivers, and makes suggestions for overall water rights analysis in California.

California Water Rights

California's surface water rights system has both riparian and appropriative rights. Riparian water right holders have equal priority among each other and must share available river flows proportionally, with water shortages affecting allocations as an equal proportion of normal diversions for all riparian users within each part of the river basin (Littleworth and Garner, 2007). These proportions are determined by water availability, with downstream users likely to receive higher proportions due to accumulations of streamflow downstream. Appropriative users have the right to use water remaining after riparian user diversions (Liebert, 2017). Appropriative diverters are allocated available water based on the priority of each appropriative water right filing. Shortages are allocated among appropriative water right holders strictly by water right seniority and water availability, both locally and basin-wide. Effectively, all appropriative users are "junior" to riparian users and receive their share after riparian rights in the basin has been met.

Most other western states exclusively use the appropriative doctrine for water rights without separate riparian rights. The appropriative doctrine follows the 'First in Time, First in Right" policy for administering water, which means the earliest diverters have the highest priority (Lord et al., 2018). California has maintained riparian water rights based on English Common Law exclusively for citizens with property adjacent to a water body. Water diverted with a riparian right can only be used on the listed riparian property and cannot be put into storage, traded, or sold. All riparian water rights are equal in priority to each other and considered senior to all appropriative users (Liebert, 2017).

Current California Water Rights Management

The California State Water Resources Control Board (SWRCB, or the Board) regulates and enforces surface water rights in California. The Board determines water availability, issues water shortage (or curtailment) notices, and enforces water users' compliance with stream regulations. The Board has more authority over appropriative water rights filed after 1914 than over both riparian and Pre-1914 appropriative water users (Escriva-Bou et al., 2016). This is due the fact that riparian and pre-1914 rights can have valid but competing claims of rights, but the Board does not always have the data or resources to investigate or adjudicate (SWRCB, 2018). Due to the constantly changing reporting and regulatory requirements, as well as a shifting climate, more frequent water right curtailments are likely in the future (Lund et al., 2014).

Major data gaps in water use, rights, and availability hinder the Board from effective water rights enforcement during drought periods. This issue is illustrated in the litigated example of *Water Board v Byron Bethany* (SWRCB, 2016; Escriva-Bou et al., 2016). These gaps in surface water right accounting and enforcement have been cited as major problem areas in California water management (Escriva-Bou et al., 2016).

Drought Water Rights Allocation Tool

To help address these needs, researchers at the UC Davis Center for Watershed Sciences developed the Drought Water Rights Allocation Tool (DWRAT) (Lord, 2015; Lord et al., 2018; Tweet, 2016; Walker, 2017; Whittington et al., 2016). DWRAT is an integrated set of statistical water availability and water right models for water use allocations and curtailments in California. DWRAT models the logic of water rights law as an algorithm, which provides a consistent and transparent framework for the complicated and often controversial process of curtailing water rights use during drought (Walker, 2017). This model is not currently used by the Board to issue definitive water shortage notices but can help improve their ability to make informed decisions regarding water rights and administration.

DWRAT provides a framework that optimizes water allocations to both riparian and appropriative water right-holders. It also can accommodate required flows for the environment, public health and safety, and operational reliability for senior water right-holders. It achieves this by using four input data sets and two linear programs to project flow availability for both riparian and appropriative water rights allocations. The components are shown below in Figure 1.

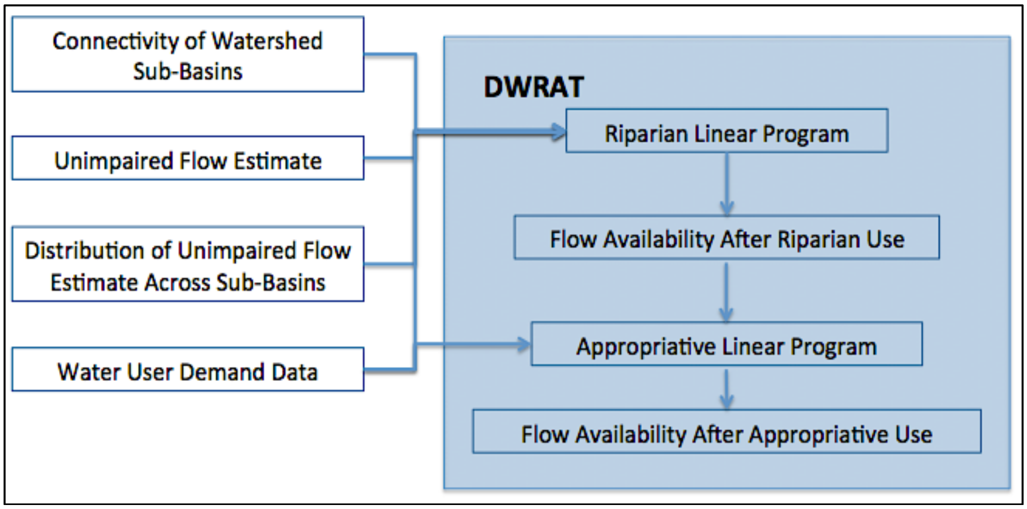
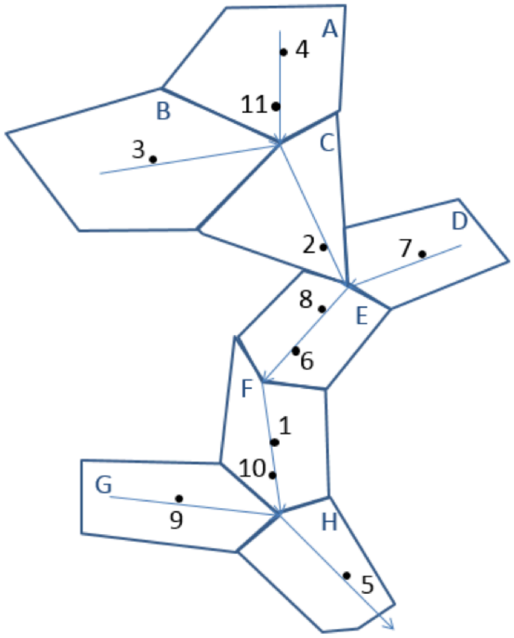


Figure 1: DWRAT Workflow Diagram showing the separate inputs and their uses in the DWRAT model

Connectivity of Watershed Sub-Basins

The first required input to DWRAT is a suite of data representing spatial connections within a watershed basin and its sub-basins. To designate each sub-basin, DWRAT uses the smallest of the USGS's Hydrologic Unit Code level, the HUC-12, which are approximately 15 to 60 square miles each. The hydrologic connection between these sub-basins is used to construct a flow connectivity matrix, which in turn allows the linear programs to properly compute the allocation decisions and mass balance constraints.



		Users										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Basins	**A**				1							1
	B			1								
	C		1	1	1							1
	D							1				
	E		1	1	1		1	1	1			1
	F	1	1	1	1		1	1	1		1	1
	G									1		
	H	1	1	1	1	1	1	1	1	1	1	1

Figure 2: Example basin with user connectivity table (Lord et al., 2018)*)*

Unimpaired Flow Estimate

DWRAT uses hydrology data from two sources: the California Data Exchange Center (CDEC) hosted by the California Department of Water Resources (DWR), and the California Nevada River Forecast Center (CNRFC) from the US National Weather Service, for forecasting. California water law dictates that riparian users have access to the natural flow of the river and that appropriative users' water availability is considered against the unimpaired flow available in a river. DWRAT uses unimpaired or "full natural flow" from these data sources. Despite some scientific disagreements on the classification of 'full natural flow' and 'unimpaired flow'

(Walker, 2017), DWRAT utilizes unimpaired and full natural flow data from these sources as unimpaired flow.

Distribution of Unimpaired Flow Estimate Across Sub-Basins

A statistical hydrology model is applied within DWRAT to estimate monthly unimpaired flow estimates for each HUC-12. This hydrology model was originally developed by the USGS by combining 20 hydrologic and geographic indicators with historical streamflow data from 1950 to 2011 (Moriasi et al., 2007; Grantham and Fleenor, 2014). As such, it captures more than half a century of flow data and incorporates some data that reflect the changing climate and precipitation patterns. Using these estimated monthly unimpaired flows, DWRAT calculates a ratio of flow between the gaged HUC-12s and other non-gaged HUC-12s in the basins. Combined with another ratio of the area of gaged and ungauged sub-basins, this produces a general scaling ratio for each HUC-12 for each month. Differences in flow availability are not considered, as DWRAT assumes that all users in a HUC-12 access their water at the outlet of their HUC-12.

Equation 1: Unimpaired flow calculation performed for each HUC-12

$$Q_{HUC} = \frac{Q_{monthly,HUC}}{Q_{monthly,STA,HUC}} \times \frac{DA_{STA,HUC}}{DA_{STA}} \times Q_{STA}$$

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. Other hydrologic analyses have used similar equations with an added component for precipitation (Trush et al., 2016).

Water User Demand Data

The final input for DWRAT is water right and user demand data. These data come from the SWRCB's Water Rights User Database System (WRUDS). The specific data used by DWRAT include the type of water right, the location of diversion, the priority (for appropriative rights), and the use quantity. User demand is represented by average reported use for each month, based on reported use in 2010 to 2013 from WRUDS. This range of years represents reported use in a variety of water availability conditions. To ensure the model accurately reflects actual usage, DWRAT omits non-consumptive use return flows for each right. An analysis of the impacts of return flows on DWRAT in a large California river basin was done by Tweet (2016). For simplicity of analysis, DWRAT also assumes that each water user only uses a single point of diversion.

Linear Programs

DWRAT runs using linear programs (LP) for both riparian rights and appropriative rights. As in all linear programs, these have an objective function and are subject to a set of mathematical constraints. The LPs for both types of water rights have objective functions that minimize shortage according to the governing laws of each right type. Since water law in California dictates that riparian rights have priority over all appropriative rights, the riparian LP is run first. The LP for appropriative rights is run subsequently and allocates any remaining water. Summaries of the structure of the linear programs appear in Table 1 and Table 2. For a more detailed discussion of the mathematical logic for these apportioning equations, see earlier DWRAT reports and papers (Lord, 2015; Lord et al., 2018; Tweet, 2016; Walker, 2017; Whittington et al., 2016).

Table 1: Riparian Linear Program Objective function and constraints

Objective Function	$\min z = \alpha \sum_k w_k P_k - \sum_i A_i$	Allocate as much water to as many users
Constraints:	$A_i = P_k u_i, \forall\, i, i \in k_{upstream-most}$	All users in a subbasin *k* receive the same portion P_k of demand
	$P_j \le P_k, \forall\, k, j \in k$	Upstream proportions cannot exceed downstream portions
	$\sum_{i \in k} A_i \le v_k - e_k, \forall\, k$	Allocations upstream of *k* cannot exceed available water at *k*'s outlet
	$0 \le P_k \le 1, \forall k$	Portions must be 0 and 1
	$A_i \ge 0, \forall\, i$	Allocations must be greater than or equal to zero
	$A_i \ge u_{i,Public\ Health\ and\ Safety}, \forall i$	Allocations must meet PHS needs
	$w_k = \frac{n_k}{n_{k,outlet}}$	Unit penalty for *P* increases with downstream basins
	$\alpha < Min\left(\frac{w_{k,i}}{u_{k,i}}\right) \forall\, i$	Defines the relative weight for *P* values in the objective function

Table 2: Appropriative Linear Program Objective Function and Constraints

Objective Function	$min\ z = \sum_i p_i(u_i - A_i)$	Minimize total shortage penalty; unit penalties increase with water right seniority
Constraints:	$\sum_{i \in k} A_i \le v_k - e_k - \sum_{i \in k} A_{upstream\ riparian\ users\ i}, \forall\, k$	Allocations cannot exceed available water remaining after riparian allocations
	$A_i \le u_i, \forall\, i$	Allocations cannot exceed reported use
	$A_i \ge 0, \forall\, i$	Allocations must be greater than or equal to zero
	$A_i \ge u_{i,Public\ Health\ and\ Safety}, \forall i$	Allocations must meet PHS needs

To solve the linear programs, DWRAT uses an open-source optimization software package called SolverStudio (Mason, 2013). 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. DWRAT currently directs SolverStudio to call the Python-based package called PuLP. Compared to other open-source solvers used earlier in the model's development, SolverStudio performs faster and does not limit the number of decision variables. This has supported model development for larger basins such as the Sacramento and San Joaquin Rivers. Use of SolverStudio software allowed DWRAT to be expanded in scope and scale. However, SolverStudio and its usage in DWRAT still has some technical issues, such as software integration challenges affecting speed and solvability. This presents opportunities for process optimization discussed later (see section on PyWRAT).

