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Drought water right curtailment analysis for California's Eel River

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Abstract

Water users in California's hybrid water rights system have different priorities to available surface water in times of water scarcity. A set of two linear programming models was developed to determine curtailments of water uses under drought conditions according to riparian and appropriative water right doctrines with spatially varying water availability and water rights within a basin. The models were implemented in spreadsheets and extended to estimate water right reliability and factors of safety in water right administration. Alternate methods for calculating water use curtailments are discussed. Curtailments from the models are compared to actual water shortage notices issued by the state for the Eel River, California for June 30, 2014. Analyzing water use curtailments with an algorithm in spreadsheet software offers a mechanistic, transparent, accessible, and precise approach derived from legal doctrines to support water rights administration during drought.

Introduction

Droughts often require users to curtail their water right diversions. Escriva-Bou et al (2016) review the curtailment of water rights, requiring some water right holders to cease or reduce diversions, in various western states and arid countries. This paper presents mathematical formulations and an example application of formal methods to fully allocate limited water supplies in California's hydrid system of surface water rights. Our approach mathematically represents the logic of riparian and appropriative water law doctrines for a basin with spatially varying available water supply and water demands. By representing California's water rights law as an allocation algorithm using linear programming, this Drought Water Rights Allocation Tool (DWRAT) provides a precise, timely, and transparent analytical framework for the complicated and often controversial process of curtailing water rights use during drought.

California's water rights and drought

Surface water rights in California predominantly follow the prior appropriation and riparian water law doctrines. Riparian rights were introduced by the adoption of English common law under California's constitution. Riparian right-holders are equal in priority and entitled to the natural flow of the water body for direct uses on their riparian land, without storage, so long as downstream users are not "unreasonably affected." The doctrine of prior appropriation was developed for resolving water claim disputes for available water among miners diverting water from streams for uses sometimes far from the point of diversion, possibly involving diversions to storage. The principle of "first in time, first in right" determines priority among appropriative water rights; early diverters have a higher priority than later diverters (Kanazawa 2015). To resolve growing conflicts among water right-holders, the 1886

California Supreme Court Case *Lux v. Haggin* ruled that riparian water rights categorically have a higher priority than appropriative water rights.

The 1913 California Water Commission Act (effective in 1914) established the predecessor of today's State Water Resources Control Board (SWRCB) to organize all new appropriations of water. All appropriative water right claims after this Act came into effect are "post-1914" appropriative water rights. Rights with dates of first use before January 1, 1914 are known as "pre-1914" rights. Riparian rights are established as a class, share shortages proportionally among each other, and have higher priority than any appropriative rights (Kanazawa 2015; Attwater and Markle 1987).

Over the next century, the SWRCB granted water right allocations exceeding five times the state's mean annual runoff (Grantham and Viersm 2014). Water rights in basins with particularly high allocations relative to natural availability, such as the Scott River, have been explicitly adjudicated as a result of legal conflicts among right holders. Over-allocation of basins (allocating more water than is normally available), coupled with the extensive impoundment of California rivers, decreases flow variability which in turn damages aquatic and riparian ecosystems (Kondolf and Batalla, 2005). Grantham et al (2014) demonstrate the need for transparent strategies during drought water years to preserve environmental flow protections while reducing water uses in an equitable manner.

Despite longstanding legal authority, the SWRCB first declared water shortages in 1977, and then not again until 2014. 2014 was the third consecutive year of drought in California, and the SWRCB issued mandatory curtailments (formally called water shortage notices), supported by a declaration of drought emergency by Governor Jerry Brown. In May 2014, the Scott River was the first watershed with issued curtailments. In the following months, junior right-holders in the Sacramento, San Joaquin, Russian, and Eel river basins also were curtailed.

Water allocation models

Several previous water allocation models use water rights for prioritizing users and demands (Wang et al. 2007). The Texas Water Availability Modelling (WAM) system (Wurbs, 2005) allocates streamflow and reservoir storage among right-holders with a prior appropriation doctrine. Many models represent priority-based water operations with different delivery, flow and storage priorities (Sigvandason, 1976), such as CalSim (Draper et. al. 2004) and ModSim (Fredericks et. al. 1998). Linear or network flow optimization often are used to represent priority-based operations. Appropriative water right priorities can be represented through cost coefficients, with junior lower-priority rights having lower penalties for shortage. Israel and Lund (1999), Ferreira (2007), and Chou and Wu (2014) extend this approach with algorithms for determining cost coefficients accounting for return flows.

Despite an extensive literature on mathematically allocating water under the appropriative doctrine, few published methods exist on allocation under the riparian doctrine. In California, riparian water right-holders (riparians), are equal in priority to each other but categorically have a higher priority than appropriative water right-holders (appropriators).

Drought water rights allocation tool (DWRAT) formulation

DWRAT allocates water for rights under both major doctrines using spreadsheets and a free and open source solver platform. DWRAT operates in two phases. The first phase distributes available water proportionally among riparian right-holders. The second phase allocates remaining available surface water by strict priority among appropriative right-holders. In both phases, water users are scattered over a network of sub-basins with local water availabilities (initially without return flows). Total flow v into sub-basin k is represented by v_k. Each user i has a normal use of u_i and receives water allocation A_i. Riparian users have unranked equal priority. Curtailment decisions among riparians limit diversions to a proportion of normal individual use varying by sub-basin P_k, with a weighted penalty coefficient of w_k.

These proportions determine a user's shortage. The shortage penalty weight per sub-basin w_k increases with the number of upstream basins u_k to balance proportions across sub-basins. Appropriative users have fixed priorities established by water right seniority. The unit shortage penalty p_i increases with seniority of right; minimizing shortages to senior right-holders reduces total penalty more than for junior right-holders. To assess allocations having mixed riparian and appropriative water rights, the riparian linear program is run first, followed by the appropriative linear program.

