Russian River Drought Water Right Allocation Tool (DWRAT)

By

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Abstract

The Drought Water Rights Allocation Tool (DWRAT) is an integrated set of water right allocation models and databases to suggest water right curtailments during drought. It incorporates hydrologic and legal objectives to optimize water allocation among right holders using a flow-forecasting model and a set of linear programs that mathematically represent water law and hydrology. DWRAT is compiled within an Excel workbook, which includes a user-friendly interface and an open-source solver that allows for straightforward model runs and easily interpretable results. DWRAT can be used to assess water reliability and legally appropriate water right curtailments for varying hydrologic conditions. As a result, water right holders can be informed on current and likely curtailment conditions. Error analysis of DWRAT's flow-forecasting model shows poor performance for sub-basins that maintain high levels of inflow and are further from DWRAT's unimpaired flow reference gage. However, the model can be improved with additional reference gages and increased historical unimpaired flow estimates. This paper focuses on applications of DWRAT for the Russian River, but the tool is also in development for the Eel, Sacramento, and San Joaquin rivers.

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Chapter 1 - Introduction

This report presents development and applications of the Drought Water Rights Allocation Tool (DWRAT) for the Russian River watershed. DWRAT is an integrated set of water right allocation models and databases to suggest water right curtailments during drought. It incorporates hydrologic and legal objectives to optimize water allocation among right holders using a flow-forecasting model and a set of linear programs that mathematically represent water law and hydrology.

Resulting from California's limited water supply, water shortages have become increasingly controversial. In the 2013-2014 water year, the State Water Resources Control Board issued water right curtailments for the first time since 1976-1977. As California's population rises and its water quality and flow standards become more stringent and the climate changes, water supplies could become scarcer and curtailments will be issued more frequently. Future droughts are likely to require formal, transparent, and data-based curtailment of water rights. A mathematically precise and straightforward method of analyzing water right curtailments is needed.

California Water Rights

California employs two major water right doctrines: riparian water rights and appropriative water rights. Riparian water rights are typically held by those who own land that borders a source of water. A riparian right authorizes landowners to divert a correlative share of the water flowing past their property (SWRCB, 2016). Such rights do not require a permit, but riparian right holders (riparian users) are only entitled to the full natural flow of the water body, and their diversions may not "unreasonably affect" downstream users (Lord, et al., 2015). In addition, riparian users may not store or divert water to other land (California SWRCB, 2016).

At the start of California's mining era, extensive networks of flumes and waterways were built to carry water far from streams and rivers. Miners adopted a "first in time, first in right" principal to stake their water claims. In 1850, California's Legislature recognized prior appropriative water right priorities as law. Pursuant to the Water Commission Act of 1913, the California State Water Resource Control Board (SWRCB) was created to administer permits and licenses for the state's surface water. Today, the SWRCB is responsible for managing water allocations and issuing water right curtailments in times of shortage. Under the prior appropriation doctrine, priority is established based on water right application filing date for post-1914 users, and date of first use for earlier appropriators. Senior water rights must be satisfied before junior water rights. Riparian rights have higher priority than appropriative rights as a class. Furthermore, the priorities of riparian rights carry equal weight, meaning that riparian users must share any shortage equally (California SWRCB, 2016).

Overview of the Russian River

The Russian River drains a 1,485-square-mile watershed in Mendocino and Sonoma counties (Kennedy, 2014). The 100-mile main stem flows southward in parallel with the Pacific Ocean and through the agricultural and rural regions of the Potter Valley, Hopland

Valley, Ukiah Valley, Cloverdale Valley, Alexander Valley, and the Santa Rosa Plains. Depending on the year, between 1.9 million acre-feet per annum (afa) and 4-5 million afa flows down the Russian River. About 90% of precipitation in the watershed transpires during November through April. There are two major dams in the watershed: Coyote Dam and Warm Springs Dam. The former regulates water from Lake Mendocino while the latter regulates water from Lake Sonoma (Sonoma County Conservation Council, 2015).

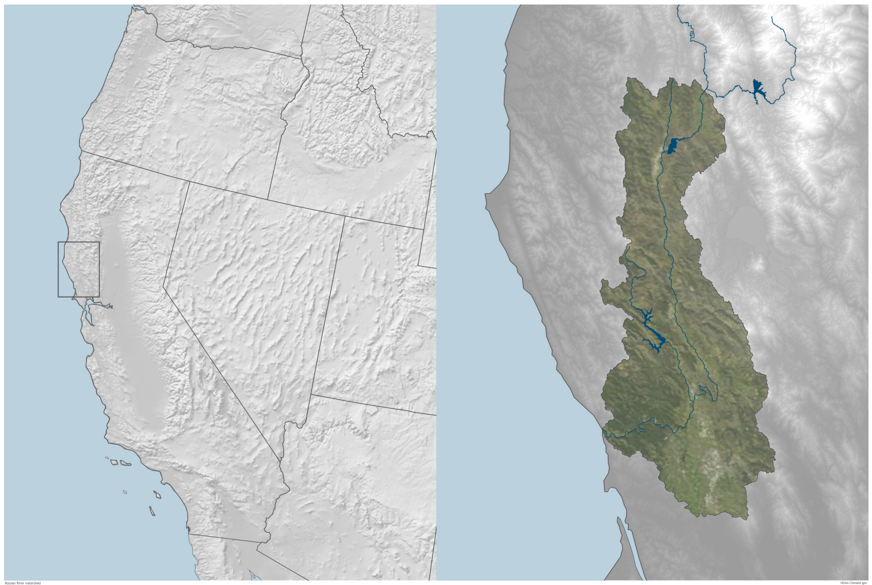


Figure 1. Russian River Watershed (NOAA, 2014).

The Russian River is considered an impaired body of water, meaning that it does not meet water quality standards of the Environmental Protection Agency and regulated by the SWRCB. The impairment is credited to historic grazing, agriculture, logging, road construction, and habitat modifications that have led to excessive sedimentation and siltation. Erosion and sedimentation in the main stem often rises with floods and peak releases from Coyote Dam and Warm Springs Dam (SCWA, 2016).

Although the Russian River is primarily affected by dry conditions, flooding occurs during wet seasons. Most areas subject to flooding in the basin lie between Mirabel Park and Duncans Mills. Flooding also has occurred along the lower and middle reaches of the Russian River, where it serves as a natural renewal process for stream habitats. Coyote and Warm Springs Dams provide flood protection. In addition, agricultural plains in Alexander Valley and Laguna de Santa Rosa can temporarily store flood runoff when the river channel overflows (SCWA, 2016).

Potter Valley Project

In 1908, a diversion tunnel was constructed to link the Eel River and the Russian River as part of the Potter Valley Hydroelectricity Project (Center for Environmental Economic Development, 2002). Water from the South Eel River now flows through the diversion tunnel and generates electricity discharging into Potter Valley. This water then flows into the East Fork Russian River, where it can be appropriated by junior right holders. Riparian users do not have legal access to the imported water since it is considered above the river's full natural flow.

Lake Mendocino Water Rights

Lake Mendocino is a reservoir on the East Fork Russian River in Mendocino County. The 2,000-acre lake formed subsequent to the construction of Coyote Valley Dam, which was authorized in 1944 and completed in 1958. The lake captures a drainage area of about 105 square miles and has a storage capacity of 118,000 acre-feet (SCWA, 2016). Currently, the reservation provides flood control, water conservation, hydroelectric power, and recreation.

In 1961, pursuant to the SWRCB's Decision 1030, Permit 12947 was issued to the Sonoma County Water Agency (SCWA), giving it year-round direct diversion of 92 cfs from the Russian River Valley and storage of 122,500 acre-feet per annum (afa) (SWRCB, 1961). Term 23 of Permit 12947 authorized the SCWA to release up to 10,000 afa from Lake Mendocino to meet the demands of appropriators. The permit required the SCWA to file descriptions of the diversion locations and their diversion quantities with the SWRCB. However, the SCWA failed to meet this condition. As a result, the SWRCB assumed responsibilities for managing the reservoir water rights in 1974 and decided that Post-1949 appropriative right holders would qualify for having claims to the reservation under Permit 12947A (SWRCB, 1974).

The maximum diversion rates allowed by Permit 12947A vary depending on minimum instream flow requirements between the East Fork Russian River and Dry Creek. For instance, when the combined water storage in Lake Mendocino and Lake Pillsbury exceeds 90% of water supply storage capacity (150,000 acre-feet) on May 31 of any year, users are granted a maximum diversion rate of 125 cfs from June through October and 185 cfs from April through May. However, if water storage between the two reservoirs is under 90% storage capacity, the maximum allowable diversion rate is 150 cfs from November through March and 175 cfs from April through May (SWRCB, 1974).

Pre-1949 appropriative water right holders are not required to file an application under Permit 12947A to divert water from Lake Mendocino releases. In 1908, the Snow Mountain Water and Power Company began diverting flow from the South Eel River and into the East Fork Russian River through turbines for power generation. Many Russian River right holders began appropriating this new source of water and the local economy became reliant upon it. Once the Coyote Dam was constructed near the outlet of Lake Mendocino, flow downstream of the reservoir became substantially more regulated, which threatened the prosperity of those who had become dependent on the increased flow from the East Fork Russian River. Thus, the State and Army Corps affirmed the right of Pre-1949 users who rely on the unregulated, but artificially increased, flow of the river. Consequently, Pre-1949 users are not subject to the restrictions set by Permit 12947A (SWRCB, 1974).

Drought Impact on the Russian River

On January 17, 2014, Governor Edmond J. Brown proclaimed a State of Emergency to address the persistent drought after reducing water supplies statewide. This proclamation required the State Board to notify all Californian water right holders of potential curtailments on water diversions. Based on reservoir storage and inflow projections, the SWRCB determined that the existing supply in the Russian River was insufficient to meet the needs of all right holders (SWRCB, 2014). Thus, on May 27, 2014, the SWRCB issued curtailment letters to junior right holders on the Russian River. The letters instructed 650 appropriative right holders upstream of the Dry Creek confluence and with application filing dates later than February 19, 1954 to cease water use. These curtailments were not lifted until November 14, 2014. Water right holders who failed to comply with the curtailment regulations were subject to immediate fines or administrative actions. This spurred controversy among water users who argued against the legality of constricting their water diversions. During a public hearing before the curtailments were issued, some water users quarreled that the state should not hold the authority to fine water right holders up to $500 a day without a hearing (Anderson, 2014).

Water Allocation Modeling

California's most recent drought has highlighted the value of a more explicit method of assessing and issuing water right curtailments. Several water allocation methods have been developed in the West to account for water rights under the prior appropriation system. For instance, Colorado State University developed MODSIM (Labadie, 2007) to assess river basin management decisions using varying objectives and water right priorities. MODSIM employs a network of nodes (i.e., storage facilities, reservoirs, and groundwater basins) and arcs (i.e., rivers, canals, and pipelines) to simulate and optimize allocation of flow in accordance with prior appropriation and other priority rankings.

The Texas Water Availability Model (WAM) is a computer simulation model that predicts naturalized water availability based on historical hydrology and a specified set of conditions. WAM can employ the Water Rights Analysis Package (WRAP) modeling system to simulate water allocations in accordance with the prior appropriation doctrine (Wurbs, 2001). The WRAP simulation process begins by reading in water rights data, geospatial data, and naturalized streamflow generated by WAM. Then, water is allocated using an iterative loop that steps through each right in priority order. After simulation, the impacts of water management strategies or project developments on water reliability can be evaluated.

California requires a water allocation approach that accounts for both appropriative and riparian rights. Unfortunately, documentation of such an approach is limited since few states recognize both doctrines. In light of this deficiency, DWRAT has been created to offer an approach to allocate water for rights under both doctrines (Lord, 2015).

Benefits of the Drought Water Right Allocation Tool (DWRAT)

The Drought Water Right Allocation Tool (DWRAT) is an integrated set of water right allocation models and databases to suggest water right curtailments during drought. DWRAT offers an approach to fully allocate California's limited water supplies by employing mathematical representations of riparian and appropriative water law doctrines across basins with spatially varying supply and demand. DWRAT is compiled within an

Excel workbook, which includes a user-friendly interface and an open-source solver that allows for straightforward model runs and easily interpretable results.

DWRAT can aid the State Water Resources Control Board (SWRCB) in making effective water right curtailment decisions. The transparency of DWRAT's framework would make it easier for water right holders to understand SWRCB curtailment calculations. Furthermore, DWRAT can be used to assess water reliability and legally appropriate water right curtailments for varying hydrologic conditions. As a result, water right holders can be informed on current and likely curtailment conditions. In addition, water users with insufficient water availability will be able to more easily identify which users have high water availability. Such knowledge could aid the development of water markets.

Chapter 2 - The Russian River DWRAT

Russian River DWRAT - Model Composition

Figure 2 shows a schematic of DWRAT's data flow. DWRAT takes input unimpaired flow data from the National Weather Service (NWS) and input diversion demand data from the SWRCB, which includes water right application filing dates and points of diversions (PODs). Such data is fed into the DWRAT Excel workbook, where it is used in linear programs (LPs) to compute legal water allocations. DWRAT employs three LPs for the Russian River to account for riparian, appropriative, and reservoir right holders. The results generated by the LPs are recorded into a spreadsheet labeled "Output". This spreadsheet can be exported as a csv file and uploaded onto an online interface that maps curtailment decisions for the watershed.

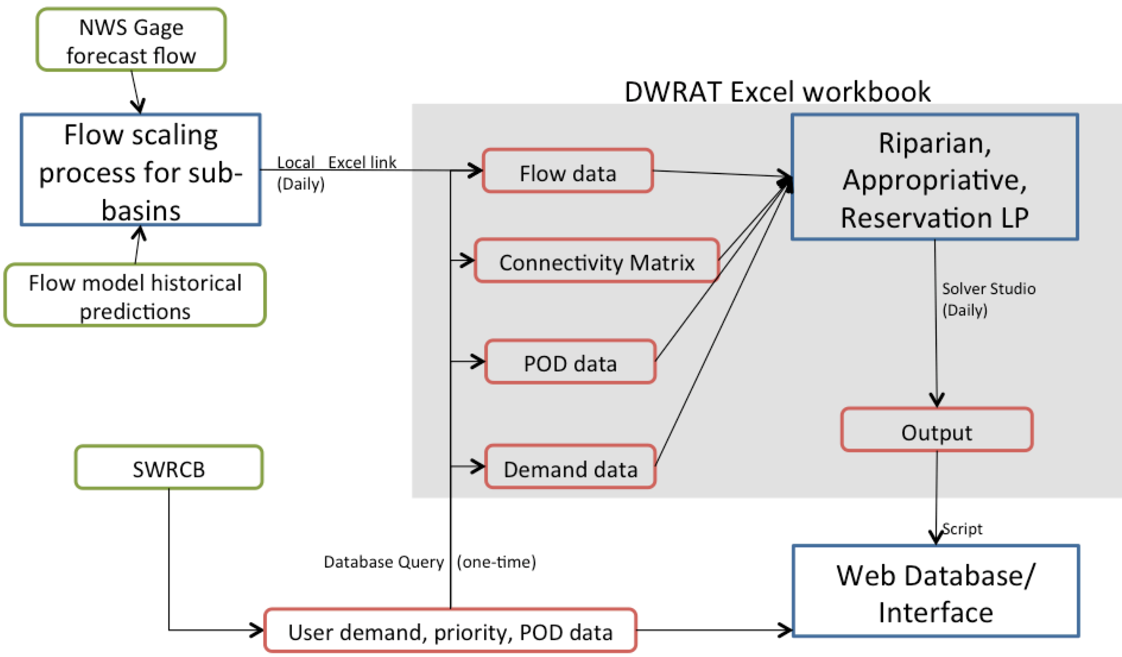


Figure 2. DWRAT Project Workflow.

Available Data

The Russian River DWRAT currently uses two sets of input data: FNF (unimpaired flow) forecasts from the NWS and reported monthly water use filed to the SWRCB from 2010 to 2013. The four years of reported water use data are averaged and used to estimate water demand. For instance, if a water right holder reported an average use of 10 acre-feet of water in May from 2010 to 2013, DWRAT assumes that the user's demand in May is 10 acre-feet. As the SWRCB's water use database is updated, DWRAT can incorporate more recent reported use data to better reflect water demand. Figure 3 shows the average reported use of water right holders for the Russian River from 2010 to 2013. Depending on the time of year, appropriative users account for 64% to 95% of all water use.

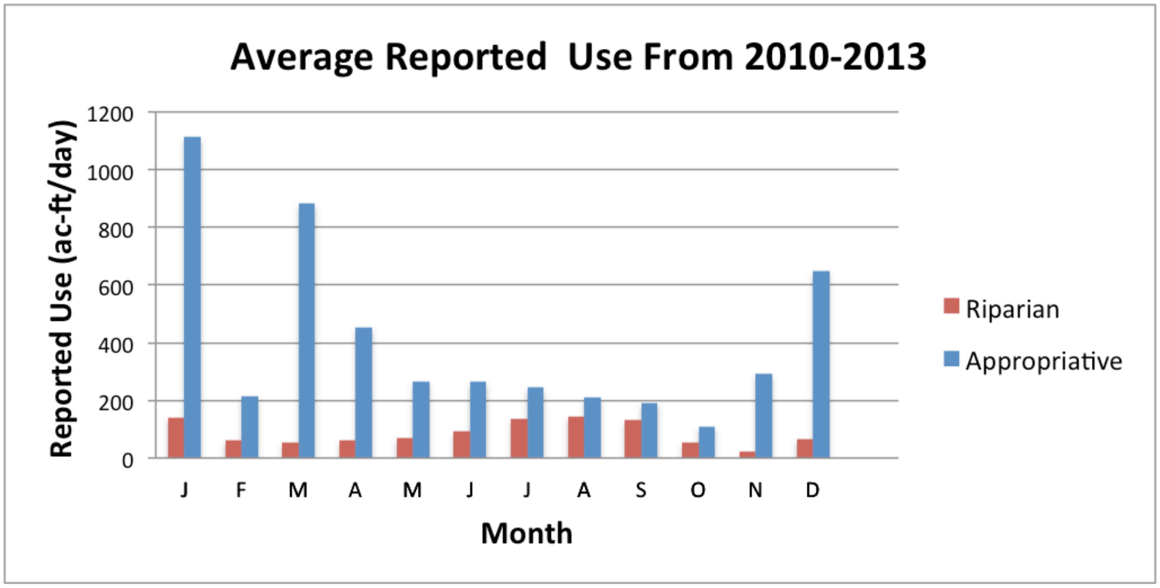


Figure 3. Total Reported Use in the Russian River (2010-2013 Averaged).

From 2010 to 2013, water demand has been highest in January, March, and December. Most diversions in the winter are made by the SCWA to regulate reservoir storage levels and maintain instream flows for recreation, fish, irrigation, and municipal purposes. The SCWA also employs conservation efforts through wastewater reclamation and conjunctive use of groundwater and surface water. The largest Pre-1914 user is the Potter Valley Irrigation District (PVID), which makes most of its diversions in the spring and summer for irrigation and stockwatering for cattle, sheep, horses, and goats. The PVID conserves water by fallowing almost 100 acres of land and installing pipes in open dirt ditches to recapture runoff. In 2013, they reduced diversions by over 1,000 ac-ft of water.

Table 1 shows the number of riparian and appropriative water right holders that reported water diversions to the SWRCB between 2010 and 2013. By numbers, the Russian River consists of 44% riparian users and 56% appropriative users. But by volume, riparian users are only 17.5% of all diversions.

Type of Right	Number	Average Total Diversions (TAF/yr)
Riparian	883	31,011
Pre-1914 Appropriative	42	3,549
Post-1914 Appropriative	1,090	143,028
Total	2,015	177,588

Table 1. Water Right Holders in the Russian River DWRAT Model.

Unimpaired Flow Forecasting Model

DWRAT incorporates a statistical flow-forecasting model (Grantham & Fleenor, 2014) to estimate unimpaired surface water supplies at the 12-Degree Hydrologic Unit Code (HUC-12) catchment-scale, which ranges from about 15 to 50 square miles in the Russian River watershed. The model uses FNF data from an NWS flood gage in Healdsburg to disaggregate daily-unimpaired flows throughout the entire watershed. The USGS model uses a Random Forest prediction method (Breiman, 2001) and USGS Gages-II database to estimate historical monthly flows at ungagged locations (Carliele et al., 2010). Then, scaling factors are obtained by computing ratios of gaged flow to un-gaged flow based on monthly mean unimpaired flow estimates from the 10 driest years between 1950 and 2011. These scaling factors are multiplied by the NWS's FNF readings at Healdsburg to acquire unimpaired flow estimates for each HUC-12. The green point in Figure 4 is the location of the NWS's Healdsburg gage.

Figure 4. NWS Flow Monitoring Stations (Grantham, 2014).

Linear Programs

DWRAT operates in two phases to account for riparian rights and appropriative rights. Riparian water right holders have equal priority among themselves. Consequently, water shortage is allocated as an equal proportion of normal diversions for all riparian users within each sub-basin. Such proportions are determined by water availability. Because of downstream accumulations of streamflow, upstream riparian users are likely to be allocated smaller proportions of water than downstream users. In contrast, appropriative water right holders are assigned priority based on the filing date of their water right application. So, shortages are allocated among appropriative users by seniority. Junior water right holders will be shorted before senior water right holders, except where more senior right holders are in drier tributaries.

Since the prioritization of water distribution varies between the riparian and appropriative system, each requires its own linear program (LP) to optimize legal shortage allocation. Since riparian users have higher priority than appropriative users, the Riparian LP is completed before running the Appropriative LP (Lord, 2015). This way, appropriative users are only allocated water after each riparian user has already been accounted for. The LPs are solved using a free open source solver platform called SolverStudio (Mason, 2013).