To date, the DWRAT model has been applied to four large river basins in California: The Eel, Russian, Sacramento, and San Joaquin (Lord, 2015; Tweet, 2016; Walker, 2017; Whittington et al., 2016). Each application and basin has different complexities, complications and brought different advances. For example, the Russian River application addresses Lake Mendocino Reservation Rights; the Sacramento River application deals with complicated Return Flow analyses; and the San Joaquin River application illustrates environmental flow accounting. These four large case studies provide insights on a broad range of river management and water allocation issues in California. These results provide an ideal platform on which to build improvements to water allocation modelling.

DWRAT was built on the data from multiple different sources with varying degrees of reliability. Given this, model outputs may be improved by refining inputs or by generally increasing data availability. For example, water right demands in the model inputs were drawn from reported use data and do not represent any given user's water right full face value. This allows the model to give results for today's usage conditions but does not account for basins that do not have all allocated water used. Additionally, hydrologic data are subject to the limitations of their availability. The sources for hydrologic data used in this model, CDEC and CNRFC, have few gage locations with unimpaired flow data. Since gages are limited in their extent and distribution, the lack of data from non-gaged sub-basins (and especially those distant from their nearest gage) results in less accurate flow estimates. And finally, the ability of the current system to handle complex computations is somewhat limited. Initially, the DWRAT model was developed to be transparent, open-source, and relatively accessible to stakeholders. While these design choices have led to a model that is easy to use, the model has limitations in the scale and complexity of the linear programs it can expediently solve. All these limitations present areas where water rights allocation modelling can be improved.

Moving the Modelling Forward

This thesis focuses on the Eel River basin and examines two improvements to the existing modelling framework. First, it discusses the application of the updated DWRAT framework and solver, then analyzes its benefits and limitations. Second, it proposes a new modelling platform: a Python-based model designed to run all DWRAT models faster, more reliably, and to allow for implementation of more refined inputs in the future. Chapter 2 of this thesis focuses on the DWRAT model application in the Eel River and shows how some potential limitations of the model can be accounted for and addressed. Chapter 3 of this thesis describes a version of the DWRAT model in the Python coding language and illustrates how it can be applied to other river basins.

Chapter 2: Eel River DWRAT Model Application

This chapter presents the hydrologic context and current modelling efforts for the Eel River. It discusses the early DWRAT model and its application to the Eel, reviews updates to the DWRAT model, shows example model results from the 2014 and 2015 water years, and closes with an implicit stochastic optimization analysis. Presenting the Eel river modelling as a case study, it sets the stage for the discussion of model improvements discussed in Chapter 3.

The Eel River is in the North Coast region of California between the Russian and Klamath rivers (Figure 1). Given its location in rural Northern California, most infrastructure in the watershed supports agriculture and small farming operations. The large exception to this is the Scott Dam, which impounds the flows from the Eel, forming Lake Pillsbury. Also among the major infrastructure in the basin is the Potter Valley Project, which diverts water from below Scott Dam south into Potter Valley for irrigation and to generate hydropower, transferring this portion of the flow to the Russian River Basin.

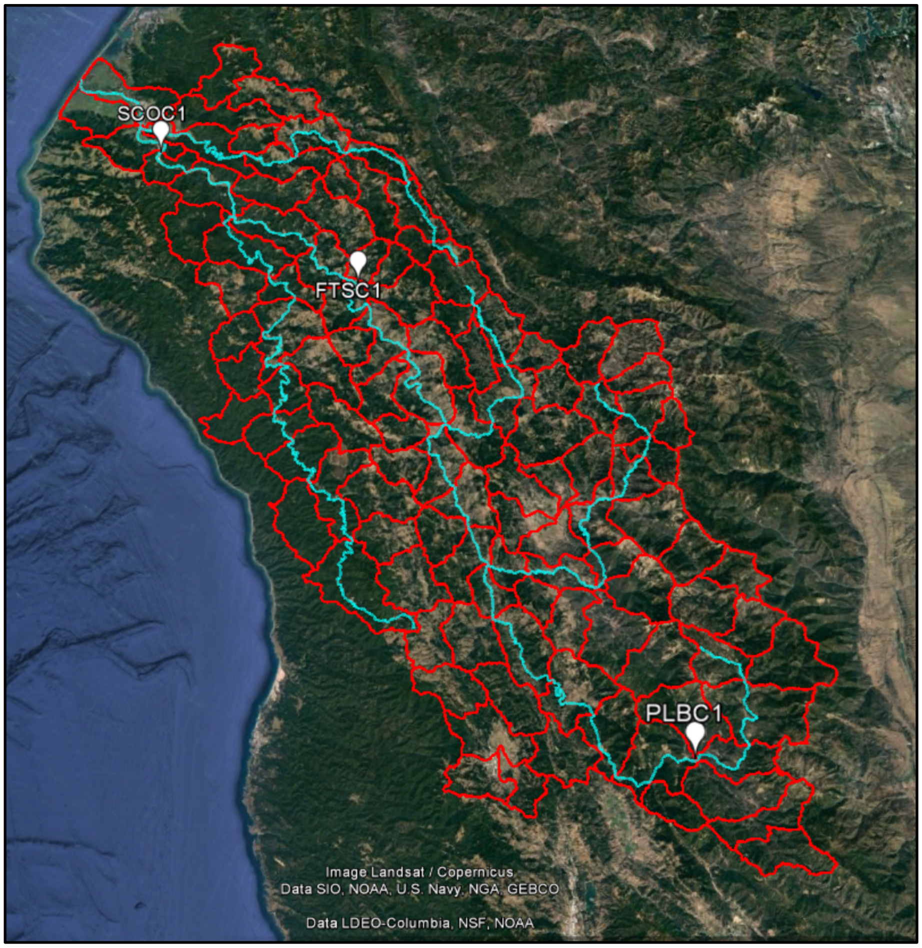


Figure 3: In the Eel River basin, the DWRAT model bases its flow predictions on data from 3 gages: one each from Scotia, Fort Seward, and Lake Pillsbury.

Unlike many California rivers, such as the Sacramento and San Joaquin, Eel basin streamflows are ultimately rain-driven. Large flow events during the winter are common, with little or no pulse of snowmelt runoff later in the spring. Due to the nature of the Eel River watershed's small tributaries with groundwater- or rain-driven flow availability, some stream reaches can go partially or completely dry in summer. Figure 4 shows monthly average runoff at Scotia, on the lower Eel River according to National Weather Service data.

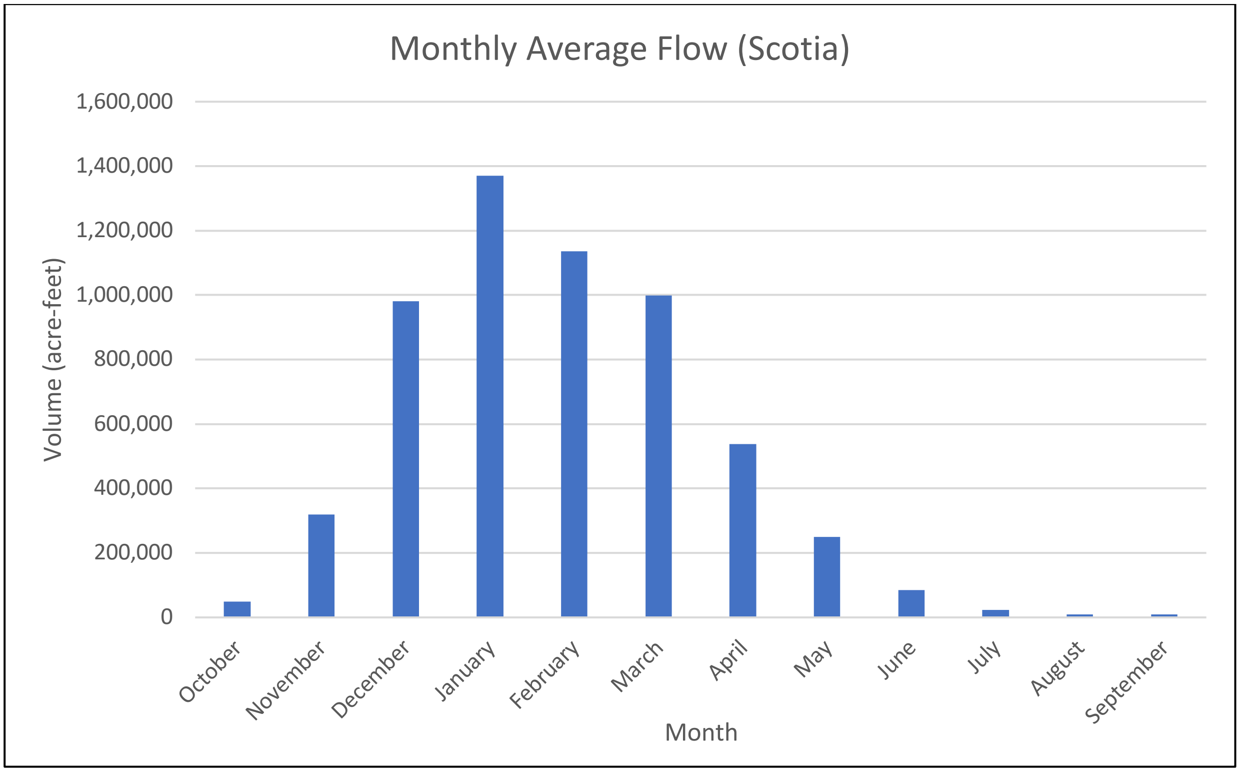


Figure 4: Historical monthly average flows at Scotia illustrating this rain-driven flow regime (CDEC 2018)

The greatest demand, by volume, for water in the Eel River is from appropriative users, although riparian rights holders have primary rights and are more numerous than appropriative users. Much of the appropriative demand comes from a small number of large appropriate rights holders who take water from relatively high in the basin. However, diversion points for these rights are located such that it is difficult, physically and legally, for flows to meet their full demand. Their uses include the hydropower generation at Lake Pillsbury and the Potter Valley diversion to the Russian River basin. As seen in Figure 5, this demand is highest during months that typically have peak winter rain events.

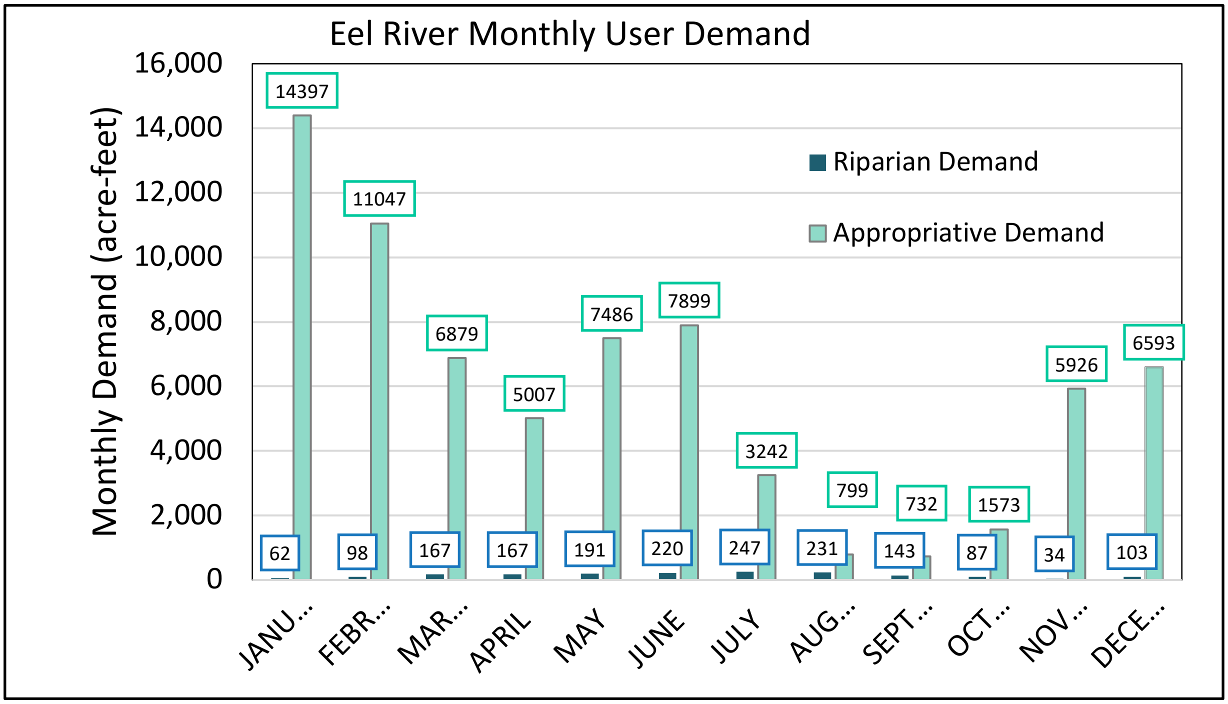


Figure 5: Total Monthly Water Demand in the Eel Basin from WRUDS

Eel River: Revisiting the Eel River Model

The following section describes what actually transpired in the Eel River basin in terms of water curtailments, and contrasts this with what the SWRCB might have implemented had they relied solely on DWRAT. The discussion captures the actual figures for the 2014 and 2015 water years, both of which were drought years. This comparison illustrates the utility of DWRAT, in refining curtailment projections and minimizing curtailment impacts for local appropriative right holders.