This overall approach represents the logic of each water law doctrine mathematically, to allow implementation in software. Figure 1 illustrates DWRAT's data flow. DWRAT models are run for a single daily time step, large enough to avoid issues of hydrologic routing for small basins.

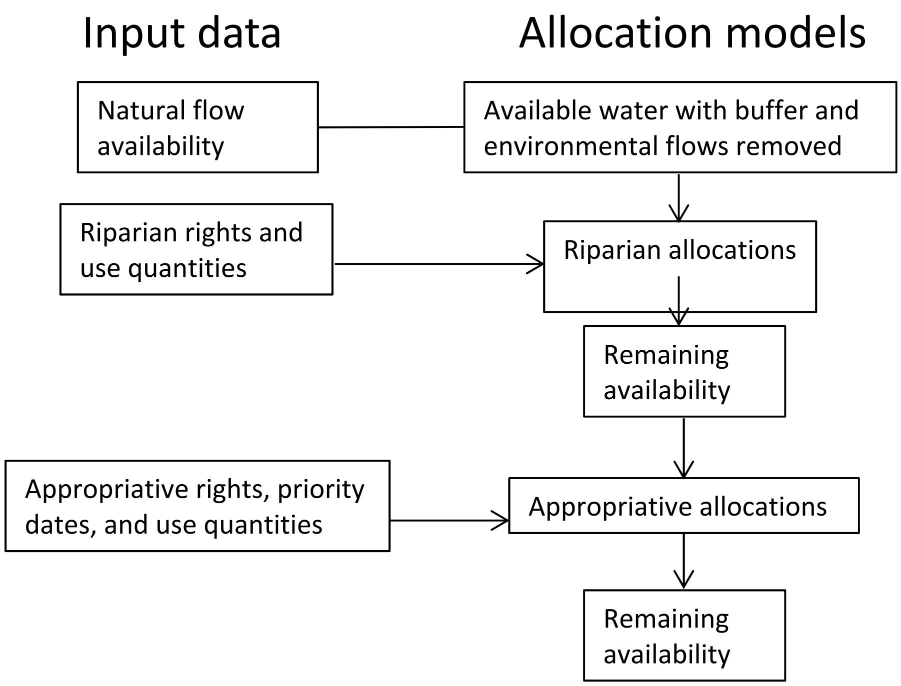

Figure 1 – DWRAT data flow. Boxes on left indicate required input data. Boxes on right indicate phases of allocation and reductions in availability.

Riparian allocation formulation

Riparian right-holders are equal in priority with water shortages distributed by restricting use proportionally across all basin users. Locally varying water availability can lead to differing proportional shortages within a basin. The following equations represent the logic of riparian water allocation.

The allocation, A_i for a riparian user *i,* is defined in Equation 1. All users in a sub-basin *k*, receive the same allocation proportion P_k of demand u_i, where P_k is a decision variable.

$$A_i = P_k u_i, \qquad \forall i, i \in k \quad (Equation\ 1)$$

The sub-basin allocation proportion, P_k is constrained between zero and one (Equation 2), enforcing allocations between zero and normal use.

$$0 \leq P_k \leq 1, \forall k \qquad (Equation\ 2)$$

The sum of all allocations (net diversions) upstream of a sub-basin outlet cannot exceed the total availability of water leaving the sub-basin. Total availability is inflows upstream of the sub-basin outlet v_k, minus environmental outflow flow requirement e_k, and "buffer" outflow b_k (Equation 3). Environmental flows, specified by the user, occur as a constraint. Alternatively, environmental flows could be represented as a water right with a relative priority. Buffer flow is used as a factor of safety to incorporate errors in water availability and actual uses.

$$\sum_{i \in k} A_i \leq v_k - e_k - b_k, \forall k \quad (Equation\ 3)$$

The riparian objective function, Equation 4, maximizes total water allocations, with a weighting term to enforce allocation proportionally among water users.

$$Minimize\ z = \alpha \sum_k w_k P_k - \sum_i A_i \quad (Equation\ 4)$$

In drought, maximizing only total allocations for all riparian users can yield multiple optima. Upstream users could receive zero allocations despite local availability while downstream users receive full allocations. Alternatively, water available in upstream reaches could be allocated entirely to upstream users with large shortages downstream. Both outcomes fail to distribute water proportionally among riparian users. So weights are included in the objective function to enforce equitable proportional allocation of shortage among riparian right-holders. The following constraints define how equal proportionality of shortage with full allocation of available water is met.

Upstream users cannot have less shortage (a higher P_k) than downstream users. If upstream users have less shortage than downstream users, some upstream use could be allocated downstream so both sets of users receive the same proportion of shortage. This constraint is implemented in Equation 5, where the allocation proportion in any upstream sub-basin *j* cannot exceed the proportion of any downstream sub-basin *k*.

$$P_j \leq P_k, \forall k, j \in k \ (Equation\ 5)$$

This constraint would need to change foprinciple cases where natural flow decreases downstream from net losses to groundwater or lake and wetland evaporation.

All riparian users with local non-zero availability should receive allocations greater than zero. To prevent upstream users receiving zero allocations despite local availability and downstream users receiving large allocations due to increased availability (from not allocating that same water upstream), a weight is given to increasingly penalize high allocation proportions in downstream basins, as in Equation 6. The downstream penalty, w_k, increases with the number of sub-basins n_k upstream of sub-basin *k*'s outlet.

$$w_k = \frac{n_k}{n_{k,system\ outlet}} \quad (Equation\ 6)$$

The sum of the products of these weights and allocation proportions is further weighted in the objective function to allocate all available water proportionally. To prioritize allocating all water, the equality terms are given less weight. The weigh α cannot exceed the minimum of all sub-basin ratios of unit downstream penalty to total upstream demand (Equation 7).

$$\alpha < Min\left(\frac{w_k}{u_k}\right) \forall k \quad (Equation\ 7)$$

Equations 5, 6, and 7 provide counteracting weights to distribute shortage equally across a watershed while maximizing total allocations to riparian users.