The Russian River DWRAT has an additional LP that optimizes water allocations for appropriative users who also have Lake Mendocino water rights. The formulation of this Reservation LP is similar to that of the Appropriative LP, where shortage is distributed among users based on water right application filing date.

Riparian Linear Program

The objective of the Riparian LP is to allocate as much water as possible proportionately to riparian users. Since riparian users have equal priority, weighting terms are used to enforce equitably proportional shortage allocations across basins while maximizing total allocations.

$$\boldsymbol{Min\ z = \propto \sum_{k} w_k P_k - \sum_{i} A_i} \qquad \text{(Eq. 1)}$$

Where:
P_k = Proportion of normal use allocated to users in sub-basin k (Decision variable);
A_i = Water allocation for user i;
$\propto$= Weighting factor (low enough so proportion penalties do not overwhelm allocating all available water);
w_k = Unit penalty for P_k (reflecting upstream location of sub-basin k);

The objective function for the Riparian LP is subject to eight constraints. The first constraint (RC 1) defines the allocation of each user (A_i) as the product of the user's normal use (u_i) and the proportion of normal use allocated to riparian users in that sub-basin (P_k). Normal use is estimated from averaged reported use data and is assumed to represent of water demand. All riparian users in the same sub-basin are assigned the same P_k value since they all share equal priorities. P_k is a the decision variable for the Riparian LP.

$$\boldsymbol{A_i = P_k u_i}\ , \forall\ i\ , i \in\ k \qquad \text{(RC 1)}$$

The second constraint (RC 2) upholds that the portion of water allocated upstream does not exceed the portion of water allocated downstream. Without this constraint, upstream users would be distributed most of the water and water availability would diminish downstream. This constraint assumes no major losses of flow downstream; so, unimpaired water availability is always assumed to be greater downstream than in upstream tributaries. This formulation will have problems if unimpaired flows decrease downstream. Subscript j represents downstream basins while subscript k represents upstream basins.

$$\boldsymbol{P_j \leq P_k}\ , \forall\ k\ , j \in k \qquad \text{(RC 2)}$$

The third constraint (RC 3) satisfies mass balance of the river system. Moreover, it ensures that the sum of all allocations upstream of basin k do not exceed the total water availability at basin k's outlet. Water availability equals the inflow of basin k (v_k) subtracted by any environmental flow requirement (e_k) and buffer flow (b_k). Environmental flow requirements can be implemented to reserve specified flow levels for the environment. Buffer flow is a factor of safety to account for error and uncertainty in water demand and flow forecasts.

$$\sum_{i \in k} \boldsymbol{A_i} \leq \boldsymbol{v_k} - \boldsymbol{e_k} - \boldsymbol{b_k} \ , \forall k \qquad \text{(RC 3)}$$

The fourth constraint (RC 4) ensures that the proportion of normal use allowed for all users in basin k (P_k) is between zero and one. The minimum amount of water a user can be allocated is zero and the maximum water user allocation is normal use.

$$\boldsymbol{0} \leq \boldsymbol{P_k} \leq \boldsymbol{1}, \forall k \qquad \text{(RC 4)}$$

The fifth constraint (RC 5) maintains that water allocation for each user is non-negative.

$$\boldsymbol{A_i} \geq \boldsymbol{0}, \forall\, i \qquad \text{(RC 5)}$$

The sixth constraint (RC 6) ensures that water allocations satisfy any public health and safety requirements.

$$\boldsymbol{A_i} \geq \boldsymbol{u_{i,public\ health\ and\ safety}} \ , \forall\, i \qquad \text{(RC 6)}$$

All users with local water availability greater than zero should receive water allocations. To prevent upstream users receiving zero allocations despite local availability and downstream users receiving large allocations (because of increased availability from not allocating the same water upstream), a weight is used to increasingly penalize high allocation proportions in downstream basins. The seventh constraint (RC 7) defines this downstream penalty (w_k) as the number of basins upstream of that basin (n_k) divided by the number of basins upstream of the outlet $\left(n_{k,outlet}\right)$. As the number of basins upstream of basin k increases, the unit penalty also increases.

$$\boldsymbol{w_k} = \frac{\boldsymbol{n_k}}{\boldsymbol{n_{k,system\ \ outlet}}} \qquad \text{(RC 7)}$$

The eighth constraint (RC 8) defines a weighting factor ($\propto$) to prioritize the proportional allocation and full allocation objectives in the Riparian LP. The weight must be less than the minimum ratio of the downstream penalty (w_k) to total upstream normal use (u_k). Without this weighting term in the objective function, the Riparian LP would allocate 100% of water availability to sub-basins one-by-one, resulting in some users being allocated 100% of their demand and others being allocated 0% of their demand. RC 2, RC 7, and RC 8 counteract each other to distribute shortage equally across the watershed while maximizing total allocations to riparian users (Lord, 2015).

$$\propto < \boldsymbol{Min}\left(\frac{\boldsymbol{w_k}}{\boldsymbol{u_{k,}}}\right), \forall\, k \qquad \text{(RC 8)}$$

Appropriative Linear Program

After riparian users receive allocations, DWRAT distributes the remaining water to appropriative users. Unlike riparian rights, appropriative rights are curtailed by individual priority. Unit shortage penalties are assigned to each appropriative user. The unit shortage penalty (p_i) of a user is the total number of appropriative users in the watershed subtracted by that user's priority rank. For instance, the tenth most senior appropriative user of the Russian River has a unit shortage penalty of 1,122 because the user has a priority rank of 10 and DWRAT accounts for 1,132 appropriative water rights in the Russian River.

The objective of the Appropriative LP is to minimize the total shortage penalty for all users, where shortage is defined as the difference between a user's normal use (u_i) and DWRAT's allocation to that user (A_i). Since unit shortage penalties increase with water right priority, the objective function is incentivized to allocate shortage to junior users rather than senior users. So, high priority users are less likely to be curtailed than low priority users (Lord, 2015).

$$\boldsymbol{Min\ z} = \sum_{\boldsymbol{i}} \boldsymbol{p_i}(\boldsymbol{u_i} - \boldsymbol{A_i}) \tag{Eq. 2}$$

The Appropriative LP is subject to four constraints, as shown by AC 1, 2, 3 and 4. The first constraint ensures mass balance of the flows in the watershed. Moreover, DWRAT's allocations for each user (A_i) may not exceed the water availability remaining after riparian users have been allocated their share of water (A_R).

$$\sum_{\boldsymbol{i \in k}} \boldsymbol{A_i} \leq \boldsymbol{v_k} - \boldsymbol{e_k} - \boldsymbol{b_k} - \sum_{\boldsymbol{i \in k}} \boldsymbol{A_R} \ , \forall\ k \tag{AC 1}$$

The second constraint ensures that allocations for right holders do not exceed their normal use.

$$\boldsymbol{A_i} \leq \boldsymbol{u_i} \ , \forall\ i \tag{AC 2}$$

The third constraint prevents negative water allocations.

$$\boldsymbol{A_i} \geq \boldsymbol{0} \ , \forall\ i \tag{AC 3}$$

The fourth constraint ensures that allocations meet public health and safety requirements.

$$\boldsymbol{A_i} \geq \boldsymbol{u_{i,Public\ health\ and\ safety}} \ , \forall\ i \tag{AC 4}$$

Potter Valley Project Water

The Appropriative LP accounts for the additional flow received by the East Fork Russian River from PG&E's Potter Valley Hydroelectric project. Since the water from this project does not contribute to full natural flow, it is not available for riparian right holders.

Consequently, DWRAT only allocates Potter Valley Project (PVP) water to appropriative users. The daily volume of PVP water diverted into the Russian River can be specified on DWRAT's Excel User Interface. After the Riparian LP finishes allocating full natural flow to riparian users, the specified PVP flow is added to the water availability of sub-basins downstream of the PVP diversion tunnel. For instance, if PVP flow is 500 ac-ft/d, then an additional 500 ac-ft/d of water is made available to appropriative users along the East Fork Russian River.

Reservoir Linear Program

A unique feature of the Russian River DWRAT is an additional linear program dedicated to the Lake Mendocino reservoir. Presently, DWRAT includes 74 water right holders in the Reservation LP, all of whom also hold separate appropriative water rights for the Russian River. Such users are free to use both water rights to meet their demand. If their appropriative water rights are curtailed, they can still divert water under their reservoir rights from stored water. Consequently, Lake Mendocino diversion permits serve as a back-up supply for these right holders if they are curtailed by the appropriative LP.

For instance, consider a water right holder who owns both a Russian River appropriative right and a Lake Mendocino reservation right. His normal use during July is 20 acre-feet per day (ac-ft/d). However, one summer is especially dry and the right is curtailed so that he can only use 15 ac-ft/d under his appropriative water right. Consequently, an extra 5 ac-ft/d is drawn from Lake Mendocino to satisfy his demand. This additional amount of water under his reservation right is available as long as Lake Mendocino releases are enough to accommodate his demand.

As shown in the example, the total shortage a user experiences from an appropriative water right curtailment becomes that user's demand for reservation water. Such demands are not guaranteed to be satisfied. Although junior appropriators are authorized up to 10,000 acre-feet per year from Lake Mendocino releases, maximum diversion rates vary daily based on hydrologic conditions to satisfy minimum instream flow requirements outlined by Permit 12947A (SWCA, 1974). The daily volume of water available for Lake Mendocino water right holders can be specified on DWRAT's Excel User Interface, shown in Figure 5.

Currently, there is no established method of assigning priority among reservation permit holders if the reservation is completely allocated. Nonetheless, the Reservation LP currently assigns priority by application filing date. The earlier an application is filed to the SWRCB to divert water under Permit 12947A, the more priority it is given. A simplified example of how the reservation model works is discussed below. Table 2 shows the priority ranking, demand, allocation, shortage, and shortage penalty of six fictitious Lake Mendocino water right holders in July. For this example, 12 units of water are considered available from storage.

User ID:	A1	A2	A3	A4	A5	A6
Priority:	1	2	3	4	5	6
Demand :	3	0	6	5	0	0
Allocation:	3	0	6	3	0	0
Shortage:	0	0	0	2	0	0
Penalty:	0	0	0	**4**	0	0

Table 2. Lake Mendocino in July LP Example.

The users in Table 2 have been assigned priority rankings based on application filing date. For instance, user A1 was the first user to file an application with the SWRCB to divert water from Lake Mendocino and has a priority ranking of one. In July, user A1 demands 3 ac-ft/d from the lake. After running the Reservation LP, user A1 is allocated his full demand. As a result, the shortage penalty for this user is zero. Furthermore, user A4 is the only water right holder in Table 2 to experience curtailment. Although this user's demand is 5 ac-ft/d, he is only allocated 3 ac-ft/d. The shortage penalty can be calculated by Equation 3.

$$Pe_i = S_i \cdot (U_T - Pr_i) \qquad \text{(Eq. 3)}$$

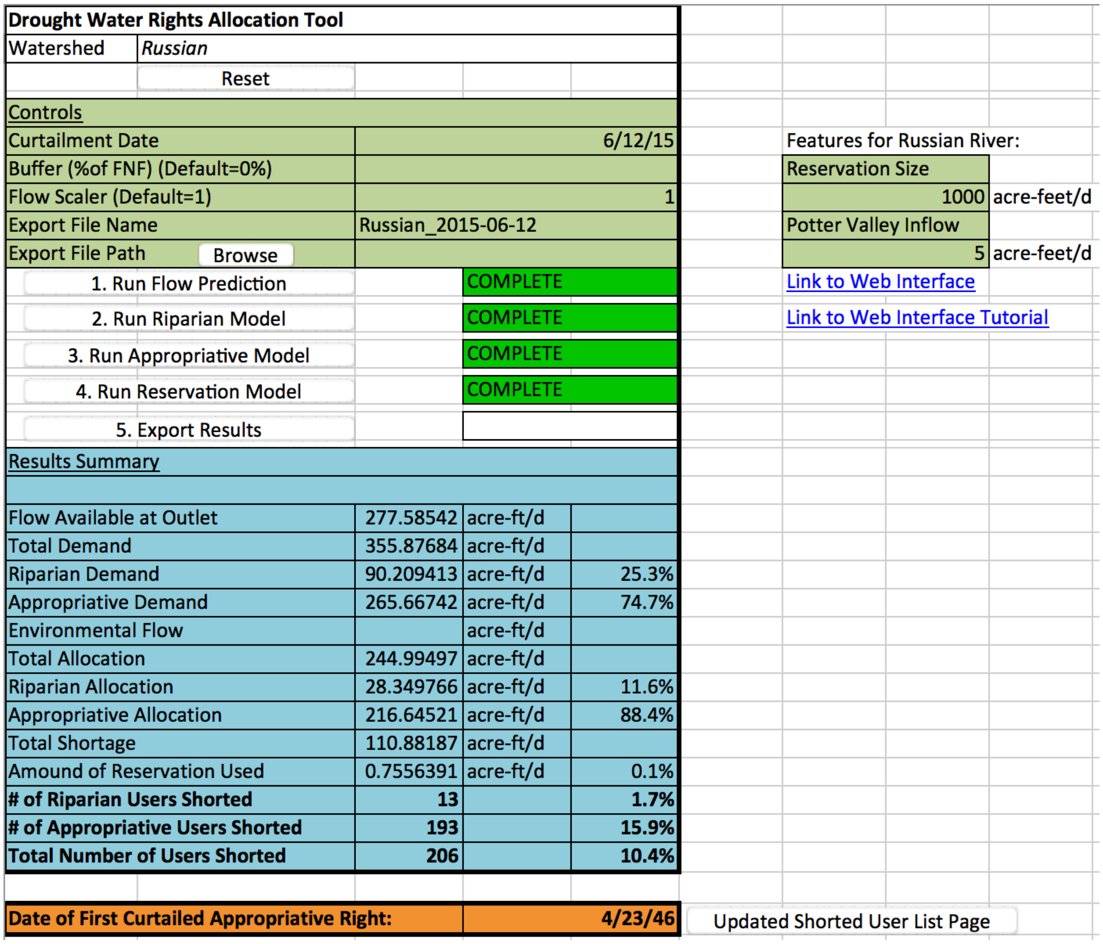
Where:
Pe_i = Penalty of user i.
S_i = Shortage of user i.
U_T = Total number of reservation right holders;
Pr_i = Priority rank of user i.

For example, the shortage penalty for user A4 in July is computed as:

$$P_e = 2 \cdot (6 - 4) = 4$$

Running DWRAT

Figure 5 shows the Excel User Interface, which consists of 5 buttons used to run DWRAT for a specified date between March 5, 2014 (when the project was launched) and the current date. The first button, "Run Flow Prediction", launches the hydrologic model and updates water availability for each sub-basin. The "Run Riparian Model", "Run Appropriative Model", and "Run Reservation Model" buttons activate the LPs to optimize water allocations. The "Export Results" button exports a csv file containing the optimized curtailment results, which can be uploaded to DWRAT's online interface for a mapped out visualization of water right curtailments.



Drought Water Rights Allocation Tool			
Watershed	*Russian*		
	Reset		
Controls			
Curtailment Date			6/12/15
Buffer (%of FNF) (Default=0%)			
Flow Scaler (Default=1)			1
Export File Name	Russian_2015-06-12		
Export File Path	Browse		
1. Run Flow Prediction		COMPLETE	
2. Run Riparian Model		COMPLETE	
3. Run Appropriative Model		COMPLETE	
4. Run Reservation Model		COMPLETE	
5. Export Results			
Results Summary			
Flow Available at Outlet	277.58542	acre-ft/d	
Total Demand	355.87684	acre-ft/d	
Riparian Demand	90.209413	acre-ft/d	25.3%
Appropriative Demand	265.66742	acre-ft/d	74.7%
Environmental Flow		acre-ft/d	
Total Allocation	244.99497	acre-ft/d	
Riparian Allocation	28.349766	acre-ft/d	11.6%
Appropriative Allocation	216.64521	acre-ft/d	88.4%
Total Shortage	110.88187	acre-ft/d	
Amound of Reservation Used	0.7556391	acre-ft/d	0.1%
# of Riparian Users Shorted	**13**		**1.7%**
# of Appropriative Users Shorted	**193**		**15.9%**
Total Number of Users Shorted	**206**		**10.4%**
Date of First Curtailed Appropriative Right:		**4/23/46**	

Features for Russian River:	
Reservation Size	
1000	acre-feet/d
Potter Valley Inflow	
5	acre-feet/d
Link to Web Interface	
Link to Web Interface Tutorial	
Updated Shorted User List Page	

Figure 5. DWRAT Excel User Interface.

The whole process can be completed within 20 seconds, as the flow-prediction update runs for 2 seconds and each linear program requires 5 to 10 seconds. DWRAT's output results include users' names, local sub-basins, water right types and application filing dates, demands, allocations, and shortage. All water quantities are expressed in ac-ft/d. In addition to exporting user demand and allocation results, the User Interface provides a summary of results with helpful overview information. This includes values such as total riparian and appropriative demand, percentage of demand from each water right type, shortage volume, and the number of users curtailed. The User Interface also includes a link to access an online application, which is currently functional for the Eel, Sacramento, and Russian River models.

Chapter 3 - Analysis of Results

This chapter presents an analysis of DWRAT's results for 2014 and 2015. DWRAT was run for every day of each year to compute 730 daily sets of unimpaired flow estimates and water allocation decisions. In 2014, the water shortage produced by DWRAT's allocations decisions can be compared to the shortage produced by the SWRCB curtailment decisions. The SWRCB issued no curtailments for the Russian River in 2015.

2014 Case

Figure 6 shows DWRAT's unimpaired flow estimates at the Russian River's outlet in 2014, based on NWS forecasts at Healdsburg and hydrologic scaling from Grantham (2014). In DWRAT, total water availability directly correlates to unimpaired flow estimates at the watershed's outlet; so, unimpaired flow at the Russian River outlet is representative of total Russian River water supply. The mean outlet flow is 2,945 ac-ft/d, but flows typically range from 60 ac-ft/d to 100 ac-ft/d throughout the summer. Storms in February, March, November, and December significantly increase water supply, but the effects of these storms are brief. Unimpaired flow estimates steadily decrease from April to November, reaching a minimum of 35 ac-ft/d (17 cfs).

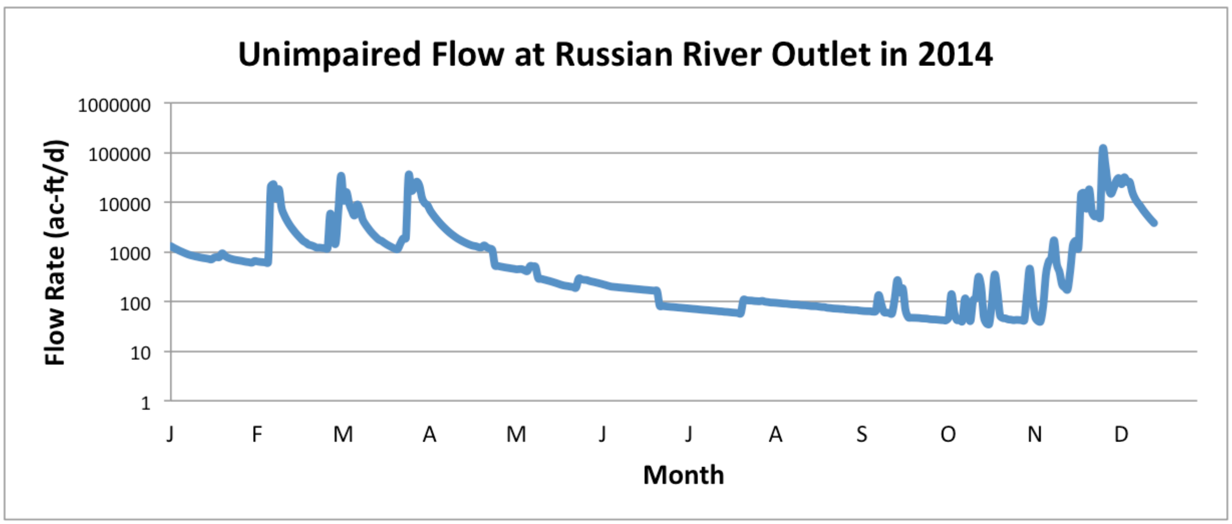


Figure 6. DWRAT Unimpaired Flow Estimates at Outlet 2014 (log scale).

Figure 7 shows the total volume of shortage experienced in the Russian River using DWRAT's allocation decisions for 2014. Appropriative users have more shortage than riparian users since they have lower priority. The greatest shortage is in January, when water demand is highest (refer to Figure 3). At this time, water availability is insufficient to meet much of the demand, which mainly consist of reservoir filling under a SCWA water right. As a result, up to 326 rights are curtailed. Almost all of these rights are released from curtailment in February because of higher inflows and decreased water demand. Shortage does not significantly rise again until March, when water supplies begin to diminish. The volume of shortage slightly reduces in October because water demand reaches its yearly minimum. However, the number of rights curtailed remains about the same because DWRAT lessens the severity of shortage for curtailed users rather than releasing additional users from curtailment.