2014 Drought Curtailment Results

In Water Year 2014, the SWRCB announced that they were issuing water rights curtailments to some water rights holders in dry California basins. Having only done this action on a broad scale once before, in the critically dry water year of 1977, there was little precedent on which to base their actions. In the Eel River basin, the Board issued shortage notices to some appropriative users after evaluating the dry conditions. They began on June 30, when the Board completely curtailed all post-1914 appropriative right holders on the North Fork, and Main stem of the Eel River, and Van Duzen River. The curtailments lasted for approximately two months. By early August, 22 of these appropriative right holders (those downstream of the confluence of the Main stem and South Fork of the Eel River) were released from curtailment after the Board recalibrated gages at Scotia and Fort Seward and reevaluated the water supply. In September the Board released all curtailed users on the Van Duzen River, based on flow data from a Bridgeville gage and on a reduction in user demand in August and September.

Ultimately, these actions protected rights belonging to the most senior users in the reach, but shorted more junior users.

This actual curtailment provides a basis from which to analyze how curtailment employing DWRAT would differ from the simpler curtailments implemented by the SWRCB. In addition, running the DWRAT model using the 2014 data provides insights into its functionality across a water year during a severe drought. DWRAT predicted significant water shortages for both pre- and post-1914 appropriative water right holders for the 2014 water year. These differences are illustrated in the figures below (Figure 6, Figure 7, Figure 8). Figure 6 shows how the DWRAT model projects noticeable peaks of shortage volume for the Eel and Van Duzen rivers in the 2014 water year. The first shortages are during the winter months when water availability is typically high and right holders declare usages as diversions to storage. The second shortage peak is during the summer, when natural water availability is very low. The two peaks of appropriative shortages are accompanied by very small shortages of riparian right holders (Figure 6). These latter shortages are very small in magnitude, with small shortage volumes distributed widely among many riparian users under riparian law.

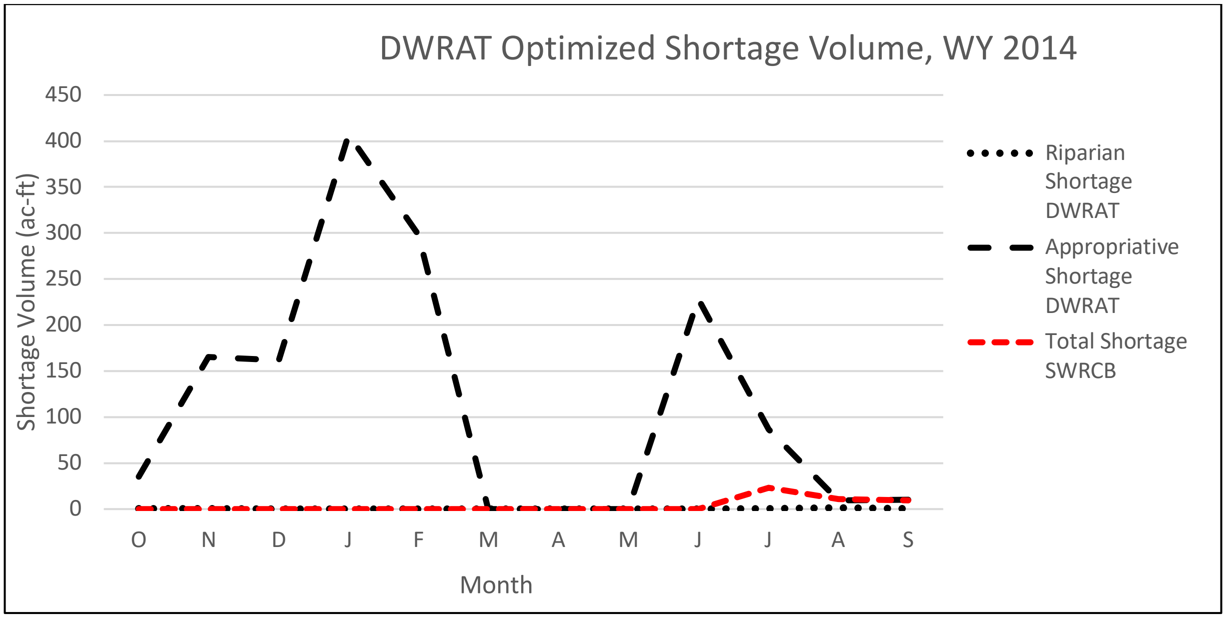


Figure 6: DWRAT Total Shortage in acre-feet in the Eel and Van Duzen Rivers in Water Year 2014 (in black) compared to Board curtailments (in red)

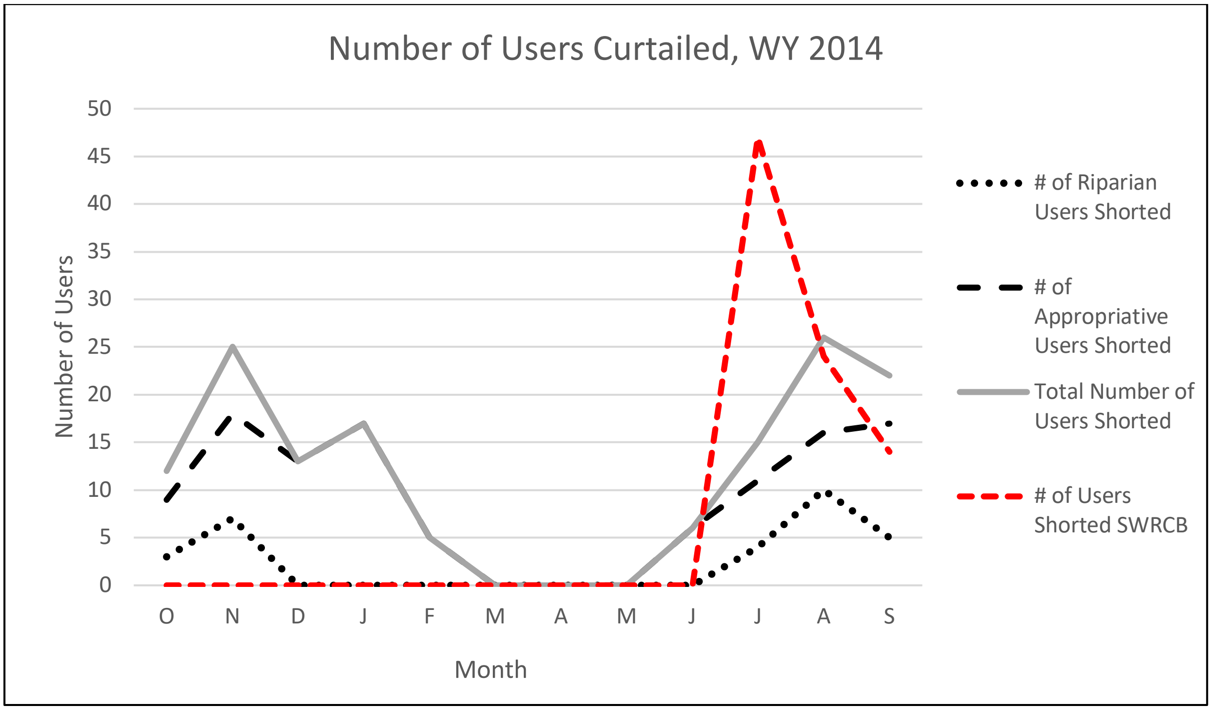


Figure 7: Percent of Total Number of Users Curtailed in the Eel and Van Duzen Rivers in Water Year 2014

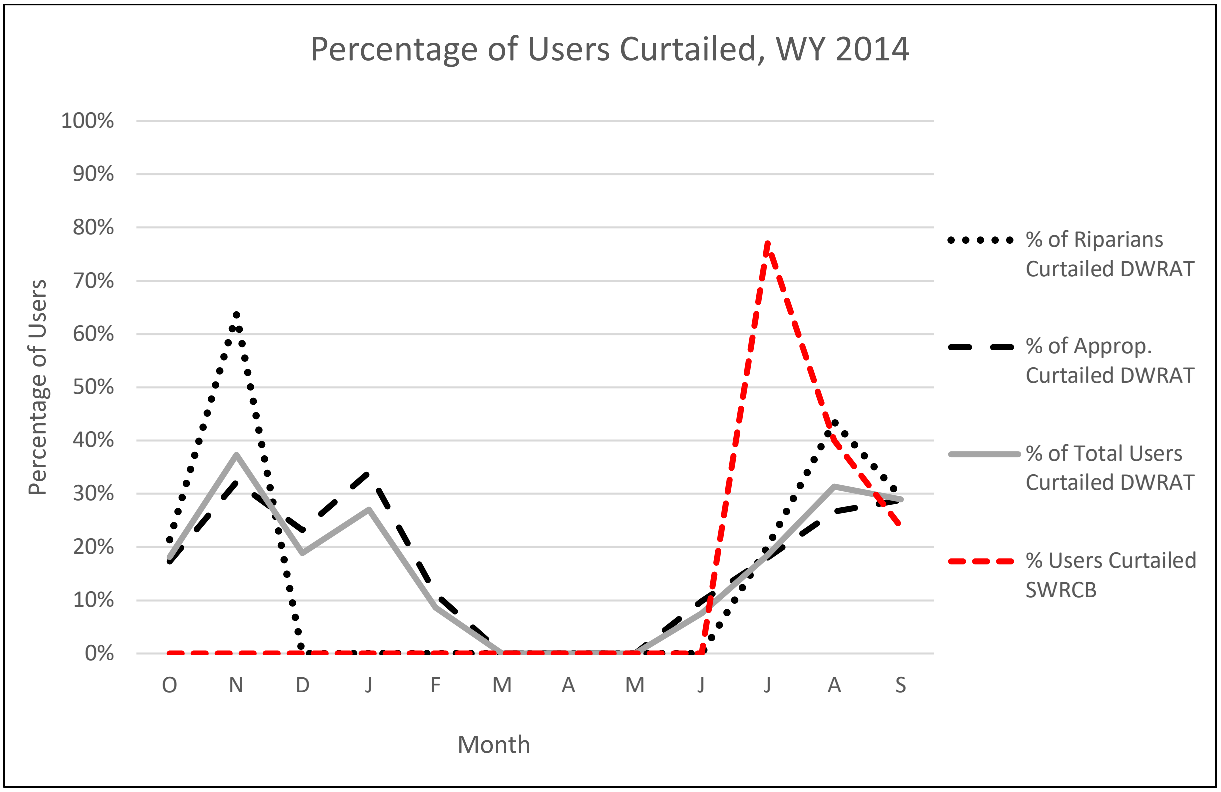


Figure 8: Percentage of Users Curtailed on the Eel and Van Duzen in Water Year 2014

This comparison highlights differences between SWRCB and DWRAT curtailment methods. Focusing specifically on the Eel river, DWRAT model results show that the Board might have significantly increased curtailments based on the data showing available water. In this case, DWRAT treats pre- and post-1914 appropriative water rights similarly (with deference to priority) but in practice, the Board is hesitant to issue curtailments to pre-1914 users. Figure 7 shows the impact of the DWRAT curtailments on significantly more pre-1914 appropriative users in the system. Some of these users may have been right holders in sub basins that ran out of available water before satisfying all demands.

Curtailments proposed by DWRAT were not distributed evenly throughout the Eel River Basin. The large majority of the shortage throughout the basin came from two HUCs containing the largest water rights in the basin. Figure 4 above shows that during two key months of demand in the Eel River, the largest rights could not escape curtailments despite their seniority. Shown are the months of January, for large diversions to storage, and June for the start of the agricultural growing season. DWRAT curtailments also differ significantly in this instance from Board curtailments in their timing and distribution.