Riparian allocation example

The example watershed in Figure 2 was created to test and demonstrate the riparian allocation linear program. Each of the 8 sub-basins (A-H) has local inflows. Available streamflow is given for the outlet of each sub-basin, with a fixed fraction for environmental flows. Flow characteristics are shown in Table 1 and user demands in Table 2.

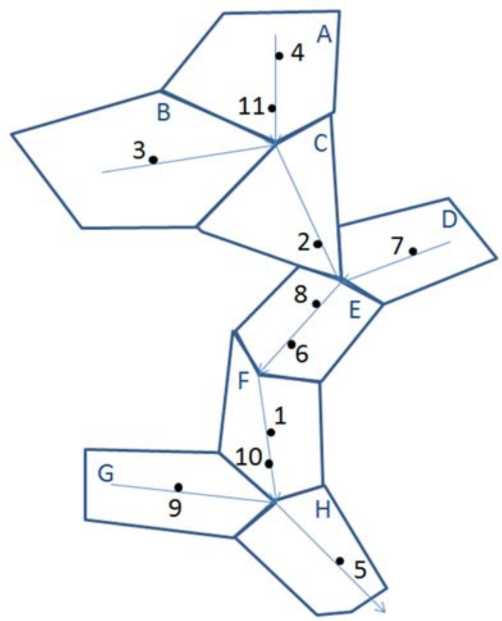

Figure 2 – Example watershed. Sub-basins are outlined and labeled A-H. Users are represented by black dots and labeled 1-11. Arrows indicate direction of flow.

Table 1 – Sub-basin hydrology. Flow units are volume/time.

Sub-basin	A	B	C	D	E	F	G	H
Local inflow	7	7	7	7	7	7	7	7
Cumulative flow (v)	7	7	21	7	35	42	7	56
Environmental flow (e)	1.4	1.4	4.2	1.4	7	8.4	1.4	11.2
Flow available to allocate	5.6	5.6	16.8	5.6	28	33.6	5.6	44.8

Table 2 – Riparian model results by user. Flow units are volume/time.

User:	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
Demand:	7	4	8	8	8	4	3	9	9	7	10
Allocation:	4.7	2.7	5.3	2.5	5.6	2.7	2.0	6.0	5.6	4.7	3.1
Proportion:	0.67	0.67	0.67	0.31	0.70	0.67	0.67	0.67	0.62	0.67	0.31

Tables 2 and 3 show user and basin results from the riparian water rights allocation model. Comparing allocations in sub-basins A and B shows insight into the riparian allocation mechanics. Basin A has a total upstream demand of 18 and a local availability of 5.6. If all flow available in A is allocated to users in A, the users would receive an allocation proportion of 0.31 (the ratio of upstream demand to availability). Basin B has a local availability of 5.6 and upstream demand of 8. If B's availability was completely allocated locally, User 3 would receive an allocation proportion of 0.7, which exceeds downstream ratios of supply to demand. Thus, B is curtailed further to reduce the shortage proportion downstream. No greater shortages occur downstream of Basin A, so all available flow is allocated locally. If unallocated flow is zero, upstream shortage exceeds potential downstream shortages. Availability directly limits upstream allocation and constraint Equation 3 binds. If unallocated flow exists, water is retained to lessen more severe shortages downstream.

Table 3 – Riparian model results by basin. Flow units are flow/time.

Basin	Allocation Proportion	Availability	Upstream demand sum	Upstream Allocation sum	Unallocated flow
A	0.31	5.6	18.0	5.6	0
B	0.67	5.6	8.0	5.3	0.3
C	0.67	16.8	30.0	13.6	3.2
D	0.67	5.6	3.0	2.0	3.6
E	0.67	28.0	46.0	24.2	3.7
F	0.67	33.6	60.0	33.6	0
G	0.62	5.6	9.0	5.6	0
H	0.70	44.8	77.0	44.8	0

The allocation proportion of 0.67, dictated by binding water availability (no unallocated flow) in catchment F, is extended upstream to catchments B, C, D and E, showing an even allocation of shortage across the larger area. Basins A and G have lower allocation proportions from more severe local shortages. Basin H has a binding water availability that forces an allocation proportion of 0.7, but this does not extend upstream due to still tighter shortages upstream. All available flow was allocated to users with no non-environmental flow leaving the system.

Appropriative allocation formulation

After riparian water right-holders receive allocations, remaining available water is allocated to appropriative right-holders by strict priority. The following mathematical formulation represents the logic of priority-based appropriative water rights, without return flows. Allocation for a user *i* is given by the decision variable A_i, between a maximum use u_i and a minimum of zero.

$$0 \leq A_i \leq u_i, \forall i \qquad (Equation\ 8)$$

Where a portion of use returns quickly to the sub-basin, each use u_i can be adjusted to represent net consumptive diversion. More complex cases are discussed by Israel and Lund (1999) and Ferreira (2007).

Similar to the mass balance for riparian users (Equation 3), the sum of all allocations upstream of a basin outlet cannot exceed the total water availability remaining after riparian allocations.

$$\sum_{i \in k} A_i \leq v_k - e_k - b_k - \sum_{i \in k} A_{upstream\ riparian\ users\ i}, \forall\ k\ (Equation\ 9)$$

Unlike riparian rights, appropriative water rights are curtailed by strict individual priority. The earliest right in a basin has the highest priority, and the most recent right has the lowest. Priority establishes unit shortage penalties for all users. The unit shortage penalty (p_i) equals the number of users minus priority rank, so the highest priority user has the highest unit shortage penalty. Shortage for a user is the difference between demand u_i and allocation A_i.