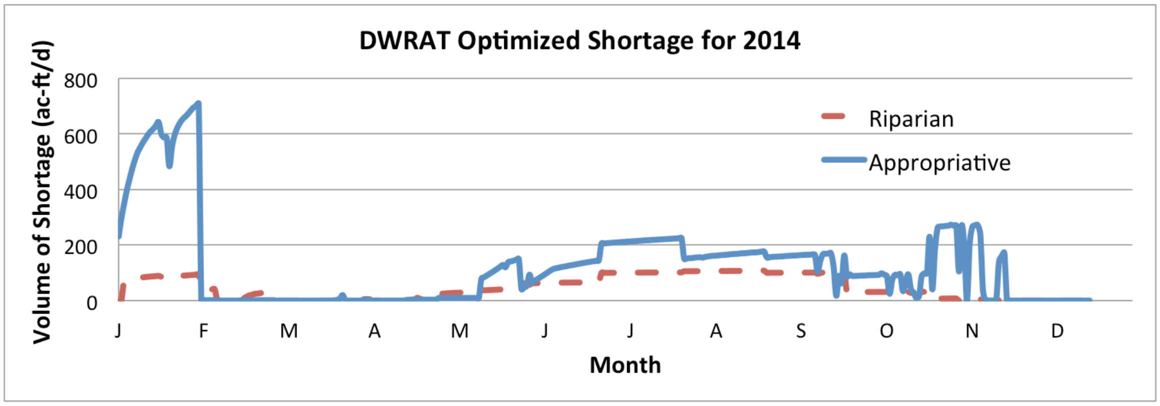


Figure 7. Total Shortage Caused in 2014 by DWRAT Optimization.

Figure 8 shows the percentage of water users allocated shortage in 2014 using DWRAT's results and the SWRCB's curtailment decisions. Only active users, those who report use to the SWRCB for any given month, can experience shortage. If a non-active user is allocated 0 ac-ft of water or is curtailed by the SWRCB, that user is not considered to experience shortage. Depending on the time of year, 0% to 3% of riparian users and 0% to 28% of appropriative users experience shortage under DWRAT's suggested allocations. Rainfall events in February and March increase water supply enough for DWRAT to release most users from curtailment until May.

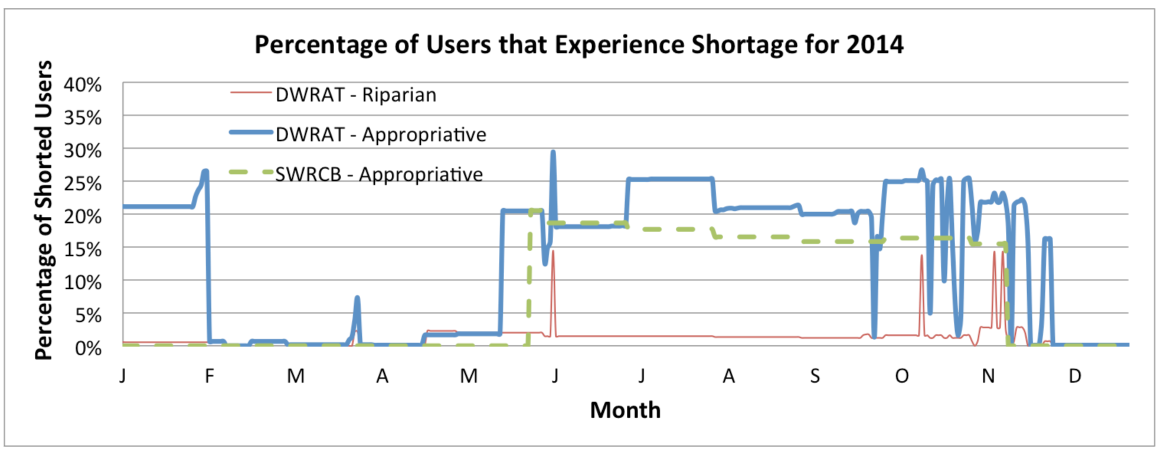


Figure 8. Percentage of Users that Experience Shortage for 2014.

The green-dashed line in Figure 8 represents the percent of users in the water rights database who would be shorted in 2014 due to the SWRCB's curtailment decisions. On May 27, 2014, all users upstream of the Dry Creek confluence with an application filing date later than February 19, 1954 were issued curtailments that lasted until November 14, 2014. About 600 Russian River users in DWRAT's database were affected by these curtailments. However, not all of these users were active each month. As the number of active users declines from May to November, so does the number of users who experience shortage from the SWRCB's curtailments. Overall, the SWRCB curtailment decisions short 15% to 20% of appropriative users between late May and mid-November. Although the number of users shorted by the SWRCB curtailments is similar to the number of users shorted by DWRAT's water allocation decisions, there are several key differences between the two curtailments.

First, DWRAT begins shorting users earlier in the spring than does the SWRCB curtailment decisions. DWRAT shorts about 20% of users on May 17, ten days before the SWRCB issued curtailments. In addition, DWRAT tends to short more users than does the SWRCB curtailment decisions. For example, DWRAT shorts 10 more users in June and 110 more users in July. DWRAT could be shorting more users than the SWRCB because its hydrologic model underestimates water availability (refer to the "Flow Error Analysis" chapter). If the unimpaired flow estimates used in DWRAT are too small, more users will be shorted than necessary.

However, although DWRAT shorts more users than did the SWRCB curtailment decisions, it does not necessarily generate greater volumes of shortage. Figure 9 compares the total volume of shortage produced by DWRAT and the SWRCB curtailment decisions during the SWRCB curtailment period. DWRAT's allocation decisions better minimize shortage when water demand is high and water supply is low. The discrepancy between the shortage volumes produced by DWRAT and SWRCB decisions decreases from June through October as water demand falls faster than water supply. The discrepancy widens again in November, when water demand significantly increases and water supply remains about constant. Based on these results, DWRAT's allocation decisions seem to minimize shortage more effectively by distributing water allocations throughout the watershed. The benefits of DWRAT's minimized shortage become more apparent when water demand is high.

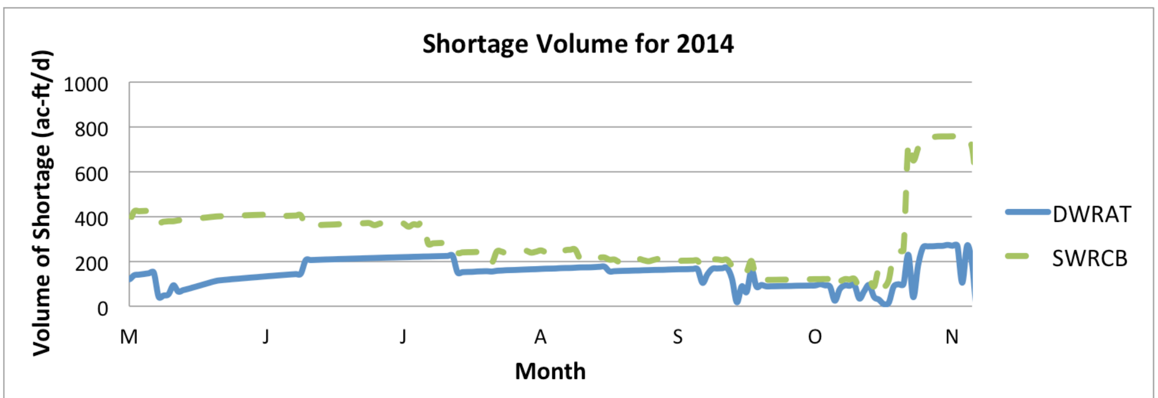


Figure 9. Shortage Volume of Appropriators for 2014.

DWRAT minimizes shortage volume more since it seeks optimal water allocations to each user based on more localized water availabilities. DWRAT strives to maximize total water allocations in addition to minimizing senior water right curtailments. As a result, the users curtailed by DWRAT do not perfectly reflect the users curtailed by the SWRCB. Rather than simply cutting off water access to all users junior to a particular application filing date or upstream of a particular region, DWRAT considers each HUC-12's water availability to make allocation decisions. For example, DWRAT often curtails senior water rights in upstream HUC-12s where flow levels are low. On the other hand, DWRAT often provides full allocations to junior users in downstream HUC-12s or sub-basins close to the main stem where flow levels are high. Using the SWRCB 2014 curtailment method, such junior users would be curtailed regardless of water availability in their sub-basins. Consequently, the volume of shortage throughout the watershed is greater than that with a more detailed analysis.

Since DWRAT runs on a daily time-step, it can release users from curtailment quickly when water availability is sufficient to meet demand, assuming the hydrologic representation is sufficiently reliable. On four occasions in September and October, DWRAT releases most users from curtailment because of sudden increased flow levels. In October 3 of 2014, the SWRCB issued a notice of potential temporary curtailment lifts during significant storm events. Pursuant to this notice, however, Russian River users were never offered short-term curtailment lifts.

2015 Case

Figure 10 shows DWRAT's 2015 unimpaired flow estimates at the outlet of the Russian River, which represent total water availability in the watershed. The mean outlet flow is 2,115 ac-ft/d, about 830 ac-ft/d less than the 2014 mean. Only two large storm events significantly affect water supply in 2015. Unimpaired flow at the outlet reaches over 92,000 ac-ft/d at the beginning of February and almost 52,000 ac-ft/d in the middle of December. Relative to historical records, the rest of the year is quite dry. From July through November, unimpaired flow estimates at the outlet range between 30 ac-ft/d and 70 ac-ft/d. Figure 11 compares DWRAT's 2014 and 2015 unimpaired flow estimates at the outlet of the Russian River. Overall, 2015 was a slightly drier year than 2014 because of smaller storm events in the winter.

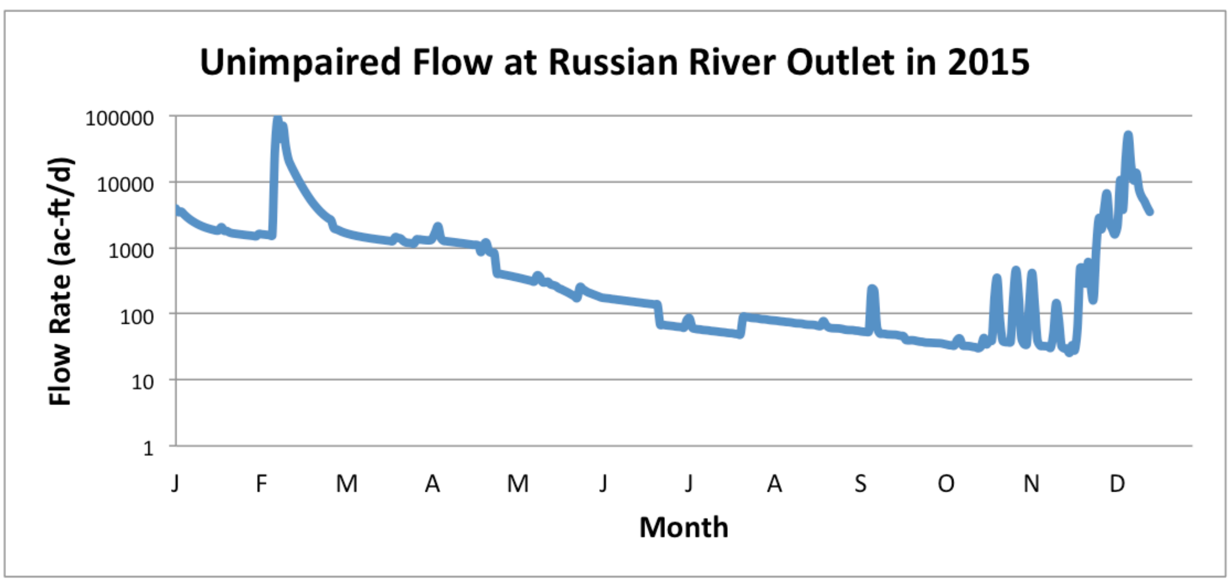


Figure 10. DWRAT Unimpaired Flow Estimates at Outlet 2015 (log scale).

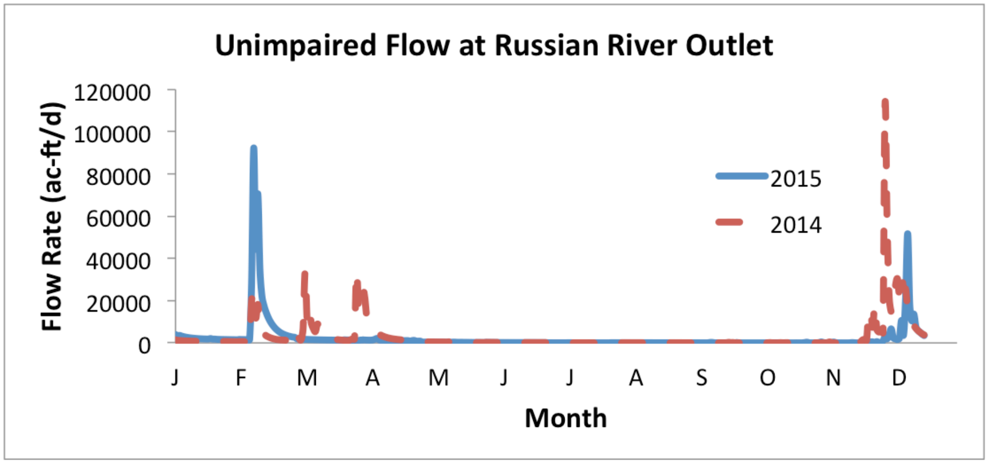


Figure 11. DWRAT Unimpaired Flow Estimates at Outlet.

Figure 12 shows the total volume of shortage caused using DWRAT's water allocation decisions for 2015 while Figure 13 shows the percentage of water rights curtailed. Water shortage is quite low in January of 2015, especially compared to shortages in January of 2014. In 2015, water availability is enough in January to satisfy most users' demand and prevent much of the previous year's shortage. For instance, DWRAT's unimpaired flow estimates at the Russian River's outlet range between 1,500 ac-ft/d and 4,000 ac-ft/d for January, 2015 and range between 650 ac-ft/d and 1,300 ac-ft/d for January, 2014. In 2015, shortage increases after March and reaches a maximum of 645 ac-ft near the end of November, when 298 rights are curtailed. Storms in December increase water supply enough to completely eliminate shortage.

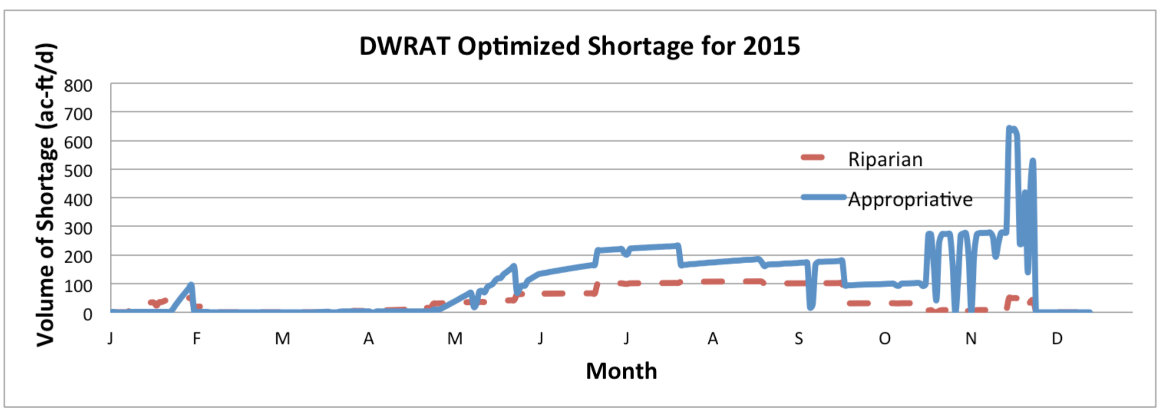


Figure 12. Volume of Shortage Caused by DWRAT's Allocation Decisions.

The curves in Figure 12 and 13 represent optimal shortage and curtailment levels for 2015's hydrologic conditions based on water demand between 2010 and 2013. Moreover, the figures show the best-case shortage scenario for 2015 when water demand in 2015 is the average water demand between 2010 and 2013. In reality, total water use was probably less in 2015 than it was in the previous five years because many users would have begun conserving more water to adapt to drought. As a result, Figures 12 and 13 likely overestimate the volume of shortage and percentage of users that would need to be curtailed to achieve the best-case shortage scenario.

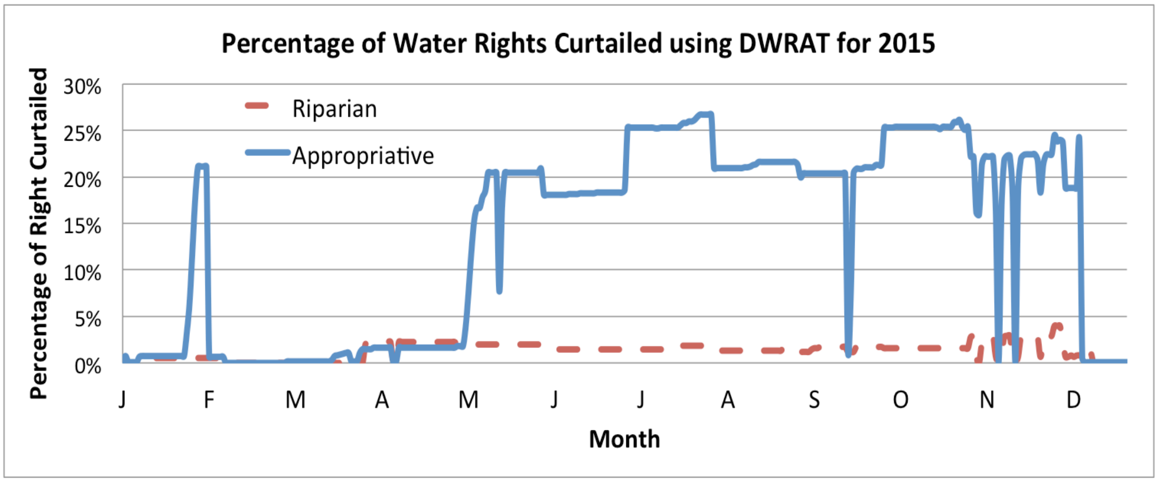


Figure 13. Percentage of Users Curtailed using DWRAT's Allocation Decisions.

The SWRCB did not issue any curtailments to Russian River users in 2015. However, DWRAT's results suggest that it should have. Traditionally, the SWRCB uses water supply forecasts to determine whether water right curtailments are needed. If forecasted supply is less than user demand, the SWRCB can issue curtailments.

However, given the complexity of climate and hydrologic conditions, water supply forecasts cannot be made with complete certainty and lead to imperfect curtailment decisions. If forecasted supply is less than true supply, fewer water rights may be curtailed than necessary. As a result, water users would be over-promised water, which increases the likelihood of senior users being deprived of water. On the other hand, if forecasted supply exceeds true supply, more water rights may be curtailed than necessary. In this case, unnecessarily curtailed water users would become upset with the SWRCB. Thus, it is important to handle water supply uncertainty so water right curtailments properly balance these two outcomes. The following chapter discusses how DWRAT can be used to construct water right curtailment decision rules given uncertain hydrologic conditions.

Chapter 4 - Water Reliability and Curtailment Decision Rules

Simulation and optimization models often are used to evaluate and compare the performance of alternative solutions to problems. However, the performance of each alternative usually depends on uncertain conditions such as future flows, demands, costs, and water qualities (Loucks, 1993). It is useful to account for such uncertainties. After all, the performance of each alternative in a simulation or optimization model often depends on assumptions regarding uncertain parameters. Parameter errors may lead to suboptimal system design and operation decisions.

Parameter uncertainty in modeling complex hydrologic systems has resulted in development of stochastically based water management models (Gates et al, 1989). Stochastic models can be classified as either 'explicit' or 'implicit'. Explicit stochastic models incorporate uncertainty within the model. An example of an explicit stochastic model would be one that explicitly accounts for several possible hydrologic conditions and the probabilities of each hydrologic condition. Implicit Stochastic Optimization (ISO) uses deterministic models to identify and evaluate system performance for a range of stochastically generated conditions (Lee, et al, 2007). ISO models include those that simulate multiple flow sequences to obtain multiple outputs that can be converted to probability distributions of future system performance (Loucks, 1993) as a basis for establishing near-optimal decision rules. First, a sequence of representative synthetic inflows is generated. Then, a deterministic optimization model is used to compute the optimal decisions for all inflows. Typically, rule curves can be constructed from the optimization results to guide water management decisions. For example, ISO has been used to generate sets of optimal operating data for reservoirs under varying inflow ensembles (Celeste et al, 2009). Such data was used to develop rule curves to aid reservoir operators in making reservoir release and allocation decisions.

ISO is often used to identify operating rules for reservoirs with uncertain inflows (Draper, 2001). Young (1967) used Monte Carlo analysis and dynamic programming to determine reservoir-operating policies. The optimal releases found by the dynamic programming model were regressed on the current reservoir storage and the forecasted inflow. Given present inflow and storage conditions, a regression equation could be used to compute optimal reservoir release at any time.

ISO Applied to DWRAT

ISO employs deterministic optimization models to estimate optimal system operation rules or decisions for conditions involving uncertainty. In this case, DWRAT is a deterministic model since it makes optimal water right curtailment decisions given a set of deterministic hydrologic conditions. Synthetic flow sequences can be fed into DWRAT so that it generates different sets of curtailment decisions for each set of flow rates. These results can be used to construct a set of curtailment rules for stochastic flows. Water regulators could then use these rules to make optimal curtailment decisions based on the watershed's current supply level and forecasted inflow. The complete process can be summarized as:

1. Generate n synthetic inflow sequences based on historical hydrology;
2. Compute optimal curtailment decisions for all n inflow sequences using deterministic optimization;
3. Use the ensemble of optimal curtailment decisions to determine water reliability for water right holders;
4. Use the ensemble of optimal curtailment decisions to construct monthly curtailment rules.