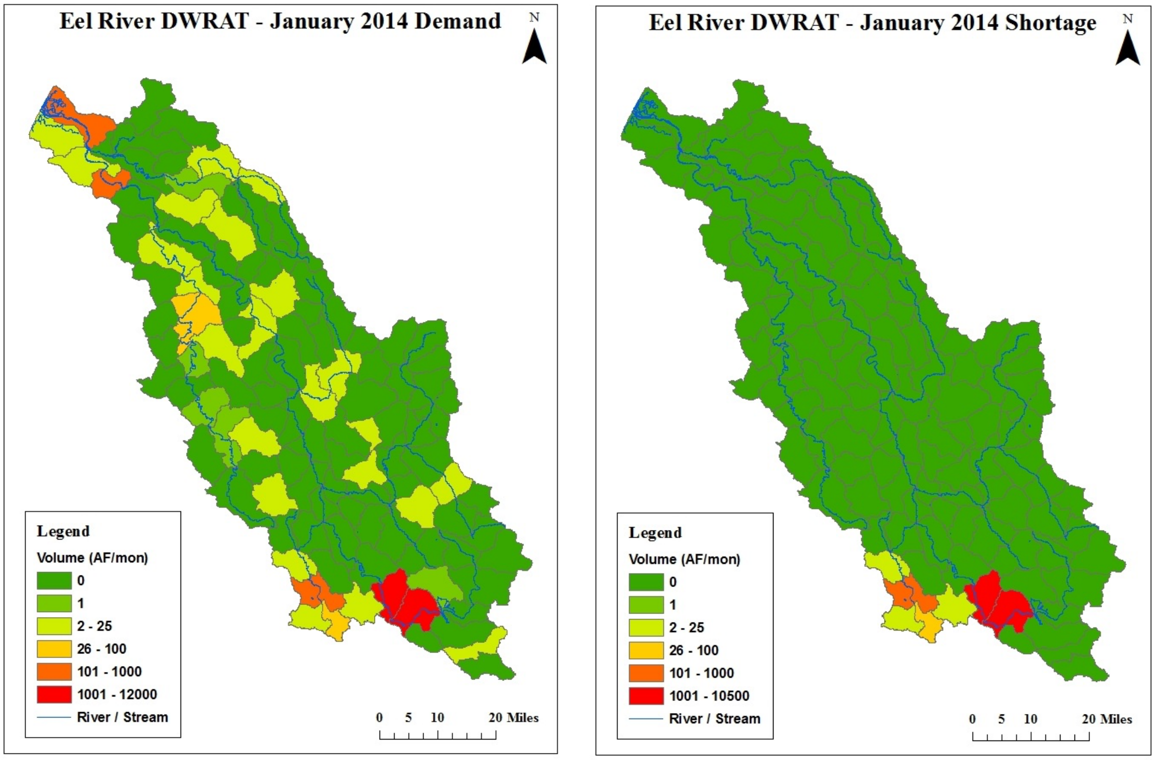


Figure 9a and b (left and right): Demand and Shortage Per HUC in the Eel River in January 2014

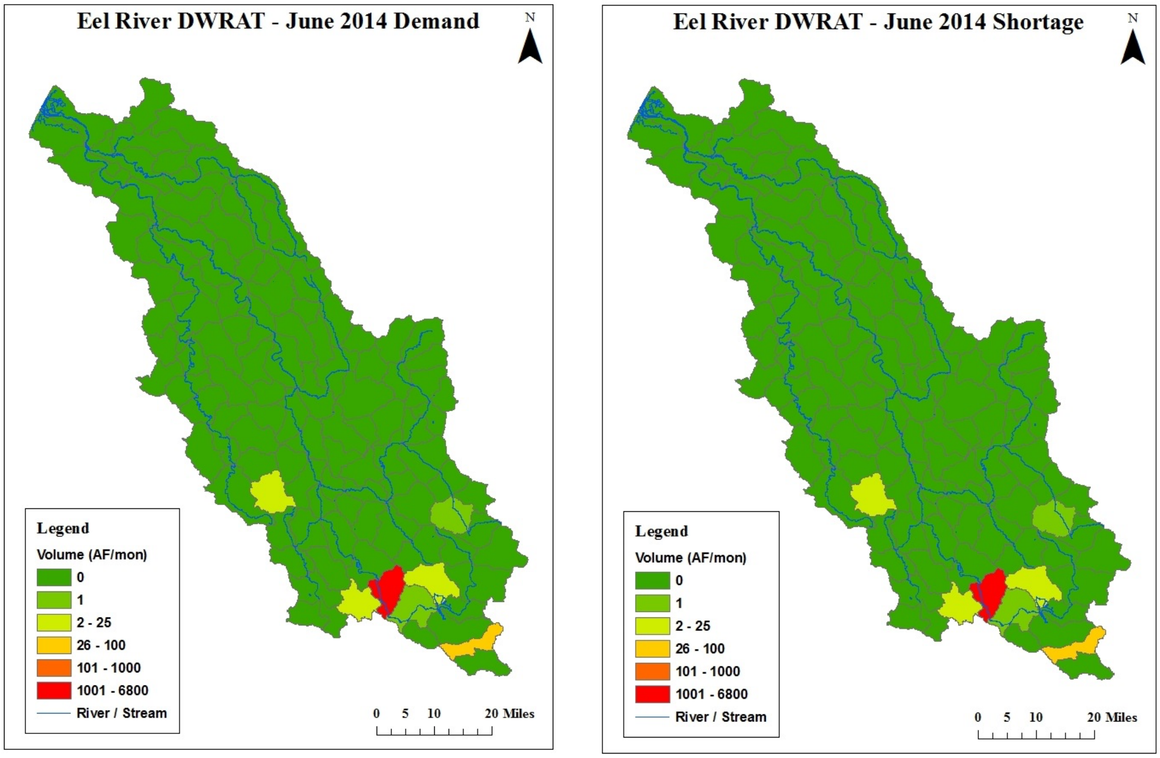


Figure 10 a and b (left and right): Demand and Shortage per HUC in the Eel River in June 2014

Water Year 2015 Drought Curtailment Results

In WY 2015, shortages look almost identical to the DWRAT optimized shortages but are slightly smaller. The SWRCB did not issue curtailments in 2015, but DWRAT results suggest that curtailments could have been justified (see Figure 11 and Figure 12 below). The Board may have elected not to curtail because downstream users voluntarily reduced their diversions or relied on diversions to storage earlier in the water year. Similar to 2014, most shortage is from curtailing a few extremely large appropriative water rights.

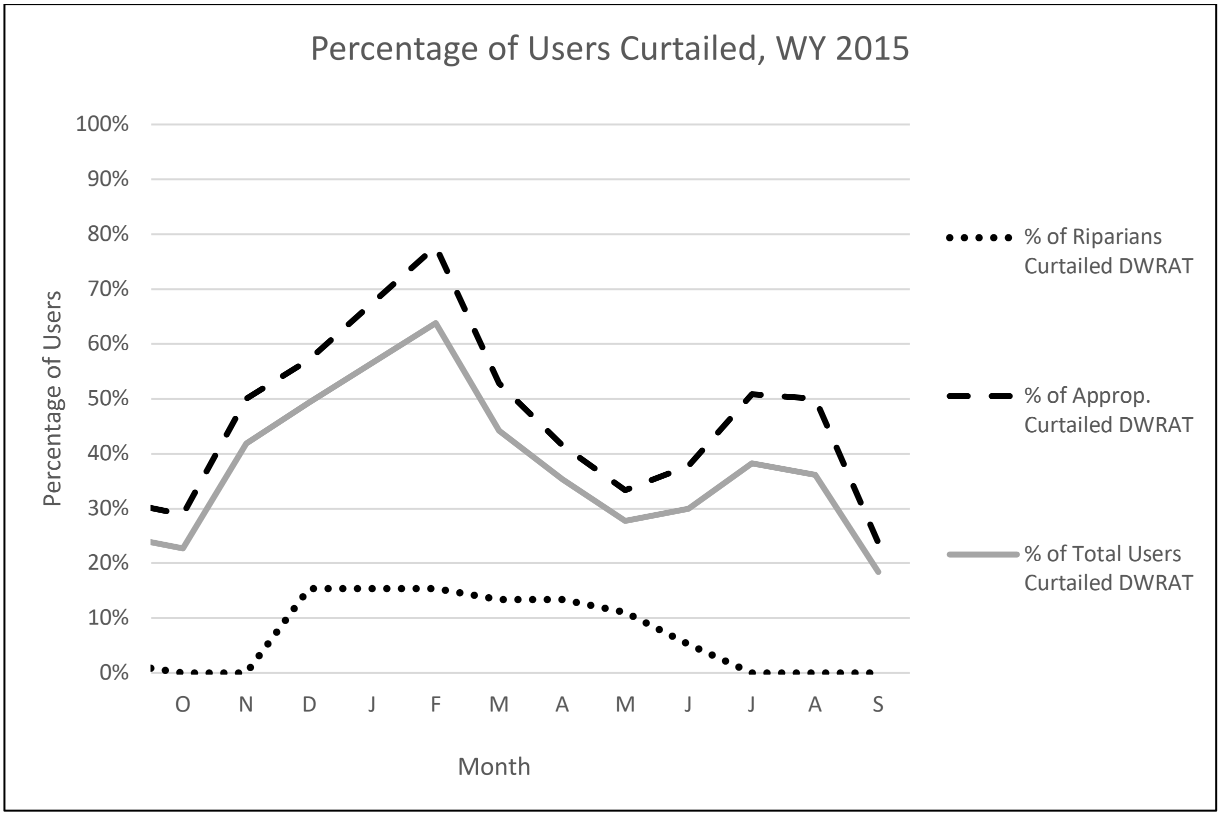


Figure 11: Percent of Users curtailed on the Eel and Van Duzen Rivers in Water Year 2015

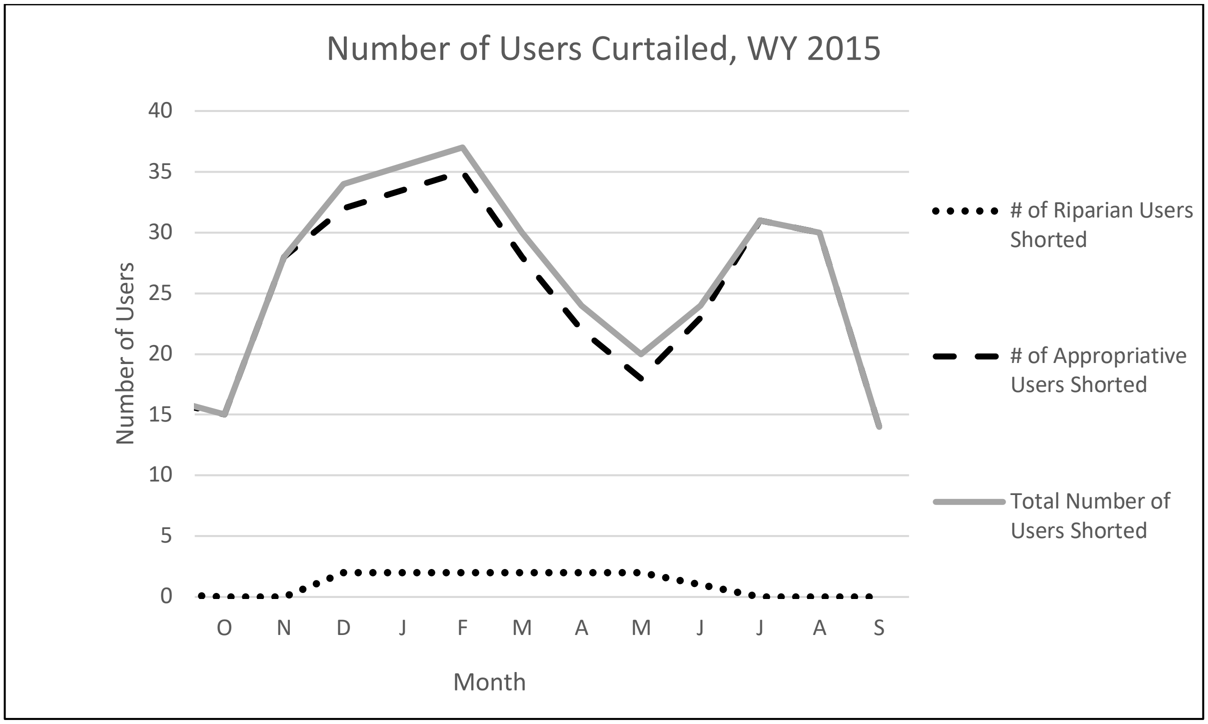


Figure 12: Total Number of Users Curtailed in DWRAT in the Eel and Van Duzen Rivers in Water Year 2015

These comparisons illustrate the utility of the more refined DWRAT curtailment modelling. Results from the most recent California drought show potential improvements to the State Water Resources Control Board curtailment methods in the Eel River basin. Despite being a small watershed, the Eel River is complex in terms of its water rights and issues.

The large differences between the DWRAT curtailments and the Board curtailments highlight the need for better Eel River data. Sources from the Board have pointed out significant differences in the unimpaired hydrology and actual flow during peak curtailment months. Board staff also cited these differences as a reason for not continuing drought curtailments in 2015. It is unlikely that most of the appropriative demand comes in the winter unless it is diversions to storage. Improving user demand estimates or installing a larger network of flow gauges may help solves some of these discrepancies for future droughts.