The objective function minimizes total shortage penalty for all users (Equation 10). Senior users have more weight in the objective function and are more likely to receive a full allocation. Likewise, junior users are less likely to receive an allocation.

$$Minimize\ z = \sum_i p_i(u_i - A_i) \qquad (Equation\ 10)$$

Appropriative allocation example

An appropriative allocation model was developed for the example watershed above (Figure 2), with the same user and basin characteristics (Tables 1 and 2). Here, all users have appropriative rights with User 1 having the highest priority and 11 the lowest. User and basin results from the appropriative water rights allocation model appear in Tables 4 and 5. User 1, on the main stem and with the highest priority, receives a full allocation whereas User 3, with a high priority but in the upper watershed, has less flow available. Thus, User 3 receives all flow available in subcatchment B, but still sees shortage, running out of water before running out of right. User 4 similarly receives all available flow in catchment A. User 11 in catchment A has a low priority and receives no water. As demands of senior users are met, remaining available flow is allocated to junior users by priority. All available water was allocated to users with no non-environmental flow leaving the system.

Table 4 – Appropriative model results by user. Flow units are volume/time

User/priority:	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Demand:	7	4	8	8	8	4	3	9	9	7	10
Allocation:	7.0	4.0	5.6	5.6	8.0	4.0	3.0	4.4	3.2	0	0
Shortage:	0	0	2.4	2.4	0	0	0	4.6	5.8	7.0	10.0

Table 5 – Appropriative model results by basin. Flow units are volume/time

Basin	Availability	Upstream demand sum	Upstream allocation sum	Unallocated flow
A	5.6	18.0	5.6	0
B	5.6	8.0	5.6	0
C	16.8	30.0	15.2	1.6
D	5.6	3.0	3.0	2.6
E	28.0	46.0	26.6	1.4
F	33.6	60.0	33.6	0
G	5.6	9.0	3.2	2.4
H	44.8	77.0	44.8	0

Combining water allocation methods

To assess allocations for basins with both riparian and appropriative water rights, the riparian linear program is run first, followed by the appropriative linear program. Riparians, having a higher priority overall, are less likely to be curtailed than appropriators. (California has some rare cases of very old appropriative rights with potentially higher priority than riparian users; these can be handled by pre-allocation of water to such users before riparian allocations in very dry circumstances.) Riparian right-holders in upper parts of the watershed are much more vulnerable to curtailment than downstream users. If any riparian is curtailed, all upstream riparians are consequently curtailed. Appropriators in upstream portions of watersheds are also more vulnerable to shortage due to low water availabilities and being curtailed to help meet downstream riparian demands.

Model limitations

All users within a subcatchment *k* are assumed to have physical access to all inflow (v_k). But some local inflow will enter downstream of some local users, restricting their access to some flow. This misrepresentation is reduced with increasing the spatial resolution of subcatchments. Ideally, each user would have a defined sub-basin, but this would greatly enlarge the problem. Error also could be reduced by restricting each user to the percentage of total sub-basin outflow available at the user's point of diversion. Also, some users have multiple points of diversion.

The maximum allocation for each user is their previous use u_i, reported under historical flow conditions. These may be less relevant during drought, particularly for riparian right-holders. Ideally, during drought water users would announce or “call” diversions for their right before each time period, allowing water right administrators to make more accurate and timely water allocations.

In times of drought, curtailed water users often replace lost surface water allocations with groundwater. However, DWRAT only includes surface water allocations and omits groundwater depletion effects on surface water availability. This may overestimate water availability, especially in longer droughts.

DWRAT currently omits return flows back to surface water. This reduces downstream water availabilities. Water uses such as hydropower and flood irrigation have high return flows to surface water. Israel and Lund (1999), Ferreira (2007), and Chou and Wu (2014) present methods for developing priority-based penalty coefficients for network flow and linear programming models of water resources system with return flows and appropriative rights. These algorithms could serve as pre-processors to account for return flows while preserving water rights priorities, or net surface water diversions could be used, assuming local return flows.

Another limitation is that estimates of water availability, use, and return flows are imperfect. Buffer flow represented in the mass balances (Equations 3 and 9) can provide a factor of safety by modifying availability. Positive buffer flow values decrease availability and increase curtailments, but reduce likelihood of over-promising water. Conversely, negative buffer values reduce curtailments, but are likely to over-promise water and increase likelihood of senior right-holders being deprived of water. Errors cannot be entirely eliminated or even entirely known without extensive monitoring. Higher buffer values increase the likelihood of false curtailments (when water is actually available) while lower (or negative) buffer flows increase false promises (when water is not actually available for a non-curtailed right-holder). Effects of uncertainty can be explored by varying the buffer flow to see the range of curtailments generated.

Estimating water right reliability

This section introduces a preliminary approach for estimating water supply reliability for individual water right holders given hydrologic variability. By varying the flow and conducting probabilistic analysis of results from DWRAT, the reliability of water allocations can be estimated for a set of users. The presented methods estimate the probability of water right curtailment in a basin given an uncertain basin outflow hydrology, with known net diversions and a fixed spatial distribution of water availability.

Any unimpaired outlet flow Q_n with a known distribution of local sub-basin inflows has a corresponding legally required set of curtailments $[C_n]$ composed of binary values 0 or 1 for each water right holder *i*, calculated by the methods above. When $C_i = 1$, user *i* is curtailed and receives less than their full water allocation. Uncurtailed users ($C_i = 0$) receive full allocations. Monte Carlo analysis and implicit stochastic optimization were used to estimate the probabilities of curtailment for individual users.