Estimating Probability of Curtailment and Water Right Reliability

Estimates of the probability of curtailment have a variety of uses, from the SWRCB assessing the need for curtailments, to water users preparing for a dry year, to the SWRCB deciding if enough water is available to issue new water rights. The first step to computing the probability of curtailment for each water right holder is to have DWRAT generate optimal curtailment decisions for a variety of flow rates. The probability of particular solutions can represent the frequency of each solution set. So, water supply reliability can be estimated for water right holders with varying priorities at varying locations.

Using the Russian River in July as an Example

DWRAT has been developed for the Russian River watershed, with 43 sub-basins and 2,015 water right holders. Local inflows for each sub-basin are assumed to be deterministic based on a statistical flow model (Grantham, et al, 2014), given an unimpaired flow rate at Healdsburg (Q_H). Equation 4 shows how the local flow rate can be computed for a given Q_H, where A_i is the drainage area of the local HUC, A_H is the drainage area of the Healdsburg HUC, and $Q_{i,m}$ and $Q_{H,m}$ are the mean modeled monthly flows from the ten driest years between 1950 and 2011 at the local HUC and the Healdsburg HUC (Grantham, et al, 2014).

$$Q_i = \frac{A_i}{A_H} \cdot Q_H \cdot \frac{Q_{i,m}}{Q_{H,m}} \qquad \text{(Eq. 4)}$$

For each flow through Healdsburg, there is a corresponding set of curtailments C_n consisting of binary values 0 or 1 for each right holder j. User j is curtailed when $C_j = 1$ and user j is not curtailed when $C_j = 0$ (Lord, 2015). A water right holder's probability of curtailment can be analyzed by comparing the number of times that user is curtailed (C_n) for a range of outlet flows (Q_H). The probability of a specific set of curtailments is the probability of the lowest outlet flow rate for which the curtailment set occurred.

This method can be extended to estimate the water reliability for each right holder. Each user (j) has an associated curtailment threshold flow rate $\left(Q_{Tj}\right)$, which is the gaged unimpaired flow at which a right holder is no longer curtailed. DWRAT ceases to short a user once that user's curtailment threshold has been reached. Whenever the reference location flow is less than Q_{Tj}, user j is curtailed. By stepping through a range of outlet flow values and solving the allocation linear programs, the curtailment threshold can be determined for each user as the minimum flow for which C_j is 0. The probability of a right holder being curtailed is the probability of flow less than Q_{Tj} (Lord, 2015). Since user demand estimates vary by month, the curtailment threshold of each user varies by month.

Number of Curtailed Right Holders for Varying Supply Levels

To calculate the probability of curtailment for each right holder, C_n was computed for a range of Q_H values, incrementing by 1 unit from 1 acre-feet to 27,000 acre-feet per day. The computations were done in Excel using VBA and an open source linear program solver.

Figure 14 shows the relationship between the flow rate at Healdsburg and the number of curtailments issued by DWRAT for July. As flow at Healdsburg increases, the local inflow through each sub-basin increases, which results in greater water availability throughout the watershed. Thus, DWRAT curtails fewer right holders as Q_H increases.

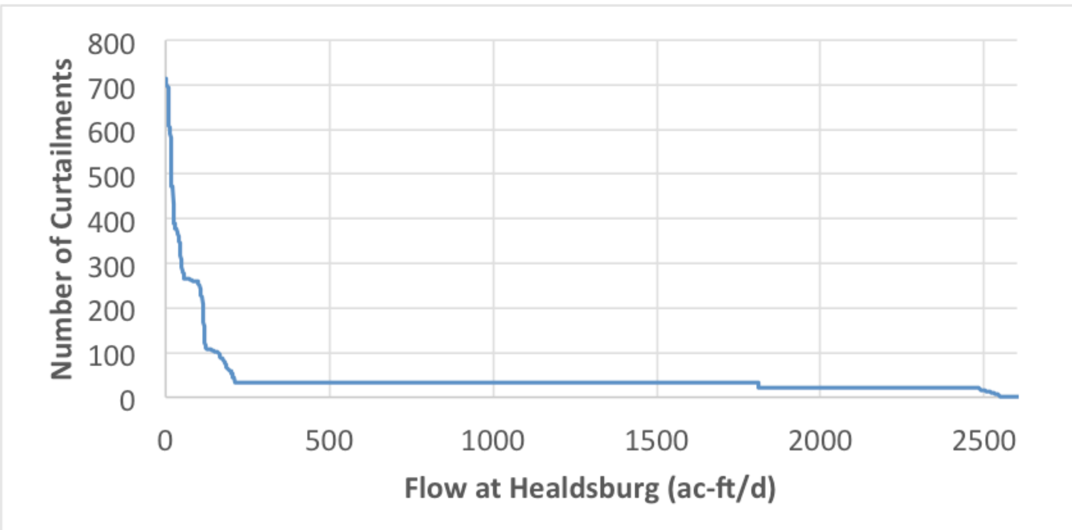


Figure 14.Total Number of Water Right Curtailments in July vs. Flow at Healdsburg.

As unimpaired flow available at Healdsburg rises from 1 ac-ft/d to 213 ac-ft/d, most water right holders are released from curtailment. However, for flow rates between 214 ac-ft/d and 1,811 ac-ft/d, no additional water right holders are released from curtailment even though 33 users are still shorted, as illustrated by long the plateau in Figure 14. Although no water rights are released from curtailment along this plateau, total shortage in the watershed declines steadily, as shown in Figure 15. Although the total number of curtailments in the watershed remains constant, partial curtailments imposed on water right holders become less severe. Typically, a plateau indicates that a significant increase in supply is needed to satisfy the demand of a single water right holder who maintains higher or equal priority to all other remaining curtailed right holders.

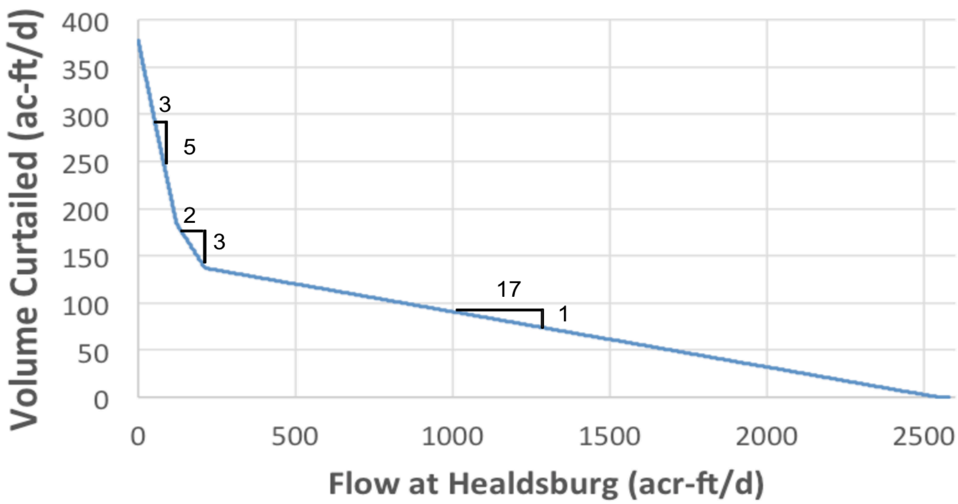


Figure 15. Total July Shortage in the Russian River vs. Flow at Healdsburg[1].

In July, DWRAT curtails 11 riparian users and 22 appropriative users when the flow through Healdsburg is between 214 and 1,811 ac-ft/d. All of these users are in the same sub-basin (HUC-12 180101100101), which is the most upstream sub-basin of the Russian River watershed. One riparian user from this HUC-12 has a relatively high demand (72 ac-ft/d). Since shortage is distributed proportionally among all riparian users in the same sub-basin, they can only be released from curtailment at the same supply level. Therefore, not one of the riparian users will be fully allocated their share of water until all riparian users can be fully allocated. When the flow rate at Healdsburg is 1,000 ac-ft/d, there is only enough water in this upstream sub-basin for the riparian user with the greatest demand to be allocated 60% of their demand. Consequently, all riparian users in that sub-basin are allocated 60% of their demands. This proportion steadily rises as river flow increases. Once the flow rate at Healdsburg reaches 1,811 ac-ft/d, the local flow in the uppermost sub-basin is enough to meet the demands of all of the riparian right holders in that sub-basin, so all are dropped from curtailment.

At this point, however, the 22 remaining appropriative users in the same upper sub-basin are still 100% curtailed, meaning that they have not been allocated any water at all. For each sub-basin, appropriative right holders are not allocated water until all riparian right holders have been released from curtailment. And since riparian water right holders have higher priority than appropriative right holders, they are allocated all water available in the HUC-12 until their uses are fully met.

Once the 11 riparian users are simultaneously released from curtailment, DWRAT begins allocating water to the highest priority appropriative water right holder. After that the most senior appropriative user is released from curtailment, the next highest[1] priority water right holder is distributed water. This continues until all water right holders are

[1] If the x-axis were basin outflow, the greatest slope for this curve would be 1. But because unimpaired outflow is greater than the Healdsburg flow, by a scaling factor greater than 1, the slope against flow at Healdsburg can exceed 1.

released from curtailment. The last right holder to be released from curtailment has the highest probability of being curtailed.

Probability of Curtailment

Historical flow records from the U.S. Geological Survey (USGS, 2016) can be used to calculate the mean flow rate at Healdsburg ($\overline{Q_H}$) along with its standard deviation for any given time of the year. For instance, historical records show that $\overline{Q_H}$ for July is 353 ac-ft/d and the standard deviation is 115 ac-ft/d. The July flow at Healdsburg appears to be normally distributed based on historical records from USGS.

The probability of curtailment for user j equals the probability that Q_j is less than or equal to the curtailment threshold (Q_{Tj}), which is calculated using the cumulative probability distribution function for flow, as shown in Equation 5 (Scott & Nowak, 2003).

$$F(Q|\mu, \sigma^2) = 0.5\left[1 + \operatorname{erf}\left(\frac{Q-\mu}{\sigma\sqrt{2}}\right)\right] \qquad \text{(Eq. 5)}$$

$$\operatorname{erf}(Q) = \frac{2}{\sqrt{\pi}}\int_0^Q e^{-t^2}\,dt \qquad \text{(Eq. 6)}$$

where μ is the mean flow, σ is the standard deviation of flow, and erf is the Gauss error function. For example, the probability that DWRAT will curtail a water user with a curtailment threshold of 175 acre-feet per day in July can be computed as:

$$F(175|353, 115^2) = 0.5\left[1 + \operatorname{erf}\left(\frac{175-353}{115\sqrt{2}}\right)\right] = 0.06 \qquad \text{(Eq. 7)}$$

Thus, the probability that a water right holder with a curtailment threshold of 175 ac-ft/d will be curtailed is 6%. Figure 16 shows the probability of curtailment for each water right holder in July based on 2010-2013 reported use. A high curtailment thresholds correlates to a high probability of curtailment.

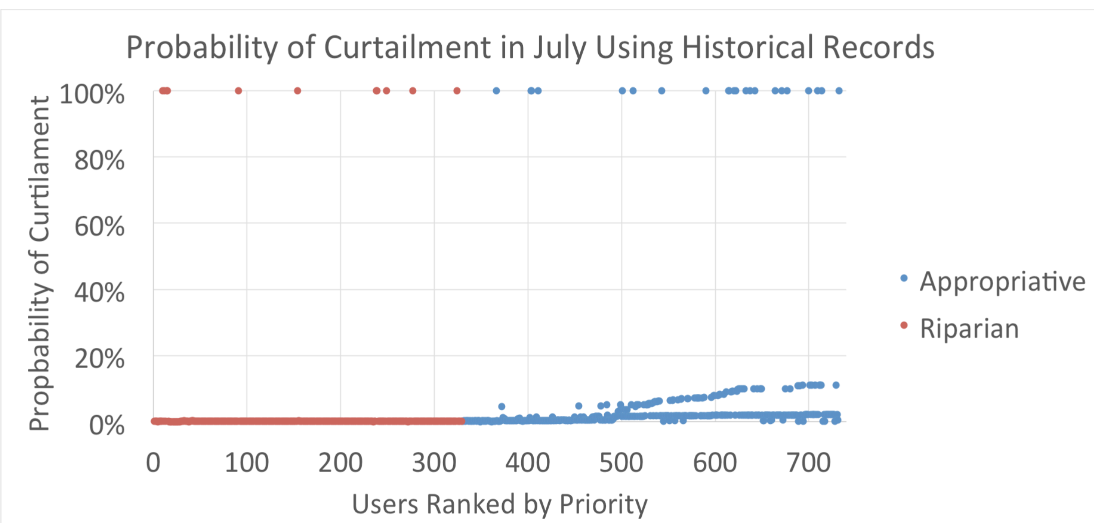


Figure 16. July Curtailment Probability for Each Users. Those with 100% probabilities of curtailment are in the uppermost sub-basin, where water availability is low.

The probability of a user experiencing shortage is based on two factors: (1) their priority and (2) their location in the watershed. In general, higher priority users (i.e., riparian right holders or appropriative right holders with early application filing dates) in downstream sub-basins have lower curtailment probabilities than lower priority users in upstream sub-basins which are more likely to have less streamflow. In Figure 16, users with priority rankings 1 through 329 hold riparian water rights and everyone else holds appropriative water rights. The curtailment probability curve begins to rise for junior appropriative water right holders with priority rankings above 400.

The users with nearly 100% probability of curtailment in Figure 16 hold water rights in the uppermost sub-basin of the watershed. Their high probability of curtailment results from the small amount of water available in their sub-basin and the high demand from a single riparian user. Figure 17 shows the same curtailment probability chart without users from the uppermost sub-basin. The split between the two curves results from spatial variance. Users with water rights in sub-basins having less water availability are more likely to be curtailed. For instance, users in Group A of Figure 4 are in upstream sub-basins with low water availability. As a result, these users are more likely to be curtailed than users in Group B, who are in sub-basins with higher water availability. Group C users are in the three most downstream HUC-12s, where water availability is the greatest and most reliable. Consequently, Group C users have extremely low curtailment probabilities despite being junior to most other water right holders. The "D" group has one senior appropriative user who is upstream of the East Fork Russian River confluence. Since water availability is low above the confluence, this user is more likely to be curtailed than are other right holders with similar priority levels. Because of spatially varying curtailment probabilities, separate curtailment probability charts for each sub-basin should used to more easily evaluate water reliability for water right holders.

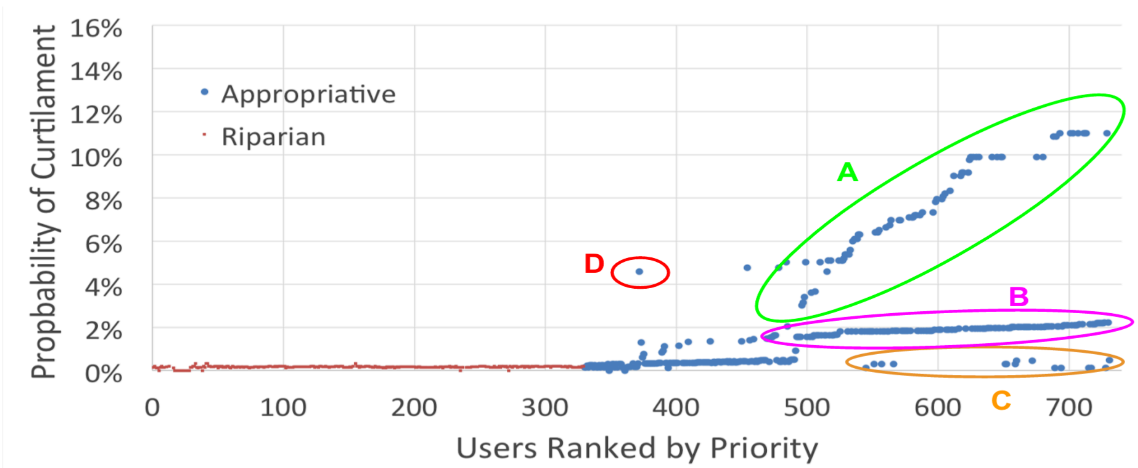


Figure 17. July Curtailment Probabilities for Users; Excluding Uppermost Sub-basin.

Figure 18 shows the curtailment probability of right holders in twelve sub-basins, ordered from most upstream to most downstream. The scales of y-axes vary significantly from chart to chart.

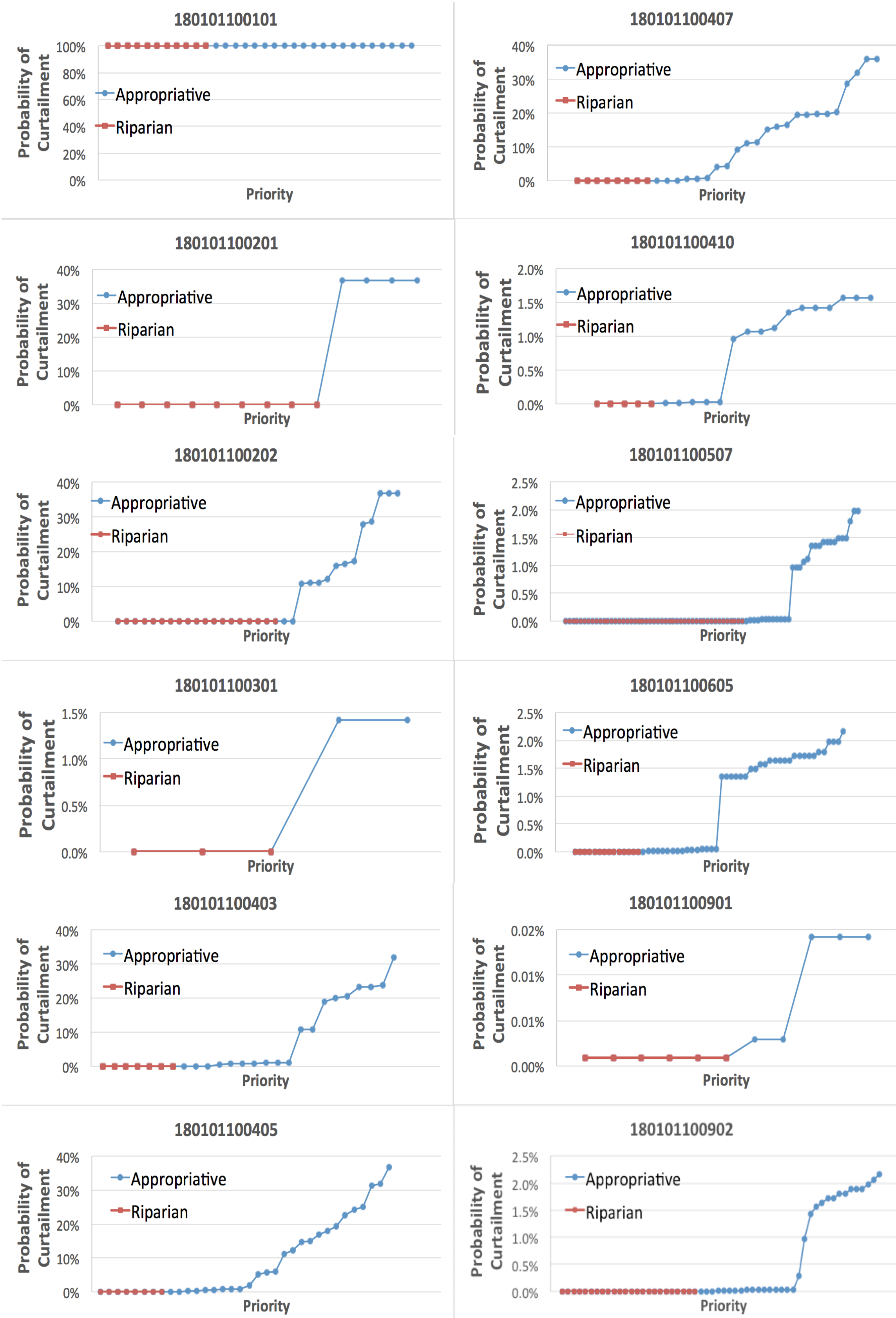


Figure 18. July Curtailment Probabilities for Users of Different Sub-basins.

Right holders further downstream are less likely to be shorted since water availability generally increases downstream as more tributaries contribute to streamflow. For instance, users in the most upstream HUC-12, 180101100101, are essentially guaranteed to have shortages. However, users from the most downstream basin, 180101100902, have less than 2.5% chance of curtailment, regardless of right type.

In addition, right holders in HUC-12s having high water demands are more likely to be curtailed than right holders in HUC-12s with low water demands. For instance, Figures 19 and 20 represent the curtailment probabilities for users in two of the most downstream sub-basins. Since 180101100901 is upstream of 180101100902, the inflow into 180101100901 is less than the inflow into 180101100902. Correspondingly, the former HUC-12 has less water available for diversions than does the latter. However, the water demand in 180101100902 (76 acre-ft/day) far exceeds water demand in 180101100901 (0.1 acre-ft/day). As a result, right holders in the less populated upstream HUC-12 have less risk of being shorted than right holders in the more populated downstream HUC-12. Even though more water flows into 180101100902, more water is also diverted from it. In some cases, those surrounded by many "big water users" are more likely to have shortage than those who compete with fewer diverters.

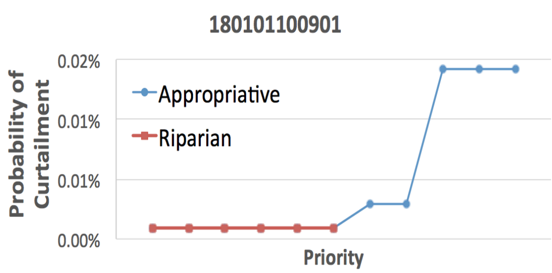


Figure 19. Curtailment Probability.