Curtailment Rules from Implicit Stochastic Optimization Analysis

DWRAT is a deterministic model whose use must address environmental uncertainties and data limitations. In general, models can account for uncertainty either explicitly or implicitly. In implicit stochastic optimization (ISO), models use stochastically-generated inputs in a deterministic model. These inputs reduce model complexity and computation load. Outputs from ISO can be used to create decision rules for making curtailments given inflows at specific locations (Celeste et al., 2009). As a deterministic model, DWRAT can utilize ISO by generating curtailments for a range of inflows, to suggest preliminary rules for water right curtailments in advance of actual droughts.

In DWRAT, the flow scaling model (Grantham and Fleenor, 2014) gives different values for each month within the water year. To calculate the probability of curtailment for a given right holder in a specific month, we can estimate the probability that the flow at which a water right would be curtailed will be reached in any given right holder’s basin.

Assumptions

For the Eel river, the current version of DWRAT uses gauge data from three locations, Scotia (SCOC), Fort Seward (FTSC), and Lake Pillsbury (PLBC). However, applying the DWRAT model to other California rivers points to the need to improve this flow data aspect of the model. For this study, a linear regression analysis provided a correlation coefficient to relate the upstream gauges (FTSC and PLBC) to the furthest downstream gauge at Scotia (SCOC). This allowed for a range of representative synthetic flows, essentially hypothetical flows for modelling purposes, to be used as inputs for a single gauge, which provided data for comparative analysis while still reflecting the hydrology of the basin. Using this method to model a range of inputs, we can estimate at what point a curtailment threshold will be reached. This allows the model to predict how each user in the various hydrologic units might be curtailed under different flow scenarios.

In applying this model refinement across the entire Eel River basin, we can see useful patterns in curtailment probabilities. First, these curtailments affect both riparian and appropriative rights holders. Figure 13 shows the probability of each right being curtailed, ranked by priority. In this graph, riparian users are shown in order of their application date -- but these riparian rights are curtailed by water availability instead of seniority. The cluster of riparian users with higher probabilities of curtailment are all located in the Lower Larabee Creek HUC-12, a small tributary with less water availability than the other sub basins. The high probability of curtailment here can be explained by the low flow availability and the relatively high concentration of riparian users. Of the eight appropriative users with 90% curtailment probabilities, the most senior right holder is PG&E, which holds the largest right in the basin. This right's high curtailment probability is expected and, as shown, is almost guaranteed to be at least partially curtailed at most flows. The lowest priority users of the 90% curtailment probability group are all located within the Davis Creek HUC-12, another small tributary creek with low flow availability and high demand.

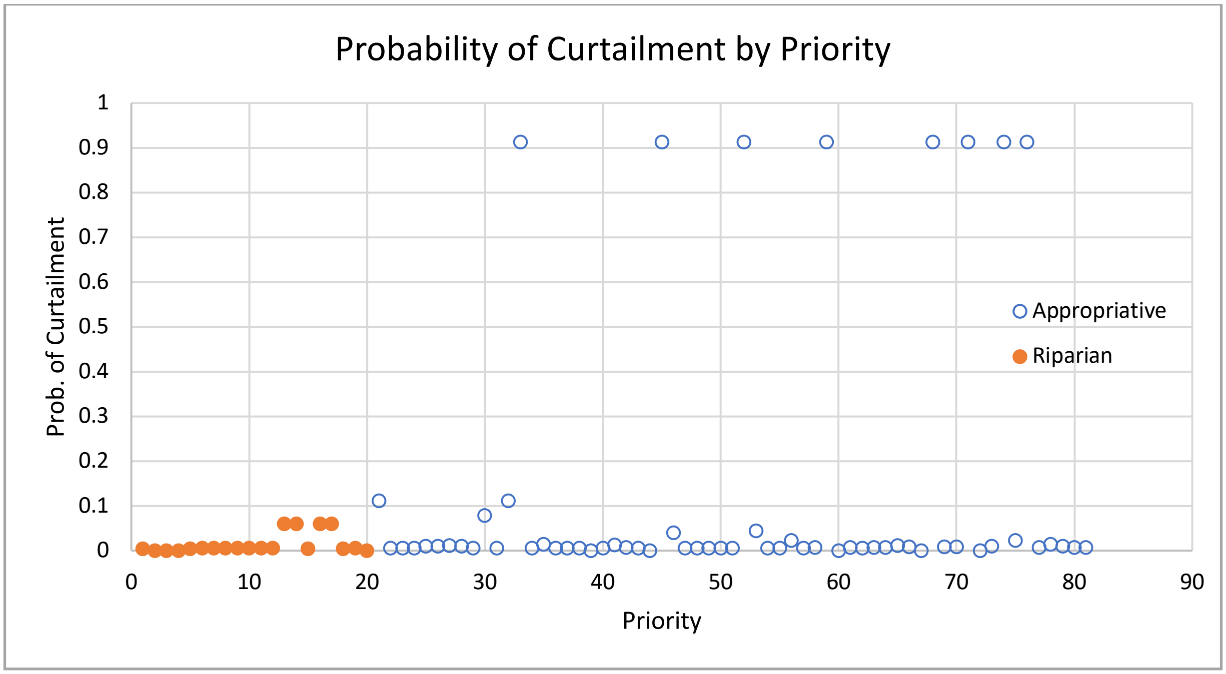


Figure 13: Probability of Curtailment in Eel River Sub-basins

Another important pattern in curtailment probabilities is how curtailment can adapt to changing flow availability. Figure 14 and Figure 15 show that both the number of users curtailed and the total shortage volume in the basin decreases as flow availability increases. Both functions are monotonic decreasing, as expected.

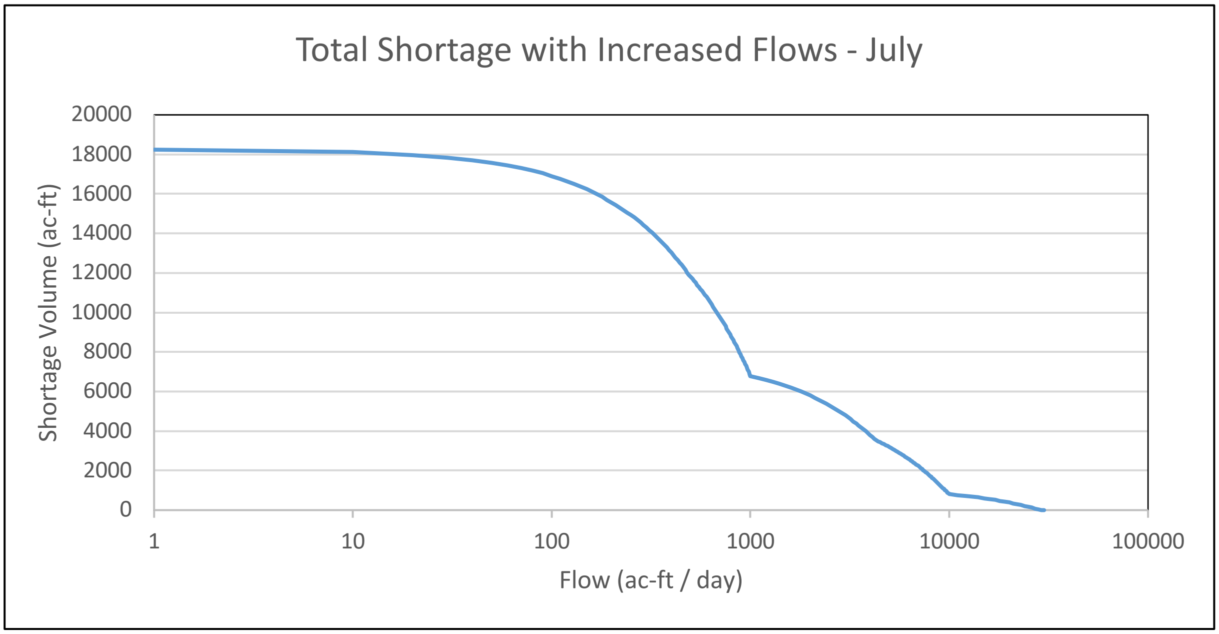


Figure 14: Total Shortage with Increasing Flows at SCOC Gauge

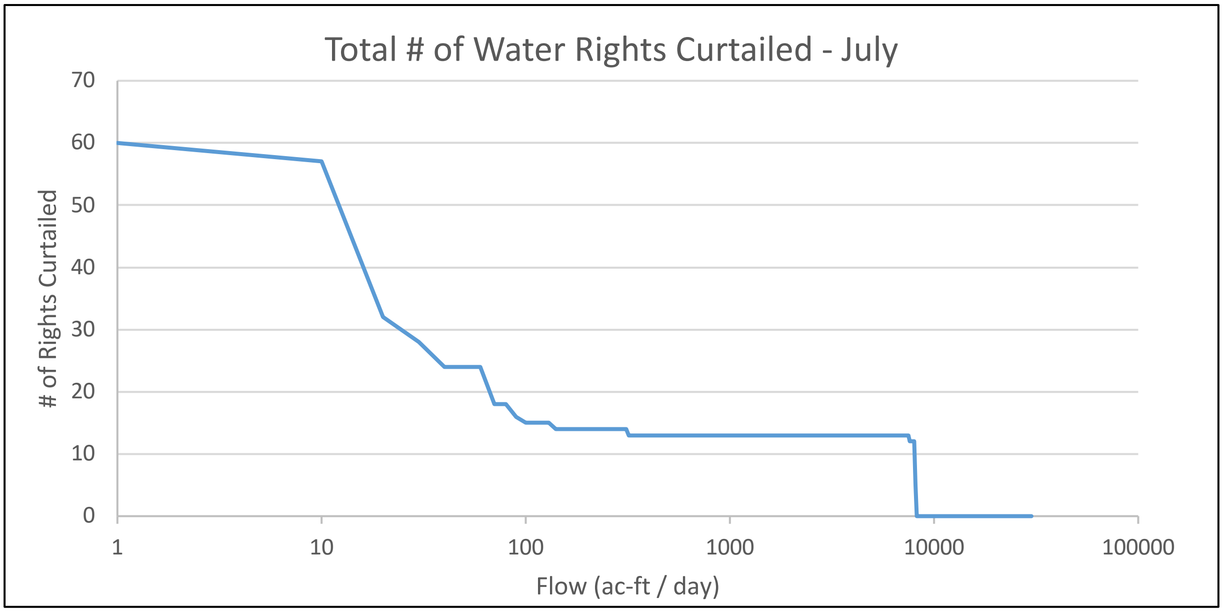


Figure 15: Total Number of Water Rights Curtailed in July with increasing flow at SCOC gauge

In addition, a refined model can better address priority of rights. Figure 15 shows how the updated model predicts probability of curtailment based on priority of rights. Significant knickpoints show that a large drop in water shortage occurs between 100 and 1,000 acre-feet per day, with correlating drops in shortage above 1100 and 8000 acre-feet per day. Changes in the slope of the function at these points are likely due to flow levels that trigger release of curtailments in specific upstream HUCs. The most-affected HUCs are usually far upstream with low water availability.

In the original analysis on the Eel River (Lord, 2015), the number of users shorted versus overall flow at Scotia was expected to be monotonic decreasing but this was not found to be purely the case in some flow ranges. This behavior occurred between 50-100 cubic-feet per second and 800 - 850 cubic-feet per second (at Scotia) and occurred for users in very few HUCs. These earlier results could not be replicated in the new version of the model, although many factors that could have affected the analysis including a different solver and a different linear regression equation.

Curtailment Probabilities Per-HUC and Curtailment Thresholds

The modelling also shows that users in similar HUCs (e.g. HUCs with large demands, upstream tributary HUCs) sometime have similar curtailment probabilities. This is useful in guiding curtailment decisions but does not always work well with the priority based right system. In cases where curtailment notices are issued based on curtailment thresholds, some users may be unnecessarily shorted due to their upstream location despite having a higher priority than downstream right holders, in times of limited availability. Lastly, following the range of flows method can create distinct flow cutoffs for users as long as the gauge data and the regression relationships are reliable. These improved model results, however, do not account for partial curtailments, only the flow level at which each user would be given their full allocation.

Future Research in the Eel River Basin: Cannabis Right Impact:

Another important need for model development in the Eel River is accounting for a newly legalized agricultural crop, cannabis. Illegal cannabis cultivation in California is problematic and results in major environmental impacts such as stream dewatering, contamination of streams from unregulated fertilizers or pesticides, and forest fragmentation due to land use (Butsic and Brenner, 2016; Wang et al., 2017). With its legalization in 2018, new water rights have been created that will allow managers to better understand the water needs for cannabis cultivation and help dampen the destructive effects of illegal operations.