In Monte Carlo analysis, model input parameters are sampled from a probability distribution. For each sample, model output is recorded. This process is repeated many times to sample a large range of possible input values with realistic relative frequencies. Frequency analysis on the full set of model outputs can estimate the likelihood of a given curtailment solution over the range of possible input values.

For small or simple basins, water right reliability can be estimated by varying inflow over a probability distribution. For each outlet flow, the optimal curtailment set $[C_n]$ is calculated. The reliability of each right is the probability that there is a corresponding outflow which supplies that right, calculated either by numerical integration or by the ratio of samples where user i is curtailed divided by the total number of Monte Carlo samples.

Operating water systems under uncertainty can be complex and computationally intensive. Numerical estimation of uncertainty can be prohibitively complex. Implicit stochastic optimization (ISO) can reduce these problems by applying deterministic modeling over a representative range of input parameters. Initially, a representative range of model input parameters is generated. For each set of inputs, the model generates a single solution set. The probability of any solution is the probability of its corresponding inputs. Frequency analysis over the set of solutions estimates probabilities of curtailment.

Perhaps more useful, the full solution set can help establish a set of rules for real-time system curtailments. Administrators could observe current conditions and look up the corresponding optimal curtailments from the ISO results without additional model runs. ISO is most often employed to identify operating rules for reservoirs with uncertain inflows (Young 1967; Lund and Ferreira 1996). Operations are optimized over a long representative time-series of inflows with perfect foresight using deterministic methods. The results are then used to infer optimal operating rules.

For this application of ISO, stochastic operation of a water rights system is considered from administrator and user perspectives. To estimate water right reliability with ISO, a range of outlet flows Q_n is selected. DWRAT calculates [C_n] for each outlet flow Q_n. The probability of a curtailment occurring is the probability of the lowest Q_n when the curtailment occurs. For simple systems, each user *i* has a corresponding "curtailment threshold flow" Q_{ti}. When the outlet flow is below Q_{ti}, user *i* is curtailed and receives less than a full allocation. By stepping through a range of Q_n values and solving the allocation models, the curtailment threshold flow can be identified for each user. The probability of a user curtailment is the probability of Q_{ti}.

Example basin

The example watershed in Figure 2 was extended to test and illustrate these methods with a mix of riparian and appropriative users. The basin has 8 sub-basins (A-H), with local flow availability v_k equal to the outlet flow (basin H) multiplied by the ratio of upstream drainage area (a_k) to total basin drainage area (Equation 11).

$$v_k = Q_n * \frac{a_k}{a_{k,outlet}} \quad (Equation\ 11)$$

Outlet flow is normally distrubted (for illustration) with a mean of 60 and standard deviation of 30, truncated at zero. Other flow distributions could be employed. Local inflows to each sub-basin are assumed to be a fixed fraction of unimpaired outlet flow. Users R1 through R5 have riparian rights (equal priority). Users A1 through A11 have appropriative rights and with priority given by their label number (A1 has highest priority). Figure 3 shows the users' locations and Table 6 shows demand for each user. (Method results are in lower rows.)

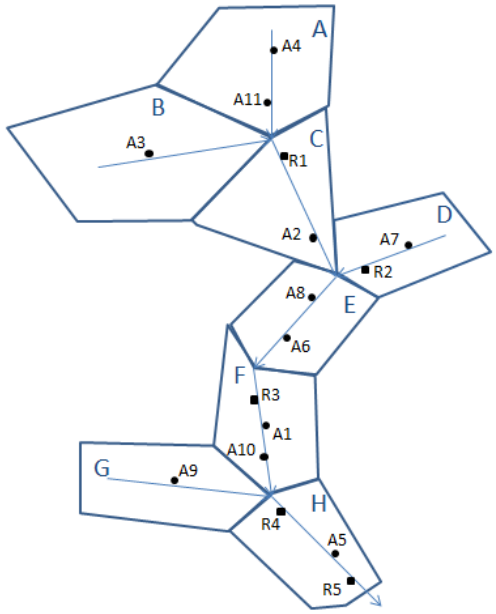

Figure 3 – Example basin with users

Table 6 – Example users and demand

User (ordered by priority)	R1	R2	R3	R4	R5	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Demand	4	6	8	2	7	7	4	8	8	8	4	3	9	9	7	10
Cumulative demand	27	27	27	27	27	34	38	46	54	62	66	69	78	87	94	104
Probability of shortage, Monte Carlo	0.105	0.390	0.105	0.105	0.105	0.190	0.235	0.555	0.555	0.535	0.565	0.630	0.75	0.80	0.875	0.995

Another way to represent the system is to view cumulative demand ranked by priority, as shown in the second-to-bottom row of Table 6. For a riparian user, cumulative demand is the sum of all riparian demand. For an appropriative user, cumulative demand equals the summed demand of higher priority users.

If all users had equal access to outlet flow, cumulative demand for user *i* would be the total amount that must be allocated before user *i* receives any water. However, the spatial variability of supply disrupts this relationship. This metric is most useful for appropriative right-holders due to their clear relative prioritization.

Monte Carlo analysis application

For the Monte Carlo analysis, $[C_n]$ was calculated for a randomly sampled Q_n from the normal error distribution. This process was repeated 500 times to form a statistically representative set. Frequency analysis over all sets of $[C_n]$ determined the reliability of water allocation for each user. The results of the frequency analysis appear in the lowest row of Table 6.

Probability of curtailment increases as priority decreases, with some deviations. Riparian users have the lowest probability of curtailment. However, user R2 is on a tributary branch and is much more likely to face local shortages than other riparian users. Similarly, users A3 and A4, high in the watershed, have higher probabilities of shortage than A5, with lower priority but on the main stem near the outlet.