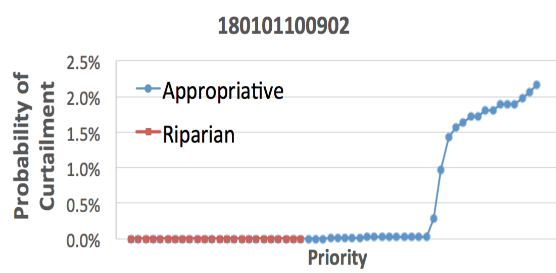


Figure 20. Curtailment Probability

Overall, this analysis shows that the likelihood of a water right holder having shortage depends on that right holder's priority and location in the watershed. Some sub-basins have plenty of water for its users while others do not. Some sub-basins have large inflows, but too many high-demand users to ensure full allocation for all right holders. The results from DWRAT reflect how shortage is optimally and legally allocated throughout a watershed and how such allocations affect supply reliability for water right holders with varying priorities and locations.

Making Rules for Water Right Curtailments

The basic DWRAT model presumes perfect foreknowledge of unimpaired streamflows and demands to generate optimal curtailment decisions. Consequently, DWRAT's decisions are unique to particular flow sequences. However, general curtailment rules can be inferred from the optimized results for each month. These decision rules can be conditioned on watershed supply levels for the current month or flow projections for the next month. For instance, consider a case where the National Weather Service issues a forecast showing that the mean flow rate for next July will be 150 ac-ft/d. To achieve optimal legal water allocations, one should curtail all water right holders with curtailment threshold less than 150 ac-ft/d. Figure 21 presents the curtailment thresholds for each Russian River water right holder in July. Users are ranked from highest priority to lowest priority (1 to 732). This chart can be helpful for determining which users should be curtailed for any flow rate at Healdsburg. The chart omits users from the uppermost sub-basin of the watershed since DWRAT results indicate a 99% probability that all such users should be curtailed in July.

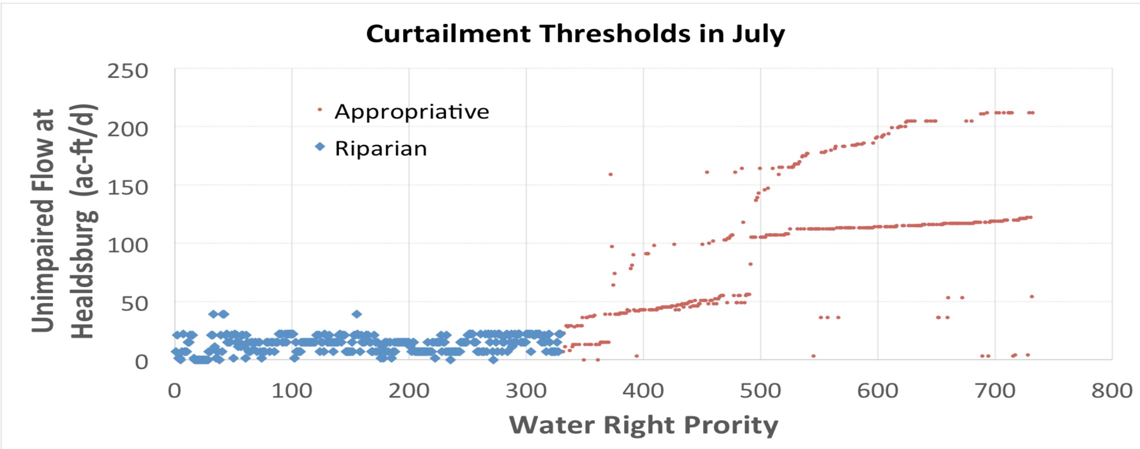


Figure 21. Curtailment Threshold Chart for Water Right Holders in July.

Figures 22 and 23 show curtailment threshold charts for six sub-basins in the Russian River watershed. Each user is assigned a priority ranking within their sub-basin based on riparian status or application filing date. Such curtailment threshold charts can serve as rules for legal curtailment decisions. All users with curtailment thresholds below the flow rate through Healdsburg in each chart should be curtailed. For example, if the flow rate at Healdsburg is 150 ac-ft/d, then all users in sub-basin 180101100403 with a priority ranking greater than 17 should be curtailed.

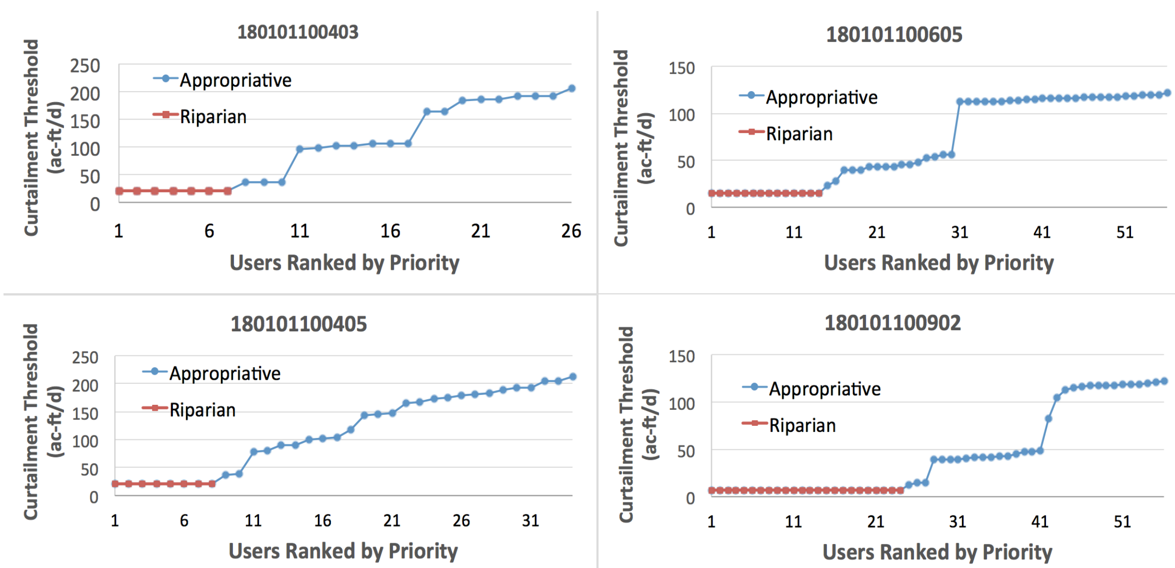


Figure 23. July Curtailment Threshold Charts for Users of Four Sub-basins.

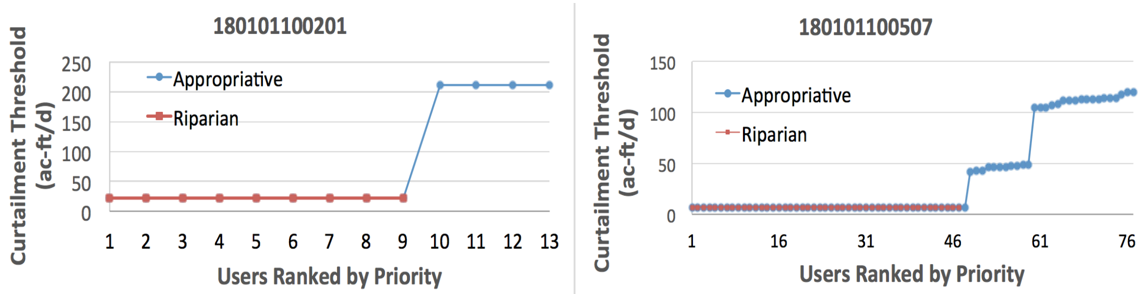


Figure 22. July Curtailment Threshold Chart for Users of Two Sub-basins.

One flaw of using curtailment threshold charts as a rule curves is that they do not represent the possibility of partial curtailment, which DWRAT occasionally suggests, but this will be subject to hydrologic uncertainty. As previously discussed, a user's curtailment threshold only represents the flow at which the user is completely released from curtailment and is allocated 100% of their demand. Using the charts in Figures 22 and 23 as a rule curves may slightly over-curtail since all users with curtailment thresholds below the projected flow rate through Healdsburg will be completely curtailed even if DWRAT only partially curtails them.

In most cases, a flow forecast that projects monthly average flows will not exist. Curtailment decisions to be made more than a week in advance usually will need to be made based only on historical data and knowledge of current watershed conditions. An approach using Markov chains could be implemented where the probability of inflows in the next month depends on the inflows of the current month. For instance, the flows observed in June could be used in combination with historical records to determine expected flows for July. Optimal curtailment decisions could then be made for July using the same rule curves as those shown in Figures 22 and 23.

Water reliability and curtailment decision rules derived through DWRAT are subject to the accuracy of the flow-forecasting model. Curtailment decision rules, such as those in Figures 22 and 23, are sensitive to the accuracy of DWRAT's predicted flows for each sub-basin. The following chapter analyzes error in DWRAT's hydrologic model. Probabilities of error in flow estimates can be used to more accurately determine probabilities of curtailment for each water right. For instance, uncertainty in DWRAT's scaling ratios can be included in water reliability estimates using Monte Carlo analysis.

Chapter 5 - Flow Error Analysis and Calibration

DWRAT relies on the accuracy of its statistical flow-estimation model.
If the unimpaired flow estimates are inaccurate, then DWRAT's allocation decisions will be less accurate. Flow error analysis should help estimate the reliability of DWRAT's results. Such analysis also can aid in calibrating and improving the flow model so that it more accurately reflects unimpaired flows throughout the Russian River basin.

Flow Error Analysis Methodology

The following steps outline a procedure for flow error analysis in DWRAT:

1. Specify a date of interest on the Excel user interface;
2. Run the flow-forecasting model to update the "Flow Data" tab for the specified date.
3. Add reservoir releases into the system.
4. Manually allocate users their reported use on the specified date (rather than running the linear programs);
5. Obtain the flow rate in each HUC-12 that remains by subtracting water allocations from water availability;
6. Compare the DWRAT-predicted impaired flows to flows recorded by USGS and CDEC gages;
7. Repeating each step for additional dates.
8. Statistically compare differences between model and observed results.
9. Gain insight for model improvements and use.

The hydrologic model's accuracy has been assessed by using SWRCB curtailment decisions as model inputs and comparing model-predicted flows to observed gage flows. Rather than using DWRAT's linear programs to make allocation decisions, water was fully distributed to users not issued SWRCB curtailment letters. On the other hand, users who were issued curtailment letters were provided zero water allocations in DWRAT. This analysis assumes water right holder demands are reported historical use and perfect compliance with issued SWRCB curtailments.

For instance, between May 27 and November 14 of 2014, the SWRCB curtailed all users upstream of the Dry Creek confluence with water right application filing dates later than February 9, 1954. Thus, in DWRAT, these junior appropriators were allocated no water during the curtailment period, while every other user was allocated their demand in full. Given a perfect hydrologic model, the flow remaining in the system should equal the flow actually present in the Russian River. The water remaining in each HUC-12 is considered "DWRAT-predicted impaired flow estimates", which is equal to DWRAT's unimpaired flow estimate minus DWRAT's water allocations. The hydrologic model's accuracy was then evaluated by comparing DWRAT-predicted impaired flows with gaged flows recorded by the USGS and CDEC. For this analysis, historical flow records from 22 gages were collected to assess flows in 18 HUC-12s. The locations of these gages are shown in Figure 24.

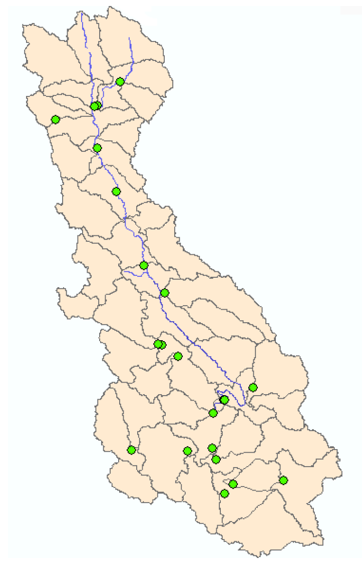


Figure 24. Russian River Flow Gages Used for Error Analysis.

DWRAT's unimpaired flow estimates do not include reservoir releases. However, reservoir releases from Lake Mendocino and Lake Sonoma significantly affect the flows observed throughout the Russian River. Thus, for purposes of flow-error analysis, reservoir releases have been included in DWRAT's hydrologic model to more accurately compare DWRAT-predicted flows to gaged flows. This study used reservoir release data reported by the US Geological Survey.

2014 Results

Figures 25 and 26 show the difference between monthly averaged DWRAT-predicted impaired flow estimates and monthly averaged gaged flow recordings for four sub-basins of the Russian River in 2014.

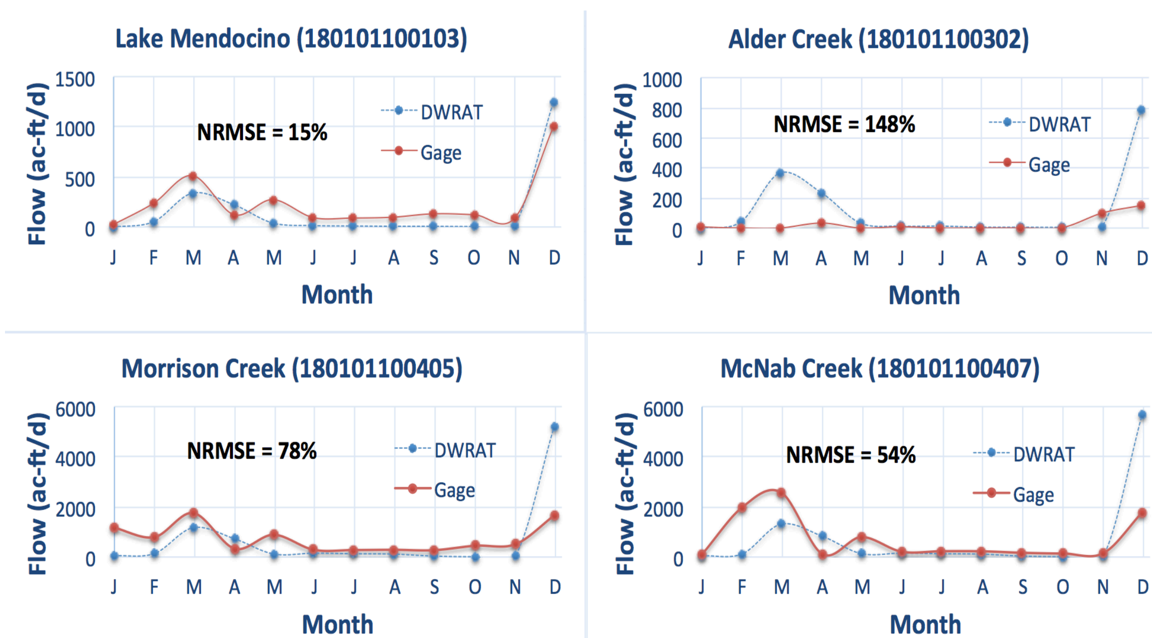


Figure 25. DWRAT-Predicted Flow vs. Gaged Flow at Healdsburg.

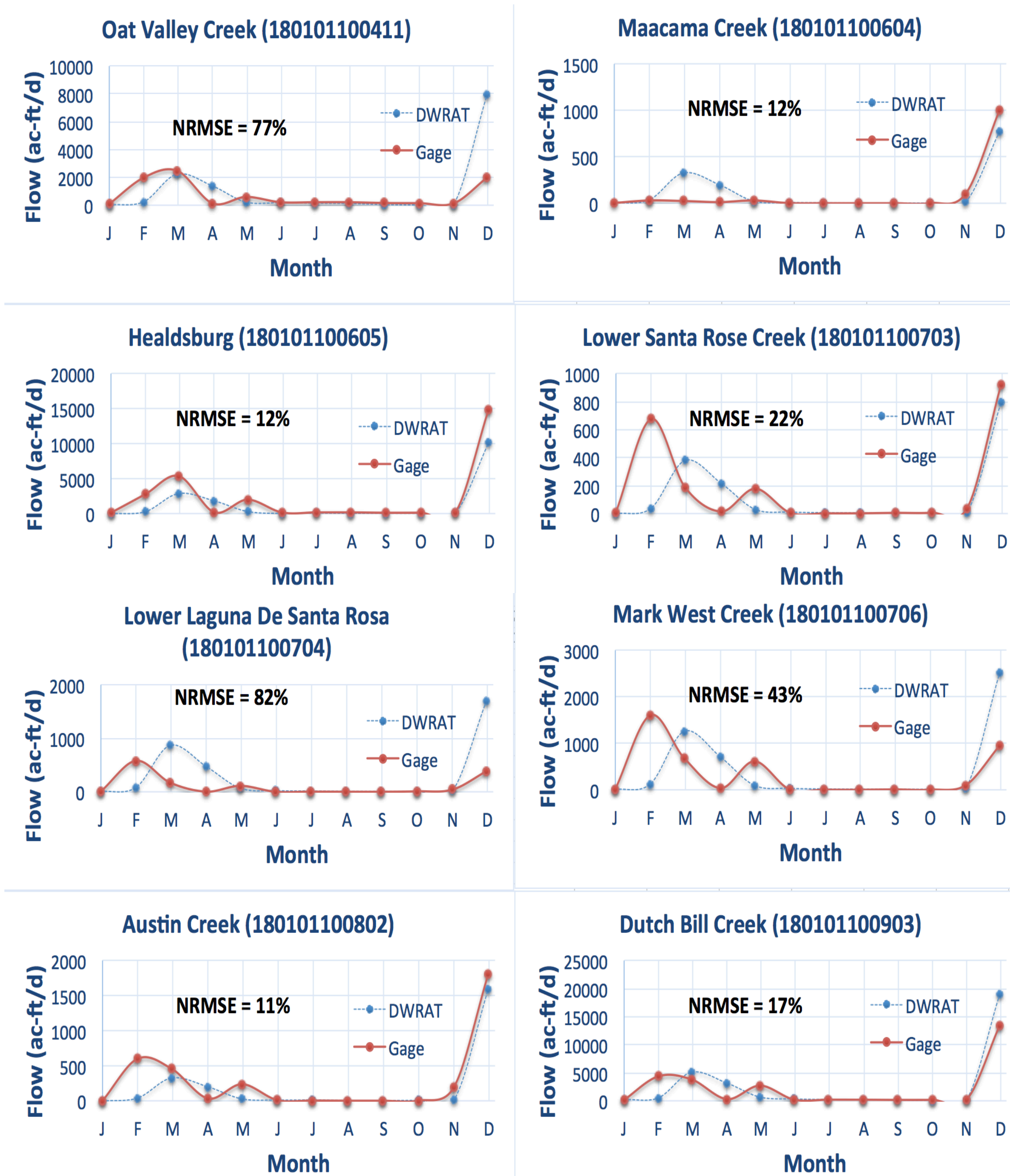


Figure 26. DWRAT-Predicted Flow vs. Gaged Flow at Healdsburg.

The Normalized Root Mean Square Error (NRMSE) has been computed for each sub-basin to evaluate the accuracy of DWRAT's flow estimates. The Root Mean Square Error (RMSE) is a measure the average deviation of DWRAT-predicted flows from gaged flows. The RMSE for each sub-basin are calculated using Equation 8, where Q_G represents gaged flows, Q_D represents DWRAT-predicted flows, and n represents the number of flow predictions. As shown in Equation 9, these values are normalized using each sub-basin's range of gaged flows to enable comparisons between datasets with different scales. The NRMSE is conveyed as a percentage, where higher values indicate greater residual variance.

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

$$NRMSE = \frac{RMSE}{Q_{G,max} - Q_{G,min}} \cdot 100\% \qquad \text{(Eq. 9)}$$

DWRAT-predicted flow error is greatest December through February, when higher flows occur in the watershed. DWRAT overestimates water availability for some sub-basins and underestimates water availability for others. These results may imply that it is more difficult to accurately estimate flows when precipitation events affect some parts of the watershed more than others. The NRMSE tends to be lower for sub-basins closer to the NWS reference gage at Healdsburg. For example, DWRAT-predicted flows for Maacama Creek and Healdsburg yield smaller NRMSE values than do the DWRAT-predicted flows at any other sub-basin.

Sources of Error

The 2014 flow error results indicate that the flow-forecasting model needs further calibration and improvement in several regions of the Russian River watershed. To assess where the model needs improvement, the following sources of error have been considered:

1. Inaccurate NWS's unimpaired flow forecasts
2. Inaccurate reported water use
3. Lack of groundwater and surface water interaction
4. Lack of return flows
5. Inaccurate HUC-12 scaling factors

Error in the NWS's unimpaired flow forecasts at Healdsburg is inevitable since unimpaired flow estimates require several approximations for soil infiltration, evapotranspiration, runoff, percolation, and assumptions for "natural" hydrologic conditions. Such error would affect DWRAT's flow predictions throughout the entire watershed since it uses the NWS's unimpaired forecasts to disaggregate flows to each sub-basin. Also, there is likely error in the SWRCB's water use database. For instance, water right holders may inaccurately report water diversions to the SWRCB or water right holders also might choose to use more or less water than their recorded use in the recent past, but within their water right quantity. Hydrologically, DWRAT does not model interactions between groundwater and surface water, which can overestimate flow predictions since surface water losses to groundwater infiltration, which might increase in drought, are not included. At some times of the year, however, groundwater can contribute additional flow to the river where the water table is above the streambed. In addition, the current Russian River model does not include return flows, which are diverted flows that drain back into the river after being applied by users. Incorporating return flows into the model would increase DWRAT-predicted water availability.