Cannabis cultivation has been an issue in the North Coast region of California for many years. Humboldt, Mendocino, and Trinity counties have been called the ‘Emerald Triangle’ and make up the largest cannabis producing region in the world (Carah et al., 2015). An estimated 20-30 percent of streamflow is used to grow cannabis in Humboldt, Mendocino, and Trinity counties alone (Bauer et al., 2015).

The outdoor plots or greenhouses for cannabis, often referred to as ‘grows’, have had a major impact on the water supply and water quality of local streams (Butsic and Brenner, 2016). Hazardous tailings from grows have overwhelmed native biota with pollution. Diversions, almost always illegal, draw water from streams and have completely dewatered some reaches (Bauer et al., 2015; Butsic and Brenner, 2016). These issues were exacerbated by the most recent drought. And with the help of shifting political climates, the California Congress passed Assembly Bill 243 (*AB 243*, 2015) and Senate Bills 837 and 94 (*SB 837*, 2016, *SB 94*, 2017) to legalize cultivation of cannabis for recreational use.

The State Water Board has developed ‘Cannabis Rights’ to address this situation (SWRCB, 2017). These rights are unique in being specifically for cannabis growers, with limitations on withdrawal timing during the water year, and use locations for these diversions. Specifically, water used for Cannabis rights can only be diverted to storage in winter and are tied to environmental flows in stream reaches, designed to prevent damage to ecosystems. While these criteria seem responsible, in practice, Cannabis rights have failed to gain traction in the region. At a recent panel on environmental flows, experts remarked that growers have operated outside of the constraints of the law in the past and are wary of entering into an agreement with the state that may limit their ability to produce. Some growers also fear disruption from federal regulators since cannabis has not been federally approved.

A study by the Board looked at cannabis grows in 4 sub-basins in the Eel River basin (Bauer et al., 2015). Using satellite imagery from Google Earth to examine greenhouses and outdoor grows, the number of plants was estimated. Then using a projected per-plant water usage figure of around 23 liters per day per plant from the Humboldt County Growers Association, the overall water demand for each HUC was calculated. The study found that as much as 20 to 30% of natural flow was being removed from tributaries in the cannabis growing season (June through October) based on local flow estimates.

Conclusions

The results for the Eel River basin suggest that more hydrologic data is necessary. The Board has recognized the need for more stream gauges and better water user demand data. These results also suggest that for large single use water rights, some calibration may be needed to better represent conditions in the basin. The Eel River in particular has two very large appropriative rights whose demands drastically change the total curtailment or shortage values for the entire basin. Forecasting methods that use synthetic hydrology, such as the ISO shown above, can help regulators, right holders, and stakeholders consider future conditions or examine reliabilities for new water rights. However, the future of water rights in the Eel River basin will depend largely on the implementation of the new cannabis water rights system and the ability of the Board to manage the current issues of depleted streamflow and declining water quality.

Chapter 3: Python Water Rights Allocation Tool: pyWRAT

Development

In recent years, software advances have allowed linear program solvers and optimization software to run faster and more reliably. Much water resource management software has transitioned or is transitioning to newer solver software, including the hydro-economic model CALVIN (Dogan et al., 2018). An outcome of this thesis research is development of a new program to reduce water right model run times for the Sacramento River basin while running analyses over 50 years of historical simulations, among other improvements.

As explained in Chapter 1, DWRAT uses a linear program solver to determine optimal water right allocations in times of water scarcity; first used was OpenSolver (a VBA solver), then SolverStudio (using an external Python library and solver). In all DWRAT versions running SolverStudio and PuLP, the chosen backend solver is Coin-or branch and cut (Lougee-Heimer, 2003). Previous studies pushed these linear solvers to their computational limits. When handling larger models, such as the Sacramento River basin or the San Joaquin river basin, these models had increasing difficulty given the number of constraints. Examining these analyses revealed that the complexity of interaction between the Excel sheets and the program performing the optimization calculations was beyond the scope of the initial linear problem solver software packages. In the most recent spreadsheet versions of DWRAT models, this meant that each piece of data had to be 'translated' from Excel, into SolverStudio, and finally to PuLP, and then back. Performing large-scale, highly complex, or repetitive analyses with the Excel DWRAT models proved to be unrealistic. The processing often either timed out or the program crashed. These limitations provided a clear indication that it is essential to update the DWRAT to best address California's complex water issues. To address these issues, a version of DWRAT was built in the Python coding language. This method reduces passing of data between Excel and PuLP.

In keeping with the initial goals of the DWRAT model, the Python-based water rights application uses open source processing tools, is easily distributed, and relatively easy to understand given some knowledge of the original DWRAT model. It also keeps the same input data as the original models to continue using publicly available data. The Python application also uses the same backend linear program solver to maintain consistency with other DWRAT models. Named pyWRAT, this new program application uses sheets directly imported from other DWRAT models in the exact same format as the spreadsheet models to expedite processing. By cutting out the software 'middlemen' between the data and the linear solver, pyWRAT shortens processing time for each model run by 50 to 90%. Model run times vary depending on the number of active users for each linear program in each month but on average, DWRAT runs for the Sacramento River take 5 to 15 minutes to run while pyWRAT runs take 1-3 minutes. Results from this model were validated with results from DWRAT results from 1922 to 2003 using historical data from CDEC.

Applications

This section presents applications of pyWRAT to improve river management for three problems: water right curtailment thresholds, water year type analysis, and addressing errors in previous DWRAT modelling. Where practicable, these application areas are addressed and discussed to demonstrate the improved utility pyWRAT for various water management cases.

Water Rights Curtailment Thresholds

Water Rights Forecasting: pyWRAT's increased processing capabilities can provide more extensive analysis of water curtailment thresholds. As shown in the Eel River model (see Chapter 2), running the model with synthetic hydrology data can help identify critical flow-based points in water right supply reliability for decision makers and water users. Implicit stochastic optimization is one method for such analysis. For example, the Sacramento River input hydrology was constructed using data from five CDEC gauges and the DWR 4-River Index of unimpaired flow estimation near the outlet of the Sacramento river into the Sacramento-San Joaquin Delta. In this analysis, unimpaired flows at other gauges are linearly scaled from flows at the 4-River index for flow scaling based on the month of July. The downside of using a single flow gage with a linear sub-basin relationship is that it may not represent a range of flows in sub basins distant from gages.

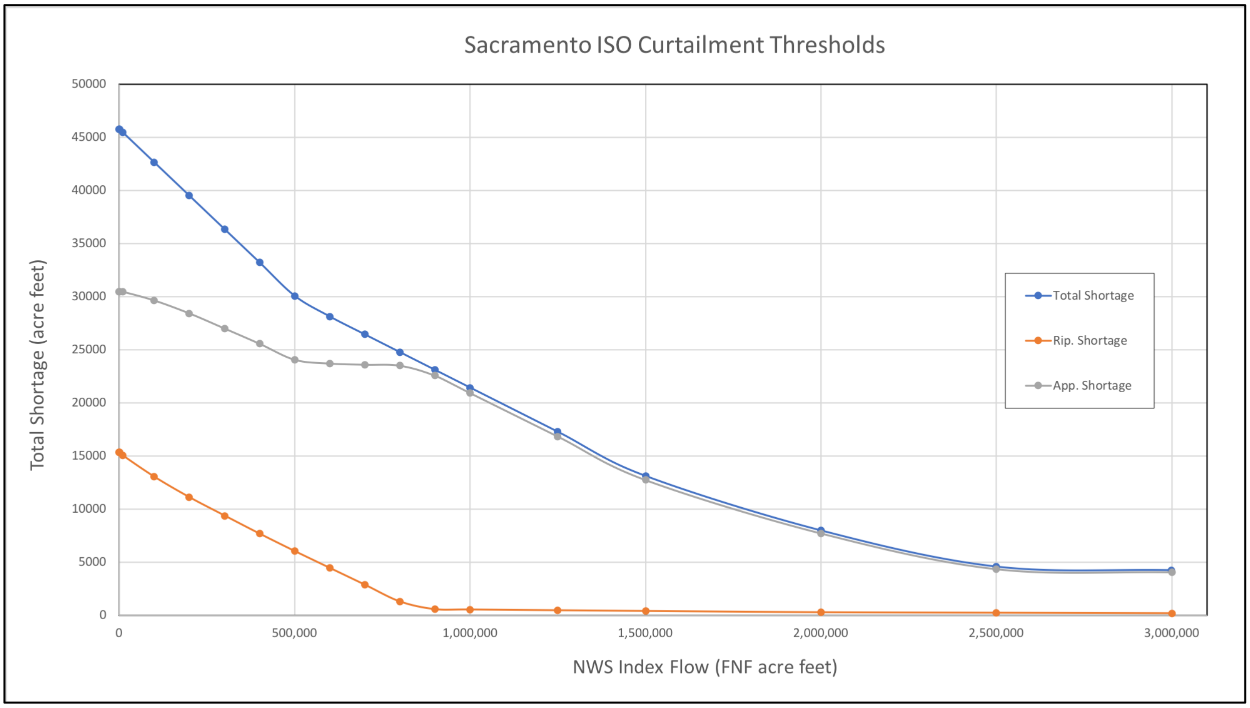


Figure 16: Water Right Shortage for the Sacramento Basin under a range of flows based on July inputs

In the case shown above in Figure 16, riparian users have almost all demands satisfied at a flow of about 800,000 acre-feet. Some riparian shortage persists in high elevation HUCs in with little water availability, as seen in other DWRAT models. It is not until the flows in the index reach around 2.5 million acre-feet (per month), the total shortage plateaus at just under 5000 acre-feet. All of this shortage is to appropriative users. These values are not perfectly accurate. Errors in this case could be from correlation relationships used to tie gages to the NWS index flow used for hydrology inputs, but could also come from misreported demand data from users in the Sacramento River basin or incorrect scaling factors for a HUC with one or more high-demand users. These results imply that under most circumstances, some appropriative users will not receive their full demand.

For reference, the graphic below (Figure 17) from the California Department of Water Resources Bay-Delta Plan (CA DWR, 2016) shows an 80-year annual series of unimpaired flow estimates for rivers in the Central Valley. The dark blue line represents the Sacramento Valley Outflow in unimpaired flow. This illustrates the extreme range of variability (from a minimum of approximately 6,000 TAF to nearly 50,000 TAF per year), which highlights value of curtailment thresholds.

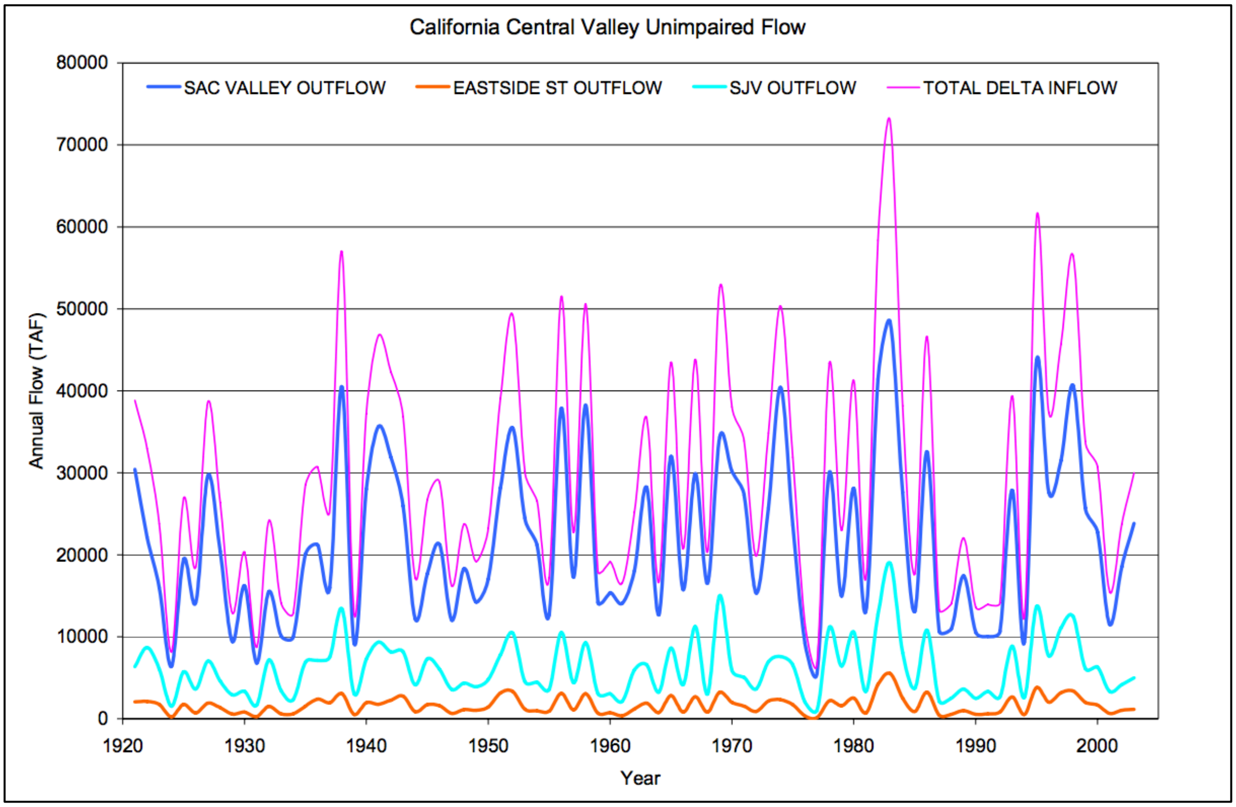


Figure 17: Historical unimpaired flow at significant Sacramento River gauges

Water Year Type Analysis

Aggregating water data can often make it easier for policy makers to manage large scale issues. One method is to classify water years into distinct types. In the Western United States, water year typology and drought indices help managers and decision makers simplify complex decisions to effective and easy to understand metrics (Heim, 2002; Null and Viers, 2013; Quiring, 2009). The example discussed below, shows how pyWRAT can be applied to help classify Sacramento River water years.