Users A3 and A4 have the same shortage probability, despite A3's higher priority. Both users are on separate tributaries with independent availabilities, so the availability in basin A is less affected by water availability or curtailments in basin B, and vice versa. Users A3 and A4 are limited by availability and location, whereas user A5 is limited by priority.

Implicit Stochastic Optimization application

To estimate water right reliability with implicit stochastic optimization, [C_n] was calculated for each outlet flow Q_n ranging stepwise from 0 to 150 in increments of 1. As outlet flow increases, fewer users are likely to be curtailed, as shown in Figure 4. Each "step" in Figure 4 corresponds to a user or set of users receiving a full allocation. The flow value corresponding to the "step" at which a user receives a full allocation is the "curtailment threshold flow" Q_{ti}. When outlet flow is below Q_{ti}, user *i* is curtailed. If all users have access to outlet flow, the curtailment threshold would be the cumulative demand for all users. Varying spatial flow availability disrupts this relationship.

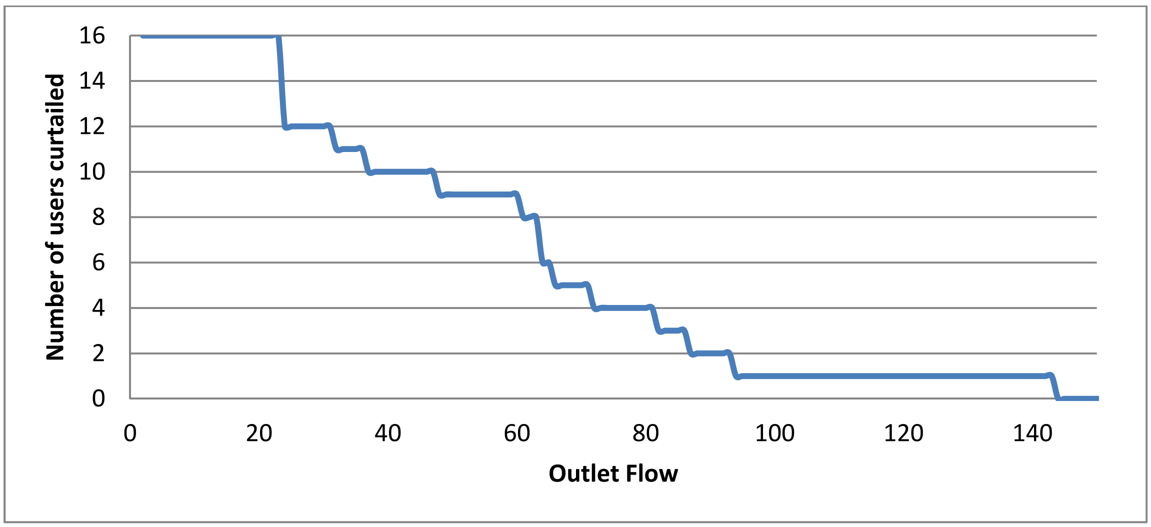

Figure 4 – Total number of curtailed users by outlet flow value

Figure 5 shows the cumulative demand and curtailment threshold for each user, assuming fixed ratios for sub-basin inflows to total basin unimpaired outflow. As a user's priority decreases, the corresponding cumulative demand and curtailment threshold increases. Users along the main branch of the river basin (subcatchments C, E, F, and H) have more access to flow and are less likely to see local supply shortages. Curtailment for these downstream users is generally dictated by priority. In Figure 5, cumulative demand and curtailment threshold values for these users are nearly equal. Users in the upper portions of the basin (subcatchments A, B, D, and G) are more likely to face curtailment from local flow shortages. This effect occurs for R2, A3, and A11, whose curtailment threshold significantly exceeds cumulative demand. User R2, despite sharing the highest priority with other riparians, diverts in a sub-basin (basin D) that is more likely to receive shortage. Because local flow availability is proportionate to outlet flow, user R2's curtailment flow threshold is the outflow sufficient in basin D to meet R2's demand. Their upstream locations make them more vulnerable to curtailment than similar priority users downstream.