Finally, inaccuracies in DWRAT's scaling ratios of Healdsburg flow to non-Healdsburg flow likely contribute the most error to the hydrologic representation. Currently, DWRAT uses constant scaling factors based on monthly mean unimpaired flow estimates from the 10 driest years between 1950 and 2011. However, there is not always a strong correlation between flow at some sub-basins and flow at Healdsburg. This is especially apparent for sub-basins further from Healdsburg. The extent to which monthly flow ratios fluctuate from year to year can lead to inaccurate flow predictions. These scaling ratios are evaluated in the following section.

Scaling Ratios

In DWRAT, a scaling ratio (flow ratio) is defined as the ratio of unimpaired flow at one sub-basin to the unimpaired flow at the Healdsburg reference location. Refining DWRAT's scaling ratios can improve the accuracy of its flow predictions. Figure 27 shows the monthly scaling ratios for eight of the driest years from 1950 to 2011. These ratios were computed using monthly-unimpaired flow estimates from Ted Grantham's model (Grantham, 2014). Each line represents a different year and each chart represents a different sub-basin. From year to year, the flow ratios fluctuate the most during the wet season. August and September have almost no variation in flow ratios.

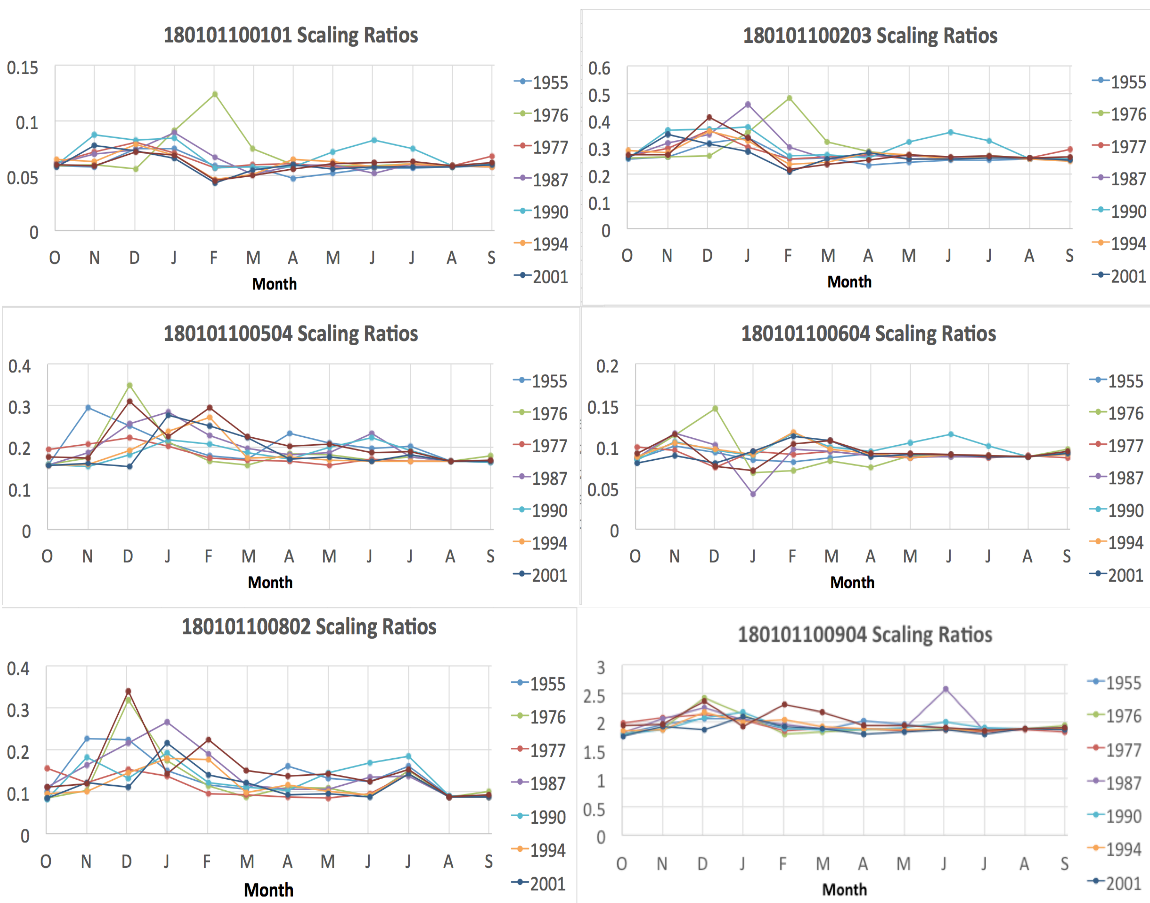


Figure 27. Scaling Ratios for 8 Dry Years.

Figure 28 shows the standard deviations of monthly scaling ratios for the 20 driest years from 1950 to 2011. Each line represents a different sub-basin. In general, scaling ratios vary more for sub-basins further from the reference gage in Healdsburg. In addition, the ratios fluctuate more for sub-basins with higher flows. For instance, the most downstream sub-basin in the watershed, 18010111001904, has the greatest unimpaired flows and the greatest standard deviations of monthly scaling ratios.

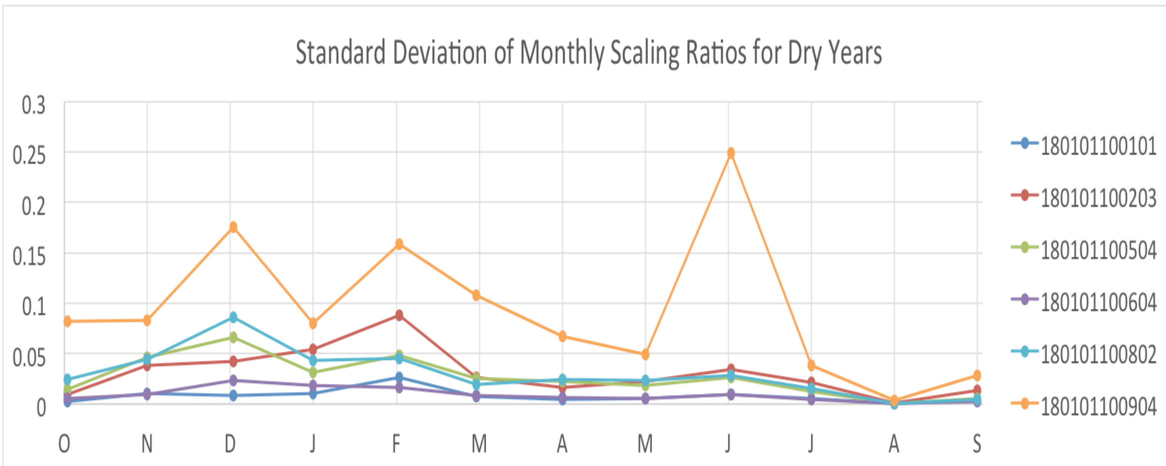


Figure 28. Standard Deviations of Scaling Ratios for Average Dry Years.

Figure 29 shows probability distributions of scaling ratios for various months and sub-basins using hydrologic model results from 1950 to 2011 (Grantham, 2014).

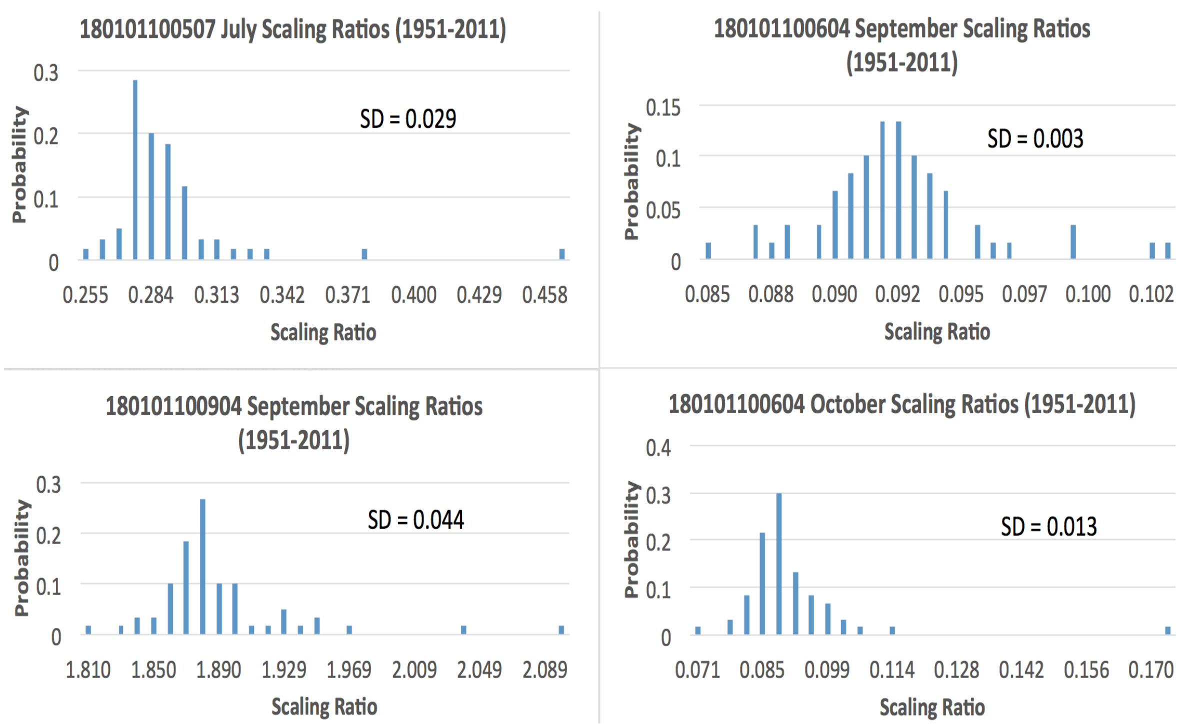


Figure 29. PDFs for Monthly Flow Ratios of Various Sub-basins and Months.

For each HUC 12 in each month, the distribution of scaling ratios is symmetric and centered on the mean (Appendix A). In addition, nearly all of the scaling ratio values fall within three standard deviations of the mean. Thus, the PDFs indicate that the distribution of monthly scaling ratios from 1950 to 2011 is normal and can be represented by Equation 10.

$$F(SR) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(SR-\overline{SR})^2}{2\sigma^2}} \qquad \text{(Eq. 10)}$$

where:
SR = Monthly scaling ratio;
σ = Standard deviation of the monthly scaling ratio;
σ^2 = Variance of the monthly scaling ratio.

Figure 30 shows the cumulative distribution functions (CDFs) for the scaling ratios of four sub-basins based on unimpaired flow estimates from twenty of the driest years from 1950 to 2011. Each line represents the CDF for a different month. The CDFs represent the probability of a monthly scaling ratio being less than or equal to a particular value any given year. Consequently, the charts portray the range of flow ratios that are typical for each month during dry years. As the months get drier, the range of flow ratios becomes smaller because there is less variance in hydrologic conditions from year to year. In August, for instance, flows are almost never affected by rainfall or snowmelt contributions. As a result, the range of flow ratios is very small during this month.

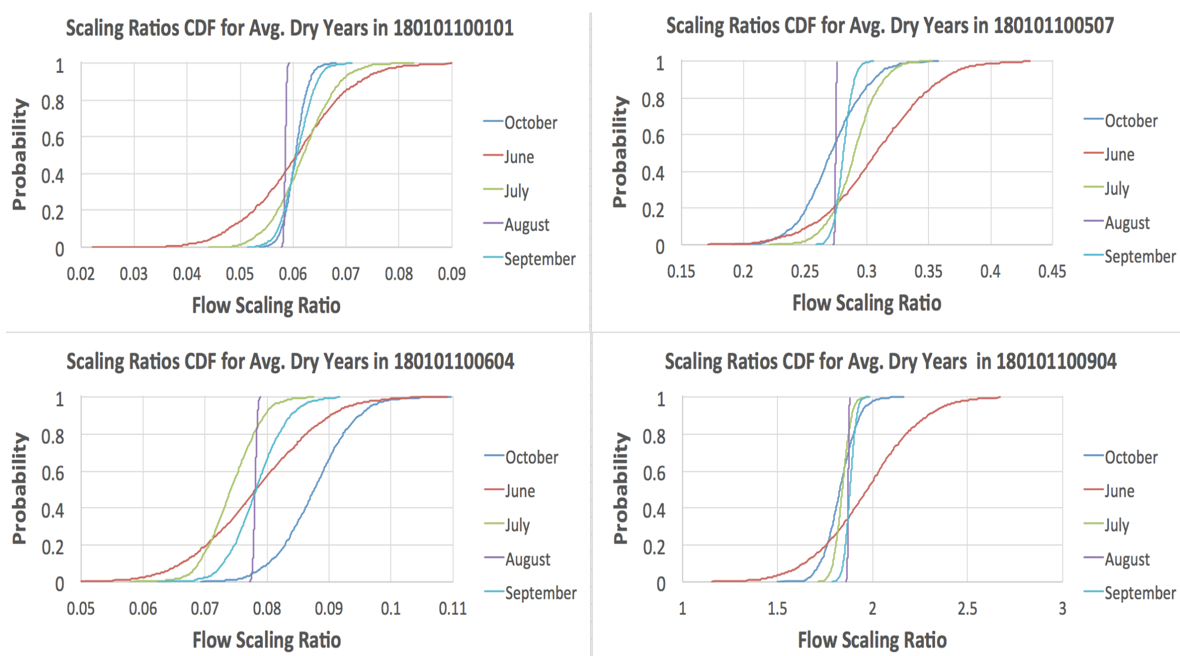


Figure 30. CDFs for Monthly Flow Ratios of Various Sub-basins and Months.

Figure 31 shows the probabilities that monthly scaling ratios for any given year will be within 20%, 40%, or 60% of the "average dry year" ratios. The "average dry year" ratios are defined as the mean monthly ratios of Healdsburg flow to local flow for the 10 driest years from 1950 to 2011. Since the distribution of scaling ratios is normal, the probabilities in Figure 31 have been computed using a two-tailed Z-test. The Z-scores have been calculated using Equation 11, where Q_{μ} is the mean monthly flow ratio from 1950 to 2011, σ is the standard deviation of monthly flow ratios from 1950 to 2011, and Q_p is a scaling ratio p% less than or greater than the average dry year scaling ratio, where $p = 20\%, 40\%, 60\%$.

$$Z = \frac{Q_p - Q_{\mu}}{\sigma} \qquad \text{(Eq. 11)}$$

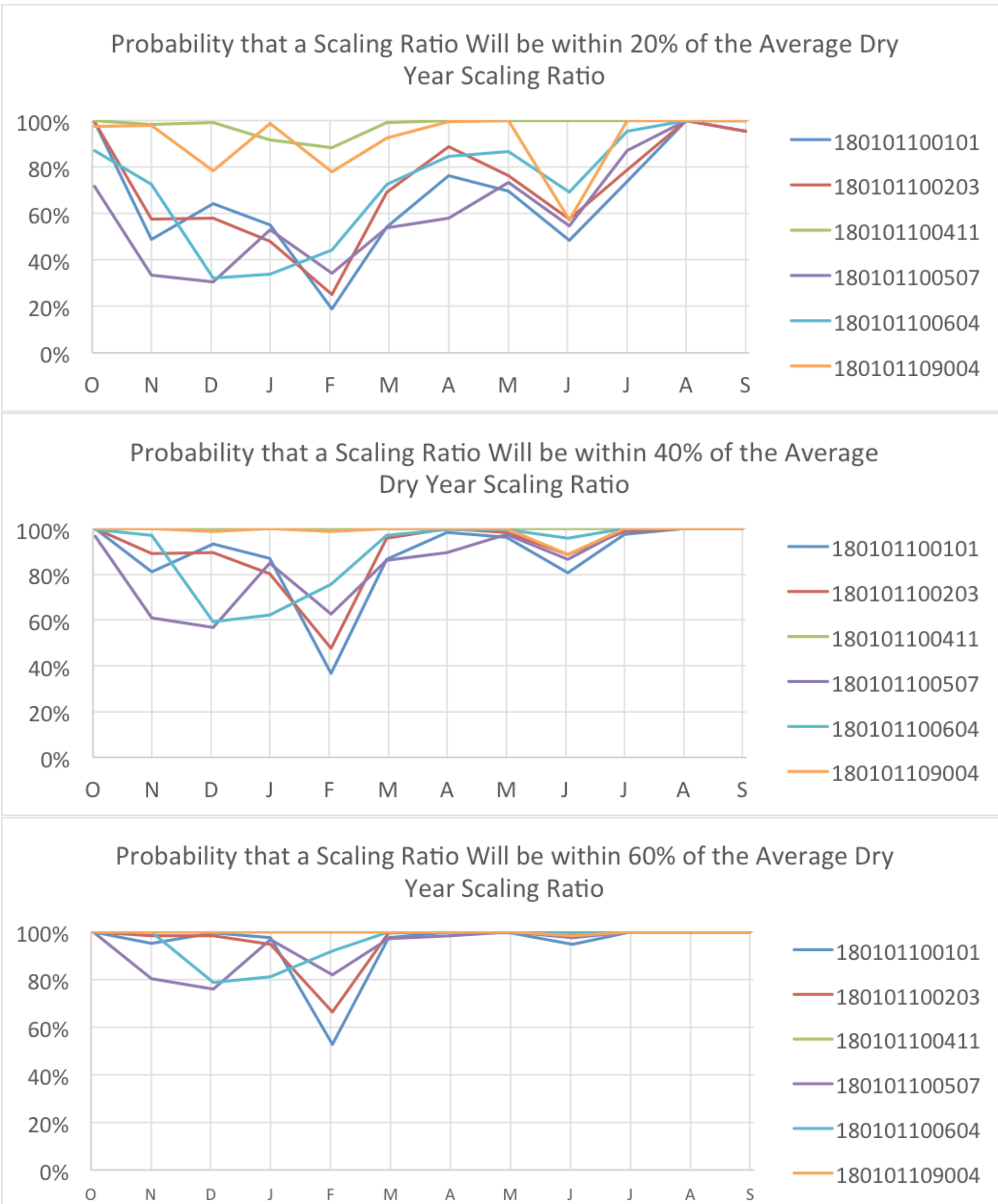


Figure 31. Probability of Scaling Ratios being within 20%, 40%, and 60% of the Average Dry Year Scaling Ratio.

Since DWRAT makes unimpaired flow estimates using "average dry year" scaling ratios, the charts in Figure 31 represent the probability of DWRAT's scaling factors being off by more the 20%, 40%, or 60% due to errors in the scaling factor. The probability of error in DWRAT's scaling factors is greatest in the wet season, when the range of flow ratios is largest because of fluctuating rainfall conditions from year to year. For most sub-basins, the probability of error goes up again in June, possibly because of inconsistent snowmelt contributions to flow from year to year. In the summer, the flow ratios for each sub-basin are almost always within 40% of the "average dry year" flow ratios. There is almost no deviation in flow ratios for August, so the probability of major error in DWRAT's August scaling ratios appears to be small.

Flow Calibration

Additional Reference Gages

The hydrologic model can be improved with the availability of more unimpaired flow data from varying locations throughout the watershed. Currently, the Russian River DWRAT uses unimpaired flow forecasts from a single gage (in Healdsburg) to estimate daily flows throughout the rest of watershed. The accuracy of DWRAT's unimpaired flow estimates depends on the accuracy of the scaling ratios between Healdsburg flows and un-gaged flows determined by the current statistical flow model for HUC12 sub-basins within the watershed (Grantham, et al., 2014). The scaling ratio method works best when the flow at a gaged sub-basin is strongly correlated to the flow at an un-gaged sub-basin. However, more distant sub-basins are less likely to have consistent flow ratios. With a drainage area of 1,485-square-miles and hundreds of tributaries and reaches, the Russian River may be too large and complex for a single reference gage to be used reliably to predict flows throughout the entire watershed. Additional unimpaired flow forecasts at several locations along the river would be helpful.

For example, consider the following hypothetical case: On May 5th of a particular year, the NWS's unimpaired flow forecast at Healdsburg is 100 ac-ft/d. Since DWRAT's scaling ratio between Healdsburg and Ukiah in May is 0.81, DWRAT computes the unimpaired flow at Ukiah to be 81 ac-ft/d (100 ac-ft/d multiplied by 0.81). Let's say that the unimpaired flow at Ukiah is actually 80 ac-ft/d, which means that DWRAT's scaling ratio does quite well in reflecting the true flow ratio between Healdsburg and Ukiah on May 5th of this particular year. However, on May 16th, a storm comes through the bottom half of Sonoma County and brings runoff into tributaries that feed into the Russian River upstream of Healdsburg and downstream of Ukiah. Consequently, the flow at Healdsburg increases to 400 ac-ft/d while the flow at Ukiah remains 100 ac-ft/d. Now, the flow ratio between Healdsburg and Ukiah is 4. Since DWRAT's scaling ratios are constant through each month, it will inaccurately estimate the unimpaired flow at Ukiah to be 324 ac-ft/d (400 ac-ft/d multiplied by 0.81) even though Ukiah was unaffected by the storm. Overall, DWRAT cannot account for storm events that reach only part of the watershed since its flow forecasts are limited to a single reference gage. Including additional reference gages with unimpaired flow forecasts can reduce this problem.

SCWA Unimpaired Flow Estimates

In cooperation with SCWA, the USGS conducted a study (Flint, et al., 2015) to estimate unimpaired daily flows for the Russian River using the Basin Characterization Model (Flint, et al., 2013). The USGS released a dataset of daily time-series of simulated unimpaired stream flow for 12 Russian River sub-basins from January 1, 1910 to December 31, 2013. Figure 32 compares mean monthly unimpaired flow estimates from Ted Grantham's model and the Basin Characterization model for water year 1977. Usually, SCWA's flow estimates are smaller than Grantham's estimates. In the summer, Grantham's estimates are typically about ten times greater than SCWA's estimates. Furthermore, Grantham's estimates increase from February to March much more definitively than do SCWA's estimates. This indicates that Grantham's model may be more sensitive to precipitation events than is the Basin Characterization Model.