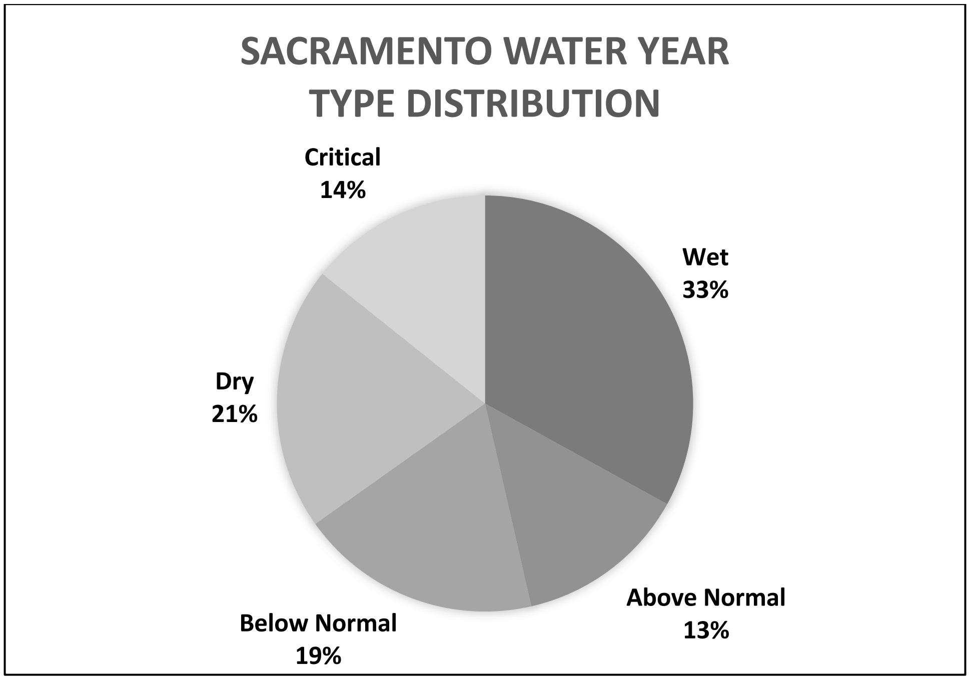


Figure 18: Distribution of Water Year types based on the Sacramento Valley Index

Water year types were formerly based solely on forecasted unimpaired flow values into key locations in the Sacramento river basin (CA DWR, 1989), but recently, more complex methods have been employed. To estimate water year types in the Sacramento River basin, the Sacramento Valley Index (SVI) uses current runoff, runoff forecast, and the previous water year index in the following formula to calculate the current water year's index value.

Equation 2: Sacramento Valley Index equation used by CA DWR

$$SVI = 0.4 * \ Current\ Runoff_{Oct-Mar}(maf) + 0.3 * Runoff\ Forecast_{Apr-Jul}\ (maf) \\ +0.3 * Previous\ Water\ Year\ Index$$

Unimpaired flow data used to estimate the current and forecasted runoff come from gages from Sacramento River above Bend Bridge, Feather River at Oroville, Yuba River near Smartville, and American River below Folsom Lake as runoff in the formula.

Understanding the typical shortages during different water year types could help provide early warning for potential curtailments. Using historical unimpaired flow data, water years were examined for their given water year type and their total annual shortage was projected using pyWRAT.

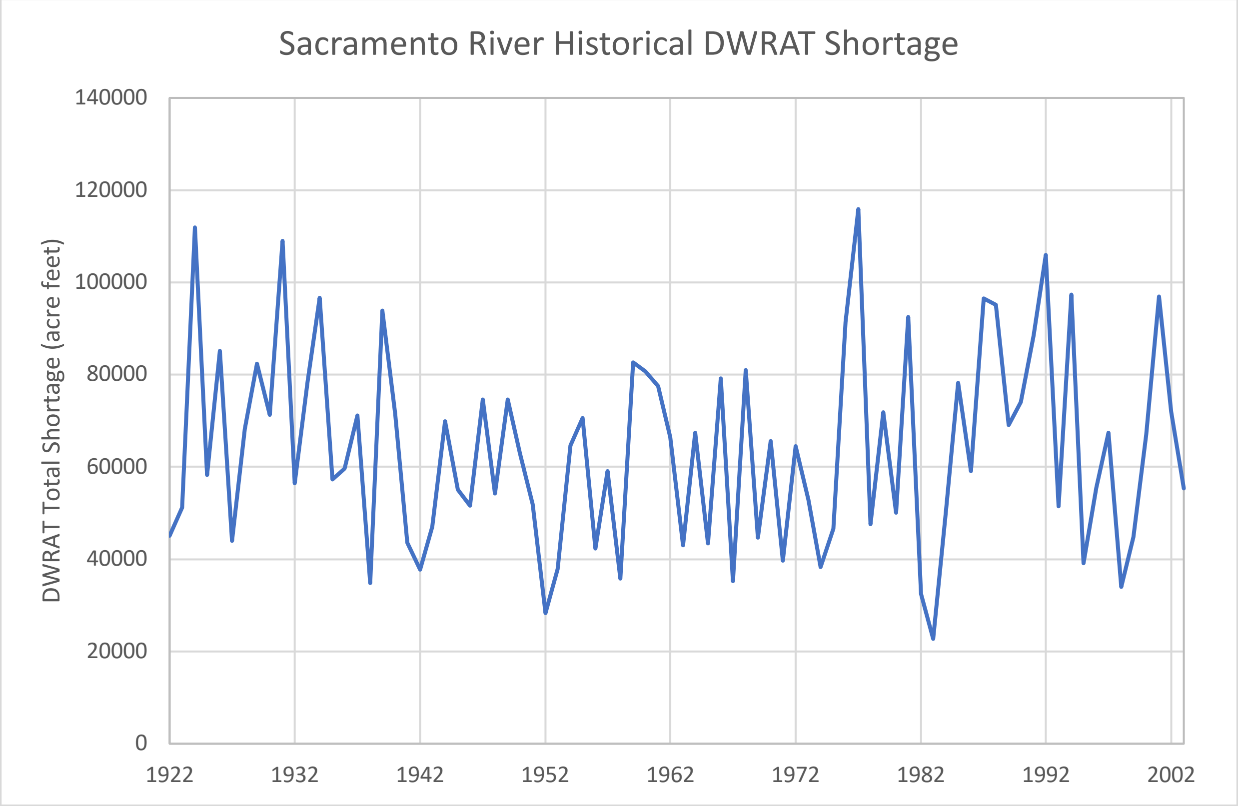


Figure 19: DWRAT Shortage Time Series (1922-2003)

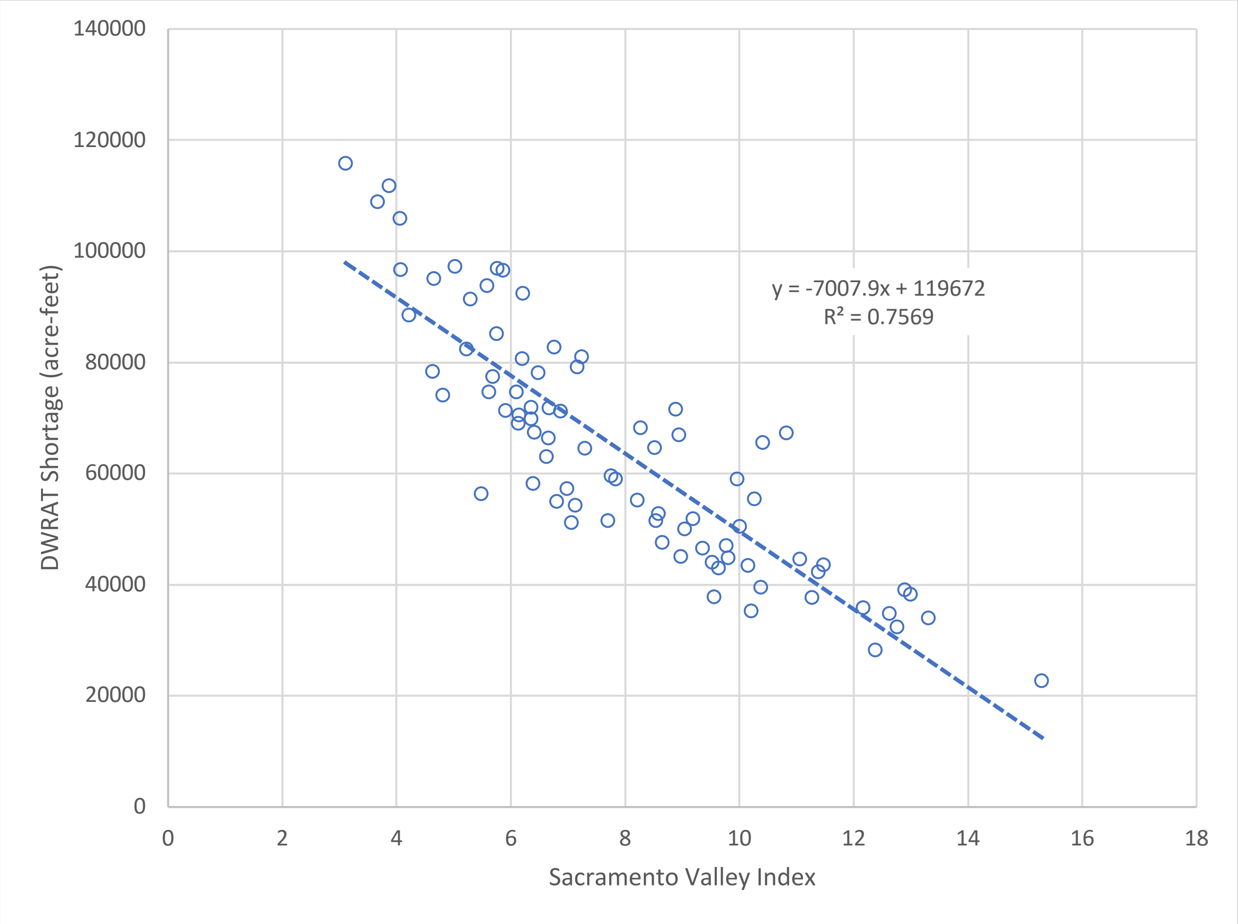


Figure 20: DWRAT Shortage vs. Sacramento Valley Indexes for 82 years of historical data

Because the Sacramento Valley Index calculation is partially determined using the previous water year's classification, there was only a moderately good correlation between total shortage in the Sacramento basin and the water year type for any specific year (Figure 20). DWRAT shortage predictions vary up to 40,000 AF for similar index values. Issues comparing shortages and index values include the following: the water rights model only considers the available surface water in each HUC and neither the water rights model nor the SVI consider groundwater availability or carryover storage. Another problem with these assessments is that they assume hydrologic stationarity and can be difficult to adapt to an increasingly variable climate.

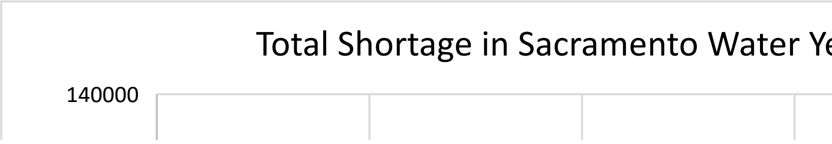


Figure 21: DWRAT shortage for water year types Critically Dry(1), Dry (2), Below Normal (3), Above Normal (4), and Wet (5)

On a coarser scale, water year typing is only a moderately good predictor for total shortage in the Sacramento Basin. Both systems of typology would have to be refined to be valuable in any useful projection of water rights shortages.