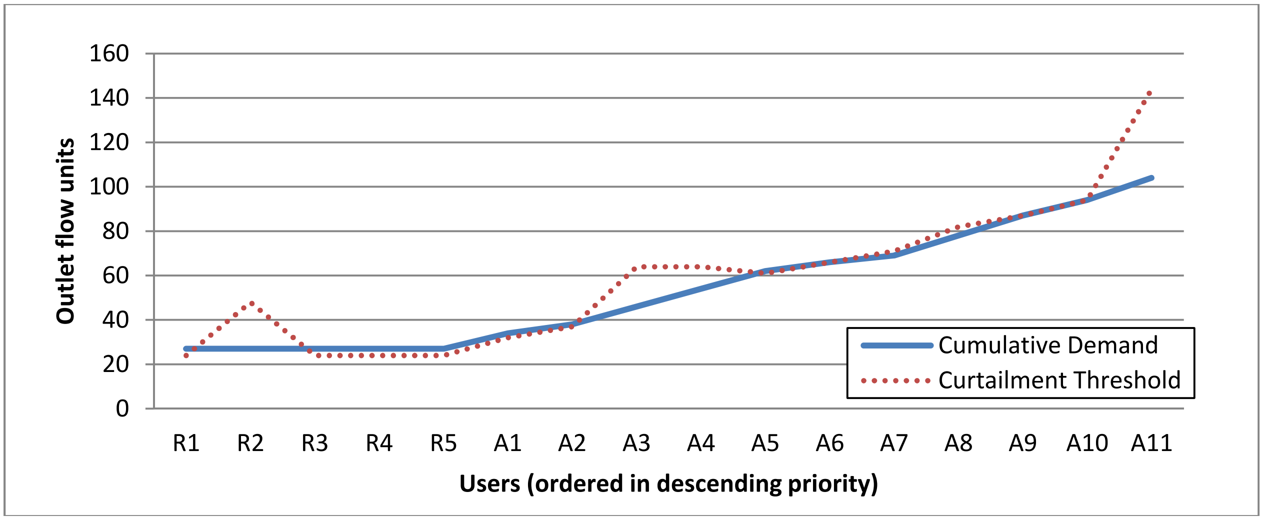

Figure 5 – Cumulative demand and curtailment threshold for all users

The probability of curtailment for a user *i* is then calculated as the probability that Q_n is less than or equal to Q_{ti}, the cumulative probability distribution function for Q. Figure 6 shows the probability of curtailment for each user, calculated by the ISO method. The Monte Carlo and ISO methods yield nearly identical curtailments. With more Monte Carlo iterations, the results should converge.

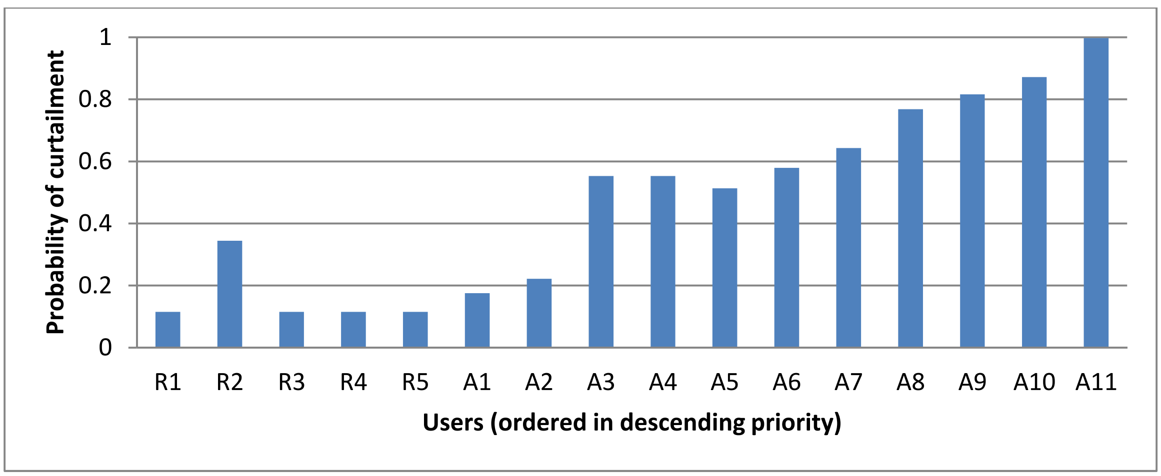

Figure 6 – Probability of curtailment for each user from implicit stochastic optimization (ISO) method

The probability of a individual water-right curtailment depends primarily on priority and location in the watershed. The results represent the probability that a water right *should* be curtailed given the forecast water availability Q and normally distributed error *σ*. However, actual probabilities of curtailment will differ from errors in estimating water demands, overall water availability, and its spatial distribution.

The presented methods might provide curtailment rules for water right administrators. When flow or forecasted flow at a nearby gage is below a specified value, some users are not allowed to divert water. This method of assigning curtailments has several advantages. DWRAT would no longer need to be run every time period for an entire basin, given known curtailment thresholds based on flow rates. Users would benefit from knowing the probability of curtailment, allowing for better planning of diversions.

Buffer Flows

Uncertainty in hydrologic forecasting can increase curtailment errors. Curtailments are likely to be calculated in advance based on a forecasted available flow and anticipated user diversions. However, actual flow and diversions may differ significantly, leading to errors in allocations. Including buffer flows can adjust curtailments for forecasting uncertainty by artificially reducing (or increasing) water availability. A higher positive buffer flow is a safety factor for senior right-holders to reduce the chance that water will be unavailable for them or environmental flows. However, this buffer requires additional curtailments for more junior right-holders. The methods below review errors caused by uncertainty and provide a framework for balancing buffer flow values and uncertainties.

False promises

When actual flow is less than forecasted, some users will be promised a full allocation, but will not have enough water available. *False promises* of water decrease with greater buffer flows. The average number of false promises, *E(FP),* can be defined as:

$$E(FP) = \int_{0}^{\infty} P(Q_{act}) FP\left(Q_{for}, Q_{act}, B\right) dQ_{act} \quad (Equation\ 12)$$

where:

$$FP\left(Q_{for}, Q_{act}, B\right) = Maximum \begin{cases} C(Q_{act}) - C(Q_{for} - B) \\ 0 \end{cases} \quad (Equation\ 13)$$

Equation 12 is the expected number of false promises over possible actual outlet flows Q_{act}, given a forecasted outlet flow Q_{for} and an outlet buffer flow *B.* False promises for a particular circumstance are defined in Equation 13 as the difference between number of curtailments with the actual flow and number of curtailments with the forecast flow minus the buffer.

False curtailments

Buffer flows increase cases when some users suffer curtailments, when the basin had sufficient flow for them to take water. These *false curtailments* increase with buffer flow values. Given the nomenclature above, the expected false curtailments, *E(FC),* can be defined as:

$$E(FC) = \int_{0}^{\infty} P(Q_{act}) FC\left(Q_{for}, Q_{act}, B\right) dQ_{act} \quad (Equation\ 14)$$

where:

$$FC\left(Q_{for}, Q_{act}, B\right) = Maximum \begin{cases} C\left(Q_{for} - B\right) - C(Q_{act}) \\ 0 \end{cases} \quad (Equation\ 15)$$

Equation 15 defines false curtailments as the difference between forecasted curtailments including buffer flow, and the ideal optimal curtailments with the actual outlet flow. Given uncertainty in water availability, there is always a likelihood of false promises and false curtailments, the balance of which is implicit in water rights administration policies and methods.