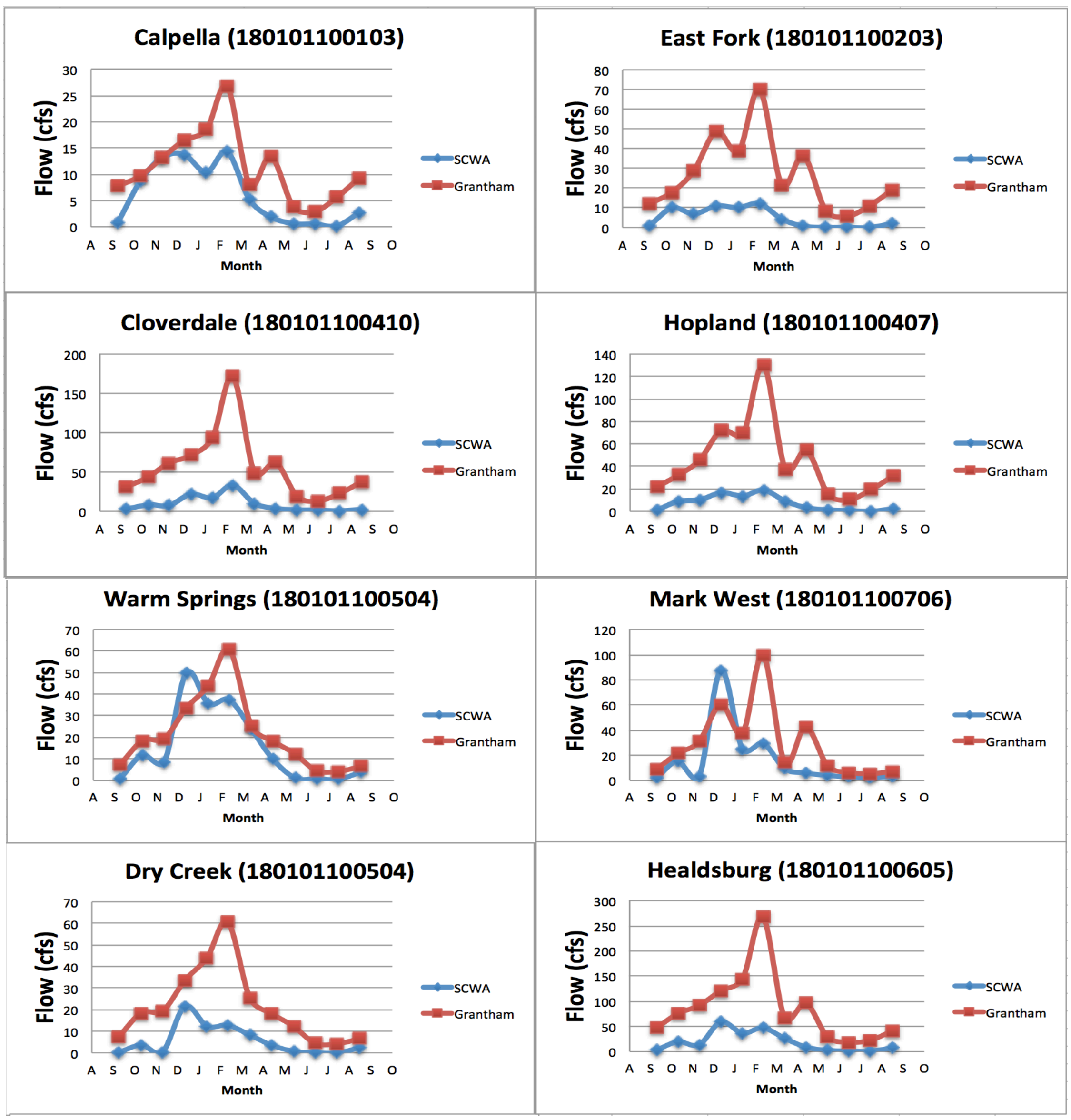


Figure 32. Grantham vs. SCWA's Unimpaired Flow Estimates for 1977.

Fortunately, flow ratio estimates based on the Healdsburg gage, which are used in DWRAT, are more consistent between the two models. Figure 33 shows the ratios of Healdsburg flow to local flow yielded by Grantham's data and the SCWA's data for four HUC 12s in water year 1977. Although the SCWA unimpaired flow estimates are smaller than Grantham's unimpaired flow estimates, the SCWA flow ratios vary much more than Grantham's flow ratios.

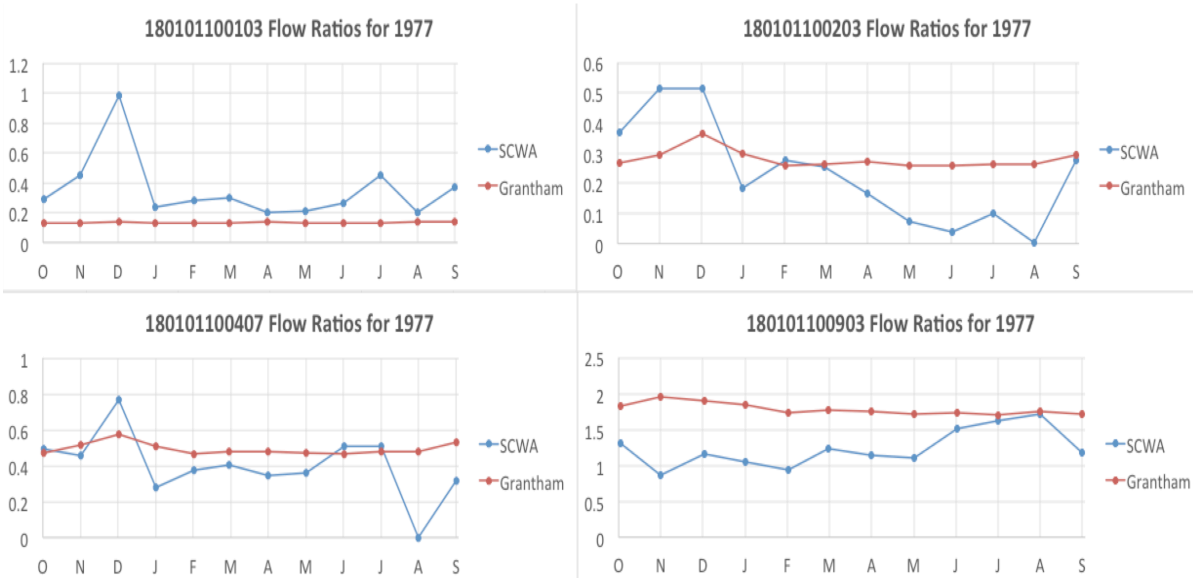


Figure 33. Ratios of Healdsburg Flow to Local Flow for Water Year 1977.

2013 Flow Error Using SCWA Reference Gages

For purposes of flow analysis, the SCWA dataset has been incorporated into DWRAT. Six of the twelve USGS unimpaired flow gages were used as reference gages to construct new scaling factors throughout the watershed. The locations of these reference gages are shown in Figure 34.

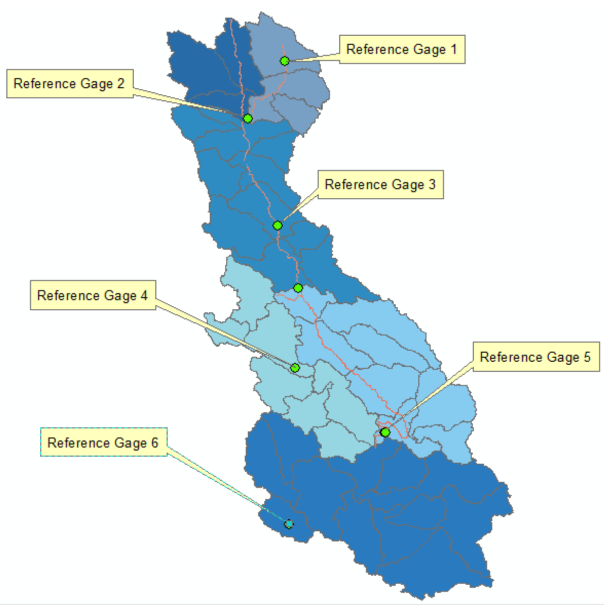


Figure 34. SCWA's Reference Gages with Unimpaired Flow Estimates.

The flow error analysis procedure described in the "Flow Error Analysis Methodology" section has been conducted for 2013 using scaling ratios generated by unimpaired flow estimates from the six SCWA reference gages in Figure 34. DWRAT-predicted flows and gaged flows are compared in Figures 35 and 36. Flow error analysis could not be performed for more recent years since SCWA has not published unimpaired flow estimates for after December 31, 2013.

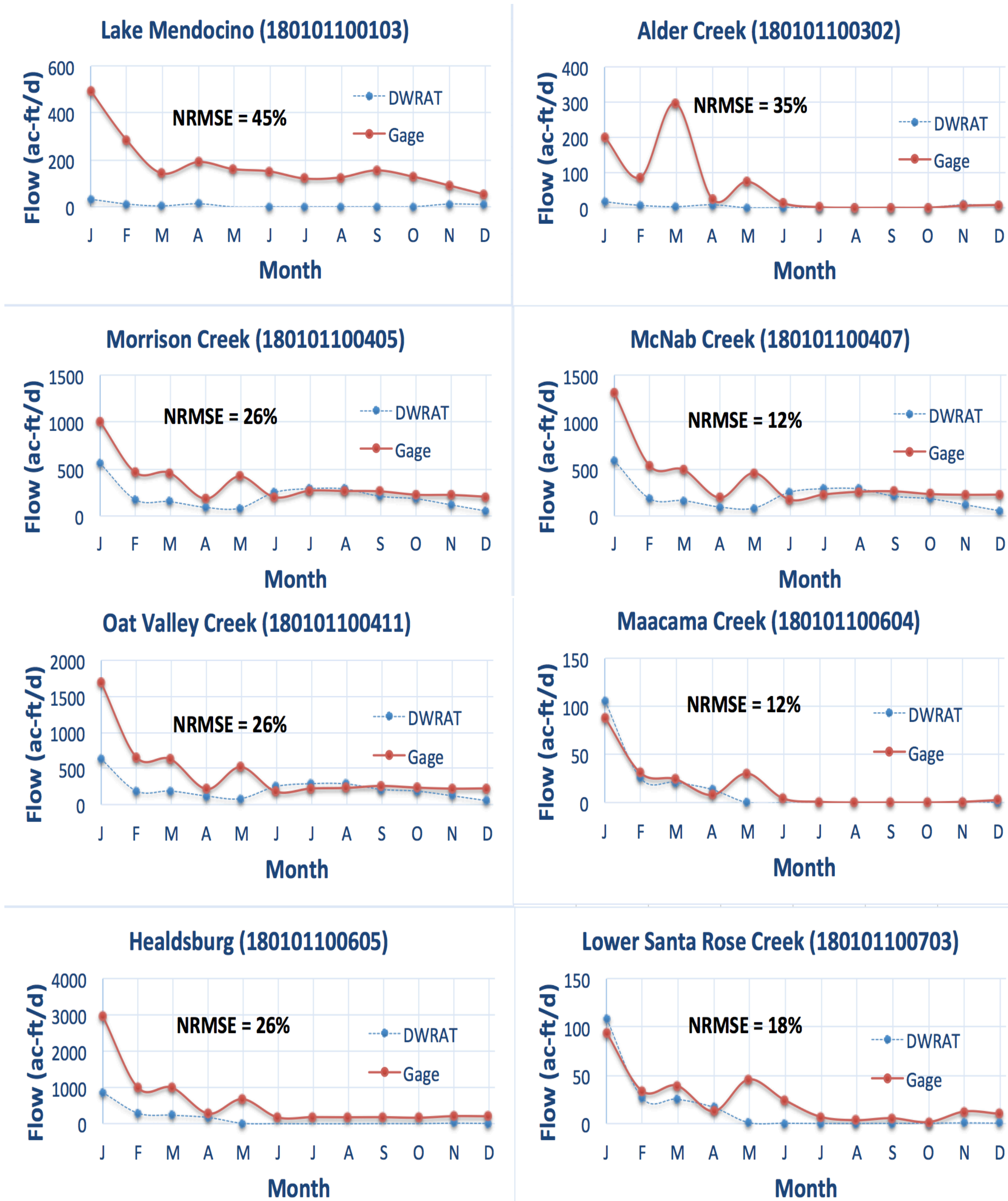


Figure 35. DWRAT-Predicted Flows vs. Gaged Flows for 2013.

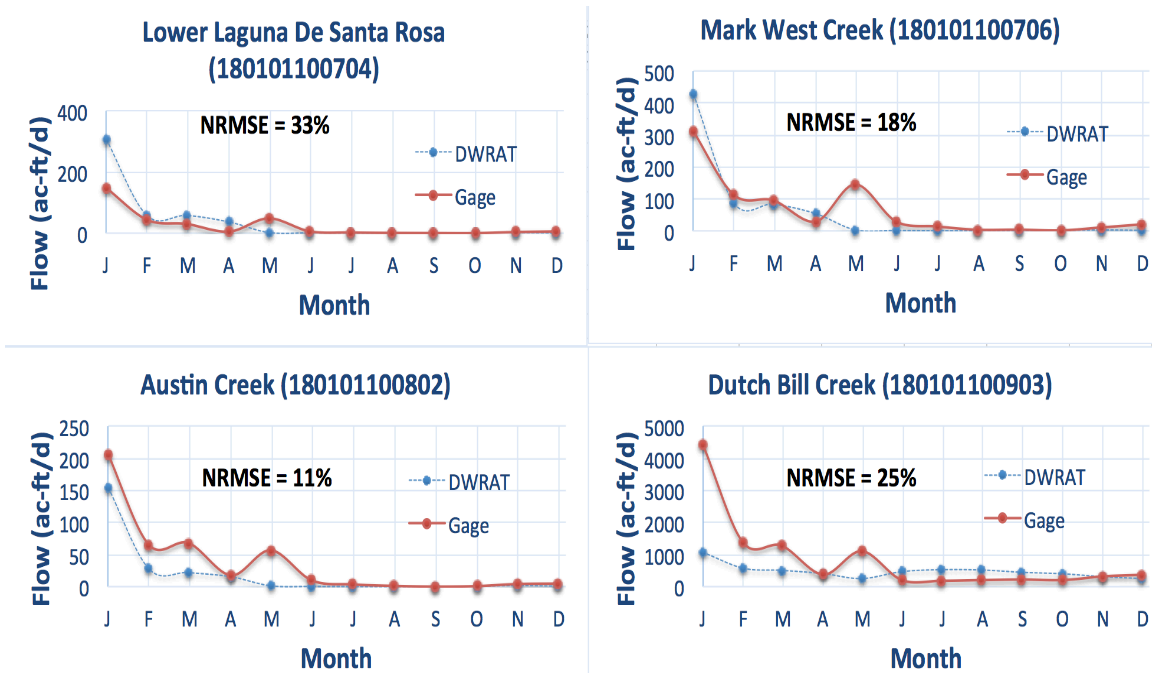


Figure 36. DWRAT-Predicted Flows vs. Gaged Flows for 2013.

Figure 37 compares the NRMSE between the one-NWS-reference gage method used for 2014 error analysis and the six-SCWA-reference gage method for 2013 error analysis. Overall, the six-reference gage method performs better than the one-reference gage method. The NRMSE is lower for 10 of the 14 sub-basins using six reference gages. In most cases, using six reference gages is much superior to just one reference gage. For 4 sub-basins, the NRMSE is lower using a single NWS reference gage, but only slightly.

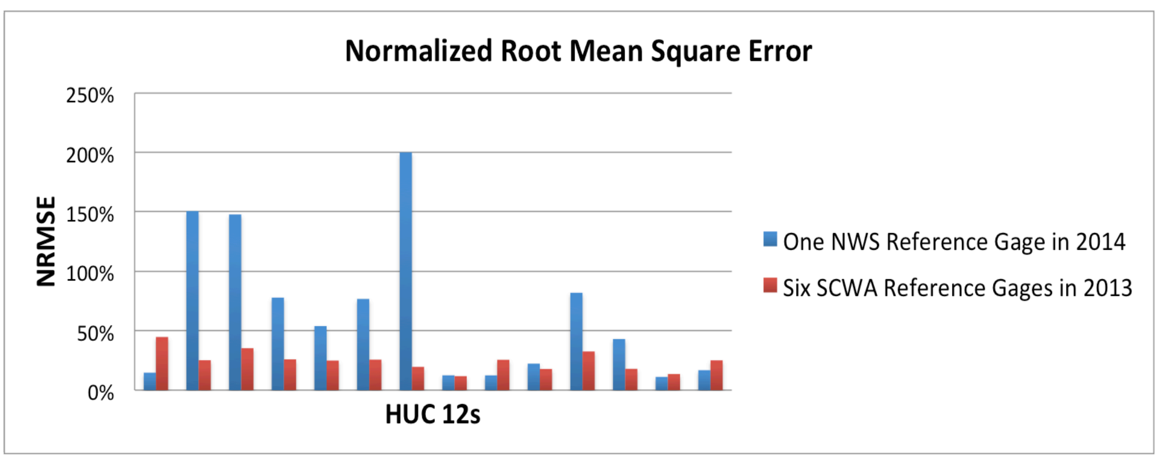


Figure 37. DWRAT-Flow prediction error using one vs. six reference gages for 14 HUC 12 locations.

Figure 38 and Table 3 compare the Nash-Sutcliffe efficiency (NSE) between the one-NWS-reference gage method and six-SCWA-reference gage method. The NSE is used to measure the accuracy of the flow model's predictions. Furthermore, it is dimensionless and can range from $-\infty$ to 1. A value of 1 indicates that the modeled flow perfectly represents gaged flow. A negative value suggests that the modeled predictions are less accurate than the mean of the gaged data (Kobor & O'Connor, 2016). The NSE is computed by subtracting the ratio of mean squared error to gaged flow variance from one, as shown in Equation 12 (Gupta, et al., 2009). $Q_{G,t}$ represents gaged flow and $Q_{D,t}$ represents DWRAT's modeled flow at time t.

$$NSE = 1 - \frac{\sum_{t=1}^{n}\left(Q_{G,t} - Q_{D,t}\right)^2}{\sum_{t=1}^{n}\left(Q_{G,t} - \overline{Q_{G,t}}\right)^2} \qquad \text{(Eq. 12)}$$

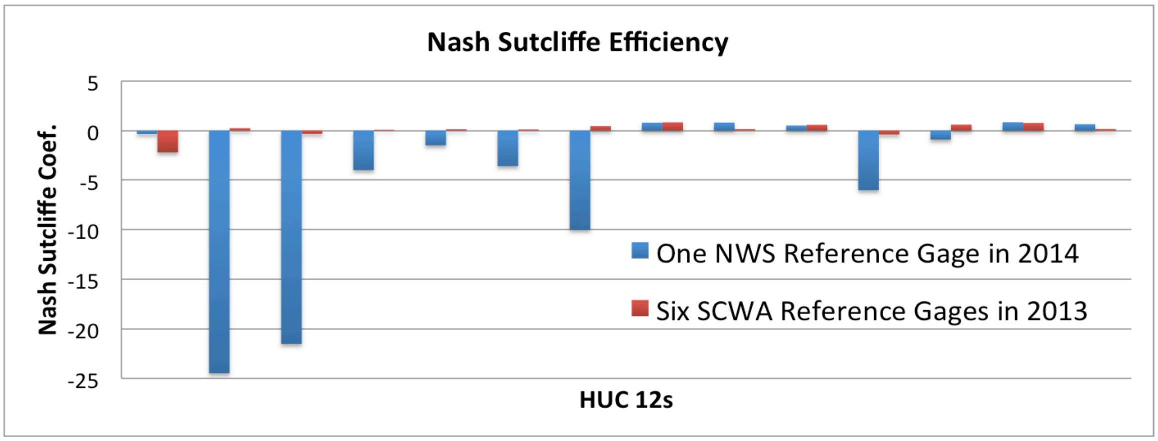


Figure 38. Nash Sutcliffe Efficiency for DWRAT-Flow predictions using one vs. six reference gages for 14 HUC 12 locations.

HUC 12	One NWS Gage in 2014	Six SCWA Gages in 2015
180101100103	-0.342	-2.200
180101100203	-24.49	0.238
180101100302	-21.53	-0.329
180101100405	-3.989	0.070
180101100407	-1.490	0.134
180101100411	-3.585	0.114
180101100507	-10.00	0.448
180101100604	0.790	0.823
180101100605	0.801	0.150
180101100703	0.508	0.576
180101100704	-6.015	-0.394
180101100706	-0.914	0.597
180101100802	0.837	0.760
180101100903	0.640	0.159

Table 3. Nash Sutcliffe Efficiency for DWRAT-Flow predictions using one vs. six reference gages for 14 HUC 12 locations.

The six-reference gage method yields better NSE values (closer to 1) than does the one-reference gage method for 10 of the 14 sub-basins. Furthermore, the one-reference gage methods produce eight negative NSE values while the six-reference gage method produces three that are only slightly below zero. Overall, flow predictions are significantly more accurate with the six-reference gage method than the one-reference gage method.