Misbehaviors in Previous DWRAT model

In a previous application of the DWRAT model (Tweet 2016) riparian users in some basins would become inappropriately curtailed. In accordance with riparian water rights and the governing formulas of the DWRAT model, if there is any water shortage deep enough to affect riparian users, all shorted riparian users will share that shortage and are "curtailed" although they receive most of their demand. Also, riparian right holders should not be completely curtailed unless there is zero water available in their basin. Under some conditions, riparian users in a few HUCs in the Sacramento river were inappropriately completely curtailed under this previous application of DWRAT while there was still water available in the HUC. This occurred in some HUCs distant from a gaged HUC. This is a critical glitch to be addressed in any improvement of the DWRAT model.

Some testing on these erroneous curtailments was done on an older version of DWRAT that included return flow calculations. This testing showed that in some sub-basins far upstream from gage locations, riparian water users were being falsely shorted. In many cases, in HUCs with a p-catchment values of 1 (this value means that all riparian users in the HUC should receive their full allocation), users were being erroneously shorted. To test the steps at which this allocation error was occurring, model runs were performed on DWRAT without return flow calculations, and also for comparison on pyWRAT. As an additional check against these errors, a line of code was added to pyWRAT to ensure that in scenarios where the p-catchment value is 1, all users in that HUC receive their full allocation before other water is allocated. Allocation values for August of 2015 were compared for all riparian users for three separate model runs: classic DWRAT, pyWRAT, and pyWRAT with the additional safeguard code.

Results from this analysis showed that 23 HUCs had riparian users that were completely curtailed in the original DWRAT model that should have received a portion of their allocation. The original DWRAT appears to have an issue allocating riparian demands when water is scarce. The riparian linear program in DWRAT was again run, both with and without the appropriative linear program, with no difference in results, suggesting that the error occurs specifically in the code used to calculate riparian allocations. Riparian shortage for the affected HUCs were not insignificant for the individual users; values ranged from 6% to 40% of demand. The difference in total overall shortage between DWRAT and pyWRAT was about 5% of total riparian demand. Both pyWRAT models, with and without the hard-coded fix, performed correctly and with no difference to the results. Neither pyWRAT runs showed any false curtailments, and their allocations matched the DWRAT model in other HUCs that did not share the scarcity issue. This suggests that the original code in pyWRAT functions as intended and does not need a hard-coded fix.

While the underlying issue with the riparian curtailments in DWRAT was never explicitly solved, testing indicates that the error likely lies somewhere in how the original DWRAT incorporates the RipLP code. While teasing out the exact coding interface error or misalignment is beyond the scope of this thesis, it was confirmed that this riparian allocation error issue does not exist in pyWRAT.

Other basins – San Joaquin and Eel

Further applications of pyWRAT could include analyses for other basins. Data for the San Joaquin and Eel River basins have been developed, but not yet applied to water rights allocation studies using pyWRAT. The San Joaquin basin is a contentious basin fraught with legal battles and complex issues. One example would be legal case of *State Water Resources Control Board vs Byron Bethany Irrigation District* mentioned earlier.

Applications such as pyWRAT that enable faster and larger analyses on these basins will allow stakeholders and managers to quickly and efficiently understand the consequences of their decisions for a wider range of possible hydrologic conditions. The Eel River is also undergoing significant changes. The basin has seen introduction of Cannabis cultivation water rights (SWRCB, 2017) and will be significantly affected by a pending transition in Lake Pillsbury's management (Kubicek, 2017). Reliable analyses that can be done on a large scale will be critically important in future management of water distribution in this basin.

Providing a refined modelling application for the Eel, Sacramento and San Joaquin Rivers will aid the SWRCB in decision-making that considers new uses, changing management conditions, increased data availability, and some complexities from a changing climate.
The pyWRAT framework for water rights analysis could lend itself to hydrologic forecasting of water rights. Stakeholders and water rights holders could update or modify their operations during the water year as forecasts improve.

This most recent version of the water rights allocation tool, pyWRAT, is faster and more reliable and powerful than the earlier DWRAT version. Additionally, this model resolves a lingering error in an earlier version of DWRAT. However, the original DWRAT has the benefit of simplicity and being completely spreadsheet-based. The original DWRAT software may be more suitable for working with less complex river systems.

Overall Conclusions

As shown in the Eel River model above, many improvements are needed to ensure that water rights can be modelled effectively. Adding and refining hydrologic data via additional gages should improve model accuracy. Calibrating user water demand estimates should also improve model accuracy. Any changes in how water demands are 'called' or notified to the Board for a few large rights could greatly improve real time and near-term forecast water demand estimates.

Curtailment thresholds shown in both the Eel River DWRAT model and the Sacramento River pyWRAT model can inform decision makers on what to expect in a range of cases with low water availability. These analyses can be used to show key points where curtailment notices should be considered.

Advancing the development of the DWRAT model into Python has provided a tool future analyses to support better batch-processing of data and simple modifications of input data. Various exploratory analyses were shown to demonstrate the Python-based program's ability to handle large inputs of data. Two other applications of the pyWRAT model, for the Eel River and the San Joaquin River, were constructed using the same format but not used for analysis in this report. Lastly, it was shown that the Python-based model corrects some errors from previous software.

Future Research

The current state of water rights modelling can be significantly improved with more data on water availability and demand. Demand data for water rights in California will become more refined and accessible in the coming years. New reporting requirements by the State Water Resources Control Board will better inform water availability and water delivery needs in all water rights modelling. In addition, ongoing data collection will improve the representativeness of the data, providing a larger range of water years that better reflect the changing nature of climate and precipitation patterns. Refining analyses for particular situations will also improve the modelling. For example, since DWRAT assumes that each water user accesses their water at the outlet of their sub basin, there is potential for error in situations where two almost equal appropriative right holders draw from the same point. Assigning each user their own sub basin that includes all of the streams and tributaries upstream of their exact point of diversion and the entirety of the main stream channel downstream would ensure that their water demand location and allocation more closely matches the 'ideal' structure for water law interpretation.

Cannabis water rights are likely going to be among the most contentious topics in water management in the Eel River basin for the foreseeable future. Many changes to water rights and water management may come about as a result of these changes. Since these rights are so closely tied to environmental flow and water quality, efforts to monitor and assess data gaps are likely to increase. In the end, this will be good for growers and environmentalists. Reaches in severe need of more gages for these purposes include the South fork of the Eel river, the Van Duzen river, and other higher elevation sub basins in the North coast region. The water supply and water quality in these areas have been hardest hit from illegal cannabis agricultural practices.

The DWRAT and pyWRAT models can continue to be improved. Implementing return flows in basins where they have a large effect (Tweet, 2016), modifying scaling ratios for the hydrologic model (Walker, 2017), and other improvements can be added to the main model as the data for these analyses become more available.

References

Assesmbly Bill 243, 2015. . California State Assembly, Sacramento, CA.

Bauer, S., Olson, J., Cockrill, A., van Hattem, M., Miller, L., Tauzer, M., Leppig, G., 2015. Impacts of Surface Water Diversions for Marijuana Cultivation on Aquatic Habitat in Four Northwestern California Watersheds. PLoS One 10, e0120016. https://doi.org/10.1371/journal.pone.0120016

Butsic, V., Brenner, J.C., 2016. Cannabis (*Cannabis sativa or C. indica*) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts. Environ. Res. Lett. 11, 044023. https://doi.org/10.1088/1748-9326/11/4/044023

California Data Exchange Center [WWW Document], 2018.

California Department of Water Resources, 2016. Estimates of Natural and Unimpaired Flows for the Central Valley of California: Water Years 1922-2014.

California Department of Water Resources, 1989. Bay-Delta Estuary Proceedings Water Year Classification Workgroup, San Joaquin River Index, Summary of Workshop Activities.

California State Water Resources Control Board, 2016. ORDER WR 2016-0015: 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.

Carah, J.K., Howard, J.K., Thompson, S.E., Short Gianotti, A.G., Bauer, S.D., Carlson, S.M., Dralle, D.N., Gabriel, M.W., Hulette, L.L., Johnson, B.J., Knight, C.A., Kupferberg, S.J., Martin, S.L., Naylor, R.L., Power, M.E., 2015. High Time for Conservation: Adding the Environment to the Debate on Marijuana Liberalization. Bioscience 65, 822–829. https://doi.org/10.1093/biosci/biv083

Celeste, A.B., Curi, W.F., Curi, R.C., 2009. Implicit stochastic optimization for deriving reservoir operating rules in semiarid Brazil. Pesqui. operacional 29, 223–234.

D. N. Moriasi, D.N., J. G. Arnold, J.G., M. W. Van Liew, M.W. Van, R. L. Bingner, R.L., R. D. Harmel, R.D., T. L. Veith, T.L., 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153

Dogan, M.S., Fefer, M.A., Herman, J.D., Hart, Q.J., Merz, J.R., Medellín-Azuara, J., Lund, J.R., 2018. An open-source Python implementation of California’s hydroeconomic optimization model. Environ. Model. Softw. 108, 8–13. https://doi.org/10.1016/J.ENVSOFT.2018.07.002

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 Accounting for Water in Dry Regions: A Comparative Review.

Grantham, T., Fleenor, W., 2014. California Water Rights Model– Supply Estimation. Cent. Watershed Sci. Univ. Calif. Davis.

Heim, R.R., 2002. A Review of Twentieth-Century Drought Indices Used in the United States.

Bull. Am. Meteorol. Soc. 83, 1149–1166. https://doi.org/10.1175/1520-0477-83.8.1149

Kubicek, P., 2017. Potter Valley Hydroelectric Project FERC Project No. 77.

Liebert, T., 2017. A Research Guide to California Water Law. SSRN Electron. J. https://doi.org/10.2139/ssrn.2921589

Littleworth, A.L., Garner, E.L., 2007. California Water II. Solano Press.

Lord, B., 2015. Water rights curtailments for drought in California: Method and Eel River Application. University of California, Davis.

Lord, B., Magnuson-Skeels, B., Tweet, A., Whittington, C., Adams, L., Thayer, R., Lund, J., 2018. Drought Water Right Curtailment Analysis for California's Eel River. J. Water Resour. Plan. Manag. 144, 04017082. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000820

Lougee-Heimer, R., 2003. The Common Optimization INterface for Operations Research: Promoting open-source software in the operations research community. IBM J. Res. Dev. 47, 57–66. https://doi.org/10.1147/rd.471.0057

Lund, J., Lord, B., Fleenor, W., Willis, A., 2014. Drought Curtailment of Water Rights-Problems and Technical Solutions.

Mason, A.J., 2013. SolverStudio: A New Tool for Better Optimisation and Simulation Modelling in Excel. INFORMS Trans. Educ. 14, 45–52. https://doi.org/10.1287/ited.2013.0112

Null, S.E., Viers, J.H., 2013. In bad waters: Water year classification in nonstationary climates. Water Resour. Res. 49, 1137–1148. https://doi.org/10.1002/wrcr.20097

Quiring, S.M., 2009. Developing Objective Operational Definitions for Monitoring Drought. J. Appl. Meteorol. Climatol. 48, 1217–1229. https://doi.org/10.1175/2009JAMC2088.1

Senate Bill 837, 2016. . California State Senate, Sacramento, CA.

Senate Bill 94 - Cannabis: medicinal and adult use., 2017. . California State Senate, Sacramento, CA.

SWRCB, 2018. Water Rights FAQs California State Water Resources Control Board [WWW Document]. URL https://www.waterboards.ca.gov/waterrights/board_info/faqs.html#toc178761091 (accessed 9.17.18).

SWRCB, 2017. RESOLUTION NO. 2017-0063 ADOPTING THE CANNABIS CULTIVATION POLICY – PRINCIPLES AND GUIDELINES FOR CANNABIS CULTIVATION.

Trush, W.J., Mierau, D.W., Rossi, G.J., 2016. A Regional Strategy for Protecting Instream Flows in North Coast California Watersheds.

Tweet, A., 2016. Water Right Curtailment Analysis for California's Sacramento River: Effects of Return Flows.

Walker, W., 2017. Drought Water Right Allocation Tool Applied to the San Joaquin River Basin.

Wang, I.J., Brenner, J.C., Butsic, V., 2017. Cannabis, an emerging agricultural crop, leads to deforestation and fragmentation. Front. Ecol. Environ. 15, 495–501. https://doi.org/10.1002/fee.1634

Whittington, C., Lund, J., Hart, Q., Grantham, T., 2016. Russian River DWRAT.