Although using more reference gages would improve DWRAT's unimpaired flow estimates, the NWS's Healdsburg gage is the only unimpaired flow gage estimate currently in the Russian River. However, flow forecasts from regular streamflow gages in the river could be converted to unimpaired flow forecasts using scaling ratios of SCWA's historical unimpaired flow estimates to Grantham's unimpaired flow estimates.

Figures 37 and 38 do not perfectly compare the performance level of one-reference-gage and six reference gages since the hydrologic conditions in 2013 and 2014 differ. However, comparisons of the two methods for the same year are currently infeasible since the SCWA's reference gages can only be used from 1910 to 2013 and the NWS's reference gage can only be used from 2014 to present. As more unimpaired flow data become available, more direct assessments between the two methods can occur.

Monte Carlo Analysis

Chapter 4 presents a method of using DWRAT to estimate water reliability for each right holder. This approach can be extended with Monte Carlo simulation to include uncertainty in unimpaired flow estimates and scaling ratios. Monte Carlo modeling involves creating a large number of statistically representative input data sets, where each data set is considered equally probable. Each input data set is run through a simulation model so that a large number of representative output data sets can be obtained and used to infer probability distributions for the output variables (Lund, 2014).

This Monte Carlo approach has been applied to DWRAT to estimate probabilities of curtailment in July based on 2010-2013 reported use. Randomly generated scaling ratios and unimpaired flows at Healdsburg are used as input values for DWRAT's flow-forecasting model. These random values are generated using their probability distributions and Excel's Random Number Generator function. Historical records for July show that July unimpaired flow at Healdsburg is normally distributed with a mean of 353 ac-ft/d and a standard deviation of 115 ac-ft/d. The probability distributions for the scaling ratios vary for each sub-basin. DWRAT has been run for 1,000 combinations of these randomly generated unimpaired flows and scaling ratios. For each run, DWRAT outputs a unique set of water allocation decisions. The frequency at which DWRAT curtails a water right can be used to infer water reliability for each user.

Figure 38 shows the probability of curtailment for each user in July using Monte Carlo analysis. Comparisons between Figure 38 and Figure 16 help show how scaling ratio uncertainty affects water reliability computations. Both figures show similar trends; however, by including scaling ratio uncertainty, the probability of curtailment for many users increases. Including scaling ratio uncertainty does not increase water reliability for any user in the watershed and the likelihood of curtailment for several appropriative users almost doubles. Only those with 0% or 100% chance of being curtailed are unaffected by including scaling ratio uncertainty.

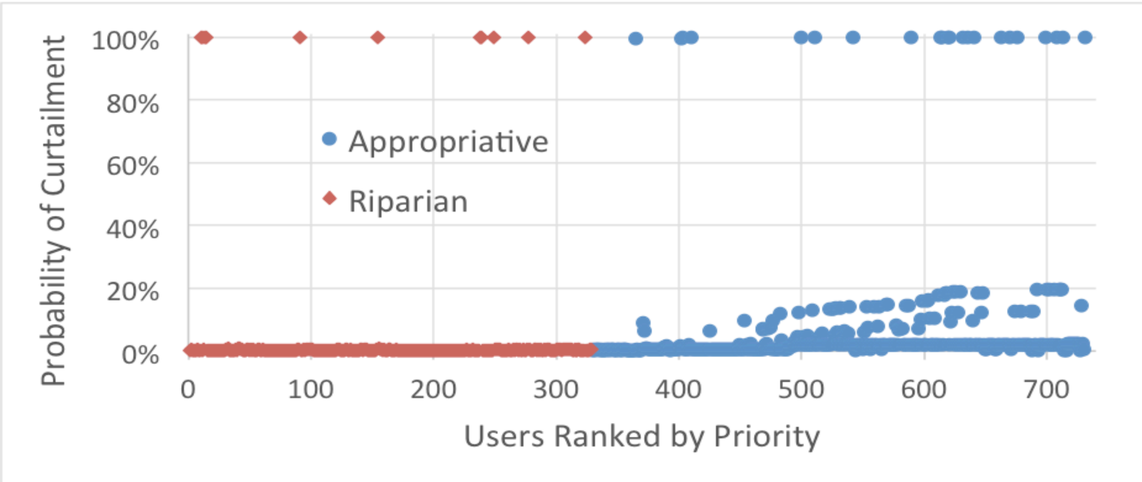


Figure 39. Probability of Curtailment using Monte Carlo modeling for Uncertainty in Unimpaired Flow- forecasts and Scaling Ratios.

Figure 40 shows the same curtailment probability chart without users from the uppermost sub-basin. By accounting for scaling ratio uncertainty, Group A (as shown in Figure 17) splits into two groups. This separation likely results from differences in the standard deviations of scaling ratios at various sub-basins. HUC 12s with large scaling ratio variance are more affected by scaling ratio uncertainty than are sub-basins with low scaling ratio variance.

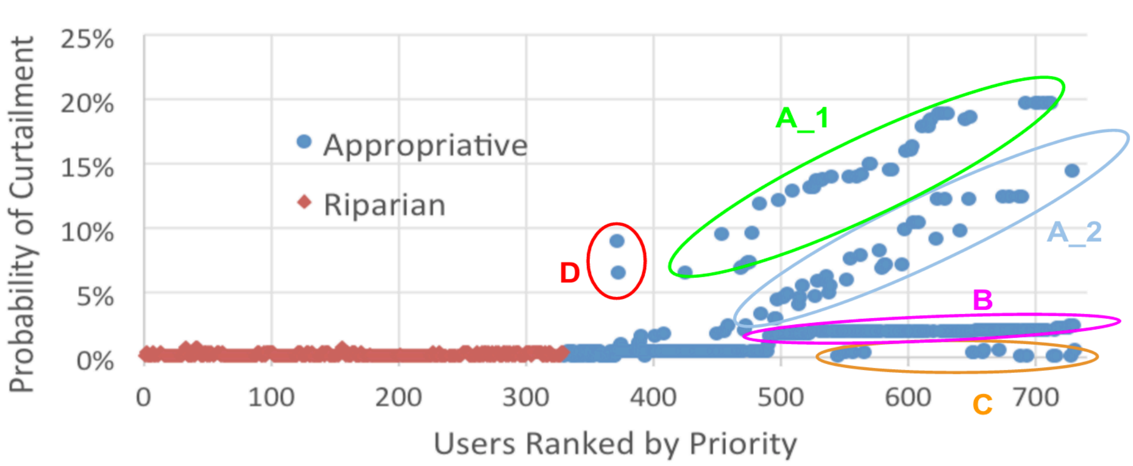


Figure 40. Probability of Curtailment using Monte Carlo modeling, excluding Users in the Uppermost Sub-basin.

For example, one appropriative right holder in HUC 12 180101100403 (Orrs Creek) has a priority ranking of 647 and a 19% probability of curtailment while another right holder in HUC 12 180101100404 (Robinson Creek) has a priority ranking of 648 and a 12% probability of curtailment. Neglecting scaling ratio uncertainty, the probability of curtailment for both users is roughly 10%. In July, the standard deviation of scaling ratios for Orrs Creek is 0.026 while the standard deviation of scaling ratios for Robinson Creek is only 0.002. Consequently, the probabilities of curtailment for users in Orrs Creek are more significantly affected by scaling ratio uncertainty than are those for users in Robinson Creek.

Monthly curtailment decision rules could be constructed using the probabilities of curtailment shown in Figures 38 and 39 to account for uncertainty in DWRAT's flow-estimates. However, including scaling ratio uncertainty allows for infinite combinations of scaling factors. As a result, DWRAT may release users from curtailment at varying Healdsburg flows, which implies that users no longer have constant curtailment thresholds. Therefore, curtailment decision rules cannot be created using curtailment thresholds. Instead, curtailment decisions could be conditioned on the likelihood of users being curtailed given unimpaired flow forecasts at Healdsburg. For instance, a "probability of curtailment threshold" could be used to determine which users to curtail for various unimpaired Healdsburg flows. For example, if the probability of curtailment threshold is set to 80%, then users with 80% or more likelihood of being shorted by DWRAT for a particular unimpaired Healdsburg flow would be curtailed.

Chapter 6 – Conclusions and Further Work

DWRAT combines mathematical representations of California's water law doctrines with data on water right holder priorities, water use quantities, and estimates of water availability to fully allocate water across basins with spatially varying supply and demand. As water demand increases and water supply declines, administration of water rights will become more challenging. Using public data and software, DWRAT can aid the SWRCB in making water right curtailment decisions. DWRAT's transparent and data-based approach also can help inform water right holders of current and likely curtailment conditions for various hydrologic conditions. The approach also would allow water users with insufficient water availability to more easily identify which users have high water availability, to aid in developing beneficial water trades and market transactions.

By using DWRAT to compute curtailment decisions for a range of hydrologic conditions, water reliability for users with varying priorities and varying local water availability can be estimated. This approach also can support curtailment decision rules conditioned on current and projected flow rates. Such rules could help the SWRCB make effective water right curtailments for each month of drought. However, DWRAT's water reliability estimates are subject to the accuracy of the underlying hydrologic model. Probabilities of error in DWRAT's flow estimates and scaling ratios can be used to more assess probabilities of curtailment for each water right. This can be useful both for water right curtailments as well as for the issuance of new water rights for different locations, seasons, and quantities.

Flow error analysis reveals significant current flow-prediction inaccuracies for sub-basins that maintain high levels of inflow and are further from DWRAT's unimpaired flow reference gage. The hydrologic model can be improved with additional reference gages and increased historical unimpaired flow data. Although there is only one currently operating unimpaired flow gage in the Russian River, flows recorded from regular streamflow gages could be scaled using unimpaired flow ratios from historical datasets to perhaps reduce these errors.

Further improvements and calibration methods to the hydrologic model are needed to improve DWRAT's water right curtailment suggestions and water reliability estimates. For example, ground water and surface water interactions should be included in the model to more accurately estimate water availabilities. Methods of including return flows into DWRAT's water allocation formulation are being developed for the Sacramento River DWRAT (Tweet, 2016). Methods of making more accurate unimpaired flow estimates also are being evaluated for the Sacramento River DWRAT (Magnuson, 2016). Once these methods have been established for the Sacramento River model, these approaches can be incorporated into the Russian River model.

References

Anderson, G. (2014). State Issues New Water Curtailment Orders, Plans Swifter Crackdown on Diversion. *The Press Democrat.* Retrieved from: http://www.pressdemocrat.com/csp/mediapool/sites/PressDemocrat/News/story.csp?cid=2371584&sid=555&fid=181

Breiman L. 2001. Random Forests. Machine Learning 45: 5-32.

Cahill, R., Lund, J., DeOreo, D., & Medellín-Azuara, J. (2013). Household Water User and Conservation Models using Monte Carlo Techniques. *Hydrol. Earth Syst. Sci*. 10(4):4869-4900.

California SWRCB. (2016). Statutory Water Rights Law and Related California Code Sections.

Carlisle DM, Falcone J, Wolock DM, Meador MR, Norris RH. 2010. Predicting the natural flow regime: models for assessing hydrological alteration in streams. River Research and Applications 26: 118-136.

Cutler DR, Edwards Jr TC, Beard KH, Cutler A, Hess KT, Gibson J, Lawler JJ. 2007. Random forests for classification in ecology. Ecology 88: 2783-2792.

Davis, D., Kisiel, C., & Duckstain, L. (1972). Bayesian Decision Theory Applied to Hydrology. *Water Resources Research – An AGU Journa*l.

Falcone J. 2011. Gages-II: Geospatial Attributes of Gages for Evaluating Streamflow. Accessed January 9, 2014 at: http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml

Gates, T., Wets, R., & Grismer, M. (1989). Stochastic Approximation Applied to Optimal Irrigation and Drainage Planning. *Journal of Irrigation and Drainage Engineering*, Vol. 115, Issue 3.

Grantham, T. (2014). California Water Rights Model – Supply Estimation*. University of California Davis, Center for Watershed Sciences.*

Gupta, H., Kling, H., Yilmaz, K., & Martinez, G. (2009). Decomposition of the Mean Squared Error and NSE Performance Criteria: Implications for Improving Hydrological Modelling. *Department of Hydrology and Water Resources, the University of Ariona.*

Hollinshead, S. & Lund, J. (2006). Optimization of Environmental Water Purchases with Uncertainty. *Water Resources Research – An AGU Journa*l, Vol .42.

Jenkins, M. & Lund, J. (2000). Integration Yield and Shortage Management Under Multiple Uncertainties. *Journal of Water Resources Planning and Management,* ACE, New York.

Liaw A, Wiener M. 2002. Classification and Regression by random Forest. R news 2: 18-22.

Lund, J. (2014). Probabilistic Design and Optimization. *University of California, Davis.* Version December 2014.

Magnuson, B. (2016). Using Machine Learning to Statistically Predict Natural Flow: The Sacramento Watershed under Dry Conditions. *University of California, Davis.*

Kaiser, A. (2002). Handbook of Texas Water Law. *Texas Water Resources Institute.* Retrieved from: http://texaswater.tamu.edu/resources/2002-037_waterlaw.pdf

Kennedy, C. (2014). Who Rules California's Russian River? *National Oceanic and Atmospheric Administration.* Retrieved from: https://www.climate.gov/news-features/features/who-rules-californias-russian-river

Kobor, J. & O'Connor, M. (2016). Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning: Green Valley\Atascadero and Dutch Bill Creek Watersheds. *O'Connor Environmental, Inc.*

Labadie, J. (2007). MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation. *Department of Civil and Environmental Engineering, Colorado State University*. Retrieved from: ftp://dwrftp.state.co.us/cdss/projects/MODSIM/MODSIMv8.1UserManual.pdf

Lee, J. & Labadie, J. (2007). Stochastic Optimization of Multireservoir Systems via Reinforcement Learning. *Water Resources Research – An AGU Journa*l, Vol. 43.

Lord, B. (2015). Water Rights Curtailments for Drought in California: Method and Eel River Application. *University of California Davis, Center for Watershed Sciences.*

Loucks, D. (1993). Implicit Stochastic Optimization and Simulation. *School of Civil and Environmental Engineering, Cornell University.* Ithaca, New York.

Mason, A.J. (2013). SolverStudio: A New Tool for Better Optimisation and Simulation Modelling in Excel. *INFORM Trans. Ed.* 14(1):45-52.

NOAA. (2014). Russian River Watershed. *Climate.gov*. Retrieved from: https://www.climate.gov/news-features/features/who-rules-californias-russian-river

Center for Environmental Economic Development. (2002). A River in the Balance: Benefits and Costs of Restoring Natural Water Flows to the Eel River. *Friends of Eel River, Redway, CA.* Retrieved from: http://www.eelriver.org/pdf/EelEconReport1.pdf

Scott, C. & Nowak, R. (2003). "The Q-function". *Connexions*. Retrieved from: http://cnx.org/contents/hDU5uzaA@2/The-Q-function

SCWA. (2016). General Plan 2020 Draft Environmental Impact Report. *Sonoma County.* Retrieved from: http://www.sonoma-county.org/prmd/docs/eir/gp2020deir/.

SCWA. (2016). Sonoma County Hazard Mitigation Plan Adopted 2011 Update. *Sonoma County*. Retrieved from: http://www.sonoma-county.org/prmd/docs/hmp_2011/chapters/ch3.pdf

SWRCB. (1961). In the Matter of Applications 12919A, 12920A, 15704, 15736, 15737, 15738, 15739, and 1577. *State of California Water Rights Board.* (Decision D 1030).

SWRCB. (1974). In the Matter of Applications 12947, 12948, 12949, and 12950 to Appropriate Water from East Fork Russian River and Russian River in Mendocino and Sonoma Counties. *State of California Water Rights Board.* (Order WR 74-30).

Tweet, A. (2016). Modeling Return Flows for Drought Water Right Curtailment. *University of California Davis*, *Center for Watershed Sciences.*

USGS. (2016). Current Conditions for Russian River near Healdsburg. *California Water Data Support Team.* Retrieved from: http://waterdata.usgs.gov/nwis/uv?

Wurbs, R. (2001). Reference and Users Manual for the Water Rights Analysis Package (WRAP). *Civil Engineering Department, Texas A&M University*. Retrieved from: http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/maps/wrap_manual.pdf

Appendix A

HUC 12	June	July	August	September	October
180101100101	0.023	0.022	0.023	0.023	0.022
180101100102	0.023	0.022	0.023	0.023	0.022
180101100103	0.131	0.133	0.135	0.132	0.132
180101100201	0.065	0.066	0.061	0.060	0.063
180101100202	0.044	0.046	0.044	0.043	0.042
180101100203	0.263	0.267	0.260	0.258	0.261
180101100301	0.042	0.057	0.040	0.043	0.041
180101100302	0.113	0.157	0.108	0.112	0.111
180101100401	0.027	0.028	0.025	0.025	0.024
180101100402	0.022	0.022	0.022	0.022	0.020
180101100403	0.339	0.344	0.335	0.333	0.337
180101100404	0.033	0.035	0.033	0.033	0.033
180101100405	0.427	0.446	0.424	0.423	0.410
180101100406	0.019	0.018	0.020	0.020	0.019
180101100407	0.470	0.491	0.470	0.468	0.471
180101100408	0.052	0.051	0.053	0.053	0.052
180101100409	0.047	0.065	0.048	0.049	0.044
180101100410	0.627	0.631	0.632	0.630	0.626
180101100411	0.771	0.751	0.769	0.767	0.765
180101100501	0.024	0.022	0.020	0.021	0.022
180101100502	0.047	0.046	0.046	0.046	0.044
180101100503	0.054	0.050	0.044	0.045	0.048
180101100504	0.182	0.178	0.165	0.166	0.168
180101100505	0.035	0.032	0.029	0.029	0.032
180101100506	0.033	0.031	0.030	0.030	0.030
180101100507	0.302	0.288	0.276	0.279	0.278
180101100601	0.822	0.800	0.820	0.818	0.816
180101100602	0.878	0.855	0.878	0.877	0.874
180101100603	0.031	0.030	0.030	0.031	0.029
180101100604	0.094	0.092	0.089	0.092	0.090
180101100605	1.000	1.000	1.000	1.000	1.000
180101100701	0.073	0.070	0.077	0.078	0.066
180101100702	0.072	0.069	0.070	0.071	0.065
180101100703	0.096	0.092	0.097	0.098	0.088
180101100704	0.207	0.201	0.214	0.216	0.186
180101100705	0.033	0.032	0.033	0.034	0.031
180101100706	0.313	0.307	0.320	0.322	0.287
180101100801	0.053	0.048	0.041	0.042	0.047
180101100802	0.119	0.150	0.091	0.092	0.107
180101100901	0.050	0.047	0.048	0.048	0.045
180101100902	1.651	1.610	1.636	1.640	1.576
180101100903	1.768	1.709	1.754	1.758	1.690
180101100904	1.923	1.843	1.876	1.884	1.825

Table 4. Mean of Scaling Ratios (Based on Grantham's 1950-2011 Unimpaired Flows).

HUC 12	June	July	August	September	October
180101100101	0.002	0.001	0.000	0.000	0.002
180101100102	0.002	0.001	0.000	0.000	0.002
180101100103	0.011	0.006	0.001	0.004	0.008
180101100201	0.010	0.005	0.001	0.003	0.004
180101100202	0.004	0.002	0.000	0.002	0.002
180101100203	0.022	0.013	0.002	0.009	0.014
180101100301	0.005	0.003	0.000	0.001	0.003
180101100302	0.013	0.009	0.001	0.003	0.008
180101100401	0.004	0.002	0.000	0.001	0.002
180101100402	0.002	0.001	0.000	0.000	0.001
180101100403	0.028	0.016	0.002	0.011	0.018
180101100404	0.003	0.002	0.000	0.001	0.002
180101100405	0.033	0.020	0.003	0.014	0.021
180101100406	0.002	0.001	0.000	0.000	0.001
180101100407	0.034	0.021	0.003	0.014	0.024
180101100408	0.004	0.002	0.000	0.001	0.003
180101100409	0.004	0.005	0.000	0.001	0.002
180101100410	0.035	0.020	0.004	0.012	0.027
180101100411	0.023	0.022	0.004	0.010	0.020
180101100501	0.004	0.002	0.000	0.001	0.003
180101100502	0.004	0.002	0.000	0.001	0.003
180101100503	0.011	0.006	0.001	0.003	0.012
180101100504	0.026	0.017	0.002	0.006	0.022
180101100505	0.007	0.003	0.001	0.002	0.008
180101100506	0.005	0.003	0.001	0.001	0.006
180101100507	0.044	0.029	0.004	0.009	0.039
180101100601	0.021	0.022	0.003	0.010	0.016
180101100602	0.020	0.022	0.003	0.008	0.014
180101100603	0.006	0.002	0.000	0.001	0.004
180101100604	0.014	0.008	0.001	0.003	0.013
180101100605	0.000	0.000	0.000	0.000	0.000
180101100701	0.017	0.007	0.001	0.004	0.007
180101100702	0.014	0.005	0.001	0.003	0.010
180101100703	0.017	0.006	0.001	0.004	0.013
180101100704	0.041	0.014	0.002	0.009	0.018
180101100705	0.007	0.002	0.000	0.001	0.003
180101100706	0.059	0.018	0.003	0.012	0.028
180101100801	0.012	0.007	0.002	0.004	0.017
180101100802	0.029	0.022	0.005	0.009	0.043
180101100901	0.010	0.002	0.001	0.002	0.009
180101100902	0.130	0.045	0.007	0.023	0.071
180101100903	0.145	0.049	0.008	0.030	0.088
180101100904	0.161	0.055	0.015	0.044	0.118

Table 5. Standard Deviation of Scaling Ratios (Grantham's 1950-2011 Flow Estimates).