Example basin application

Equations 12 and 14 were applied to the example basin with varying buffer flows and an outlet flow forecast of 60. Figure 7 illustrates the effect of increasing buffer flows. With no buffer flow, 1.1 false promises and 2.6 false curtailments can be expected. Larger buffer flows make false curtailments more likely and false promises less likely. At a buffer flow exceeding 40, only 20 units of flow are available for allocation and the number of false promises and curtailments stabilizes as all users are curtailed.

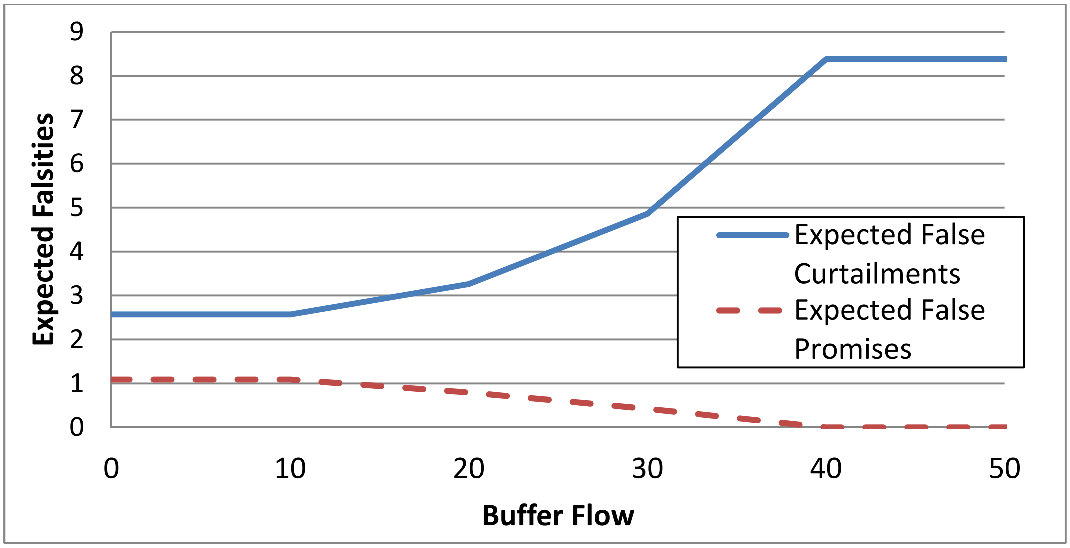

Figure 7 – Expected false promises and curtailments with varying buffer flow

Selecting a proper buffer flow may vary with the policy balancing of water rights administrators. If a basin administrator seeks to minimize total falsites, a buffer flow of zero would be optimal. However false promises may be more damaging than false curtailments (or vice versa). In this situation a buffer flow that would decrease the probabilty of false promises would be optimal, but at the cost of increasing false curtailments.

Here, only positive buffer values are evaluated. Negative buffer values, which would increase supply, would reduce the number of false curtailments and increase the number of false promises. If a water rights administrator seeks to minimize falsities, a range of buffer flow values should be explored. Also, only uncertainty in outflow is examined here. Other sources of uncertainty should be explored, such as sub-basin flow distribution and water demand. Methods for identifying probability of curtailment could be extended further. Monte Carlo analysis could identify users most likely to face false curtailments or false promises. False promises could result from upstream users withdrawing more than allocated, resulting in a physical absence of water for downstream users.

Applying DWRAT in the Eel River

The Eel River is the first basin for which DWRAT has been developed for application. The Eel River watershed on California's North Coast region has rugged terrain and a low human population density. The basin has an average annual precipitation of 60 inches, largely from November through March, and is mostly undeveloped. Lake Pillsbury and its forebay, Van Arsdale Reservoir, are the only significant storage projects. At Van Arsdale Reservoir, flow is diverted to the Russian River watershed via the interbasin Potter Valley Project (PVP).

Water Availability and Demands

The United States Geological Survey (USGS) operates 11 gages in the Eel. The lowest elevation gage, at Scotia, has records dating back to 1911, with a mean annual flow of 28,800 acre-feet/day (af/d).

Allocations in DWRAT rely on natural surface water flow estimates at the 12-Degree Hydrologic Unit Code (HUC12) scale. The National Weather Service (NWS) operates flood gages quantifying natural flow at three locations in the Eel River: Scotia, Fort Seward, and immediately downstream of Lake Pillsbury (ordered from downstream to upstream). A statistical model extrapolates these unimpaired

NWS flows to all ungaged HUC12 outlets using ratios of gaged to ungaged flow from a random forest model based on the USGS Gages-II database that predicts historical monthly flows at ungagged HUC12 locations (Carlisle et al., 2010). A series of scaling factors was calculated using these historical monthly flows. The scaling factors were then used to predict flow at ungaged locations with measured or forecasted flow at gaged locations (Lord 2015).

Water rights information on type of right, date of first use, and 2010-2013 monthly reported withdrawals for the Eel River is available from the SWRCB's Electronic Water Rights Information Management System. The dataset contains 206 riparian, 30 pre-1914 appropriative, and 447 post-1914 appropriative rights. Average monthly consumptive water demand is estimated by averaging the four years of use data and removing hydropower and other fully non-consumptive diversions. Daily demand is estimated in DWRAT by dividing the average monthly reported use by the number of days per month. This introduces some error, as water users rarely divert the same amount each day of a month. Figure 8 shows total average monthly demand for each water right category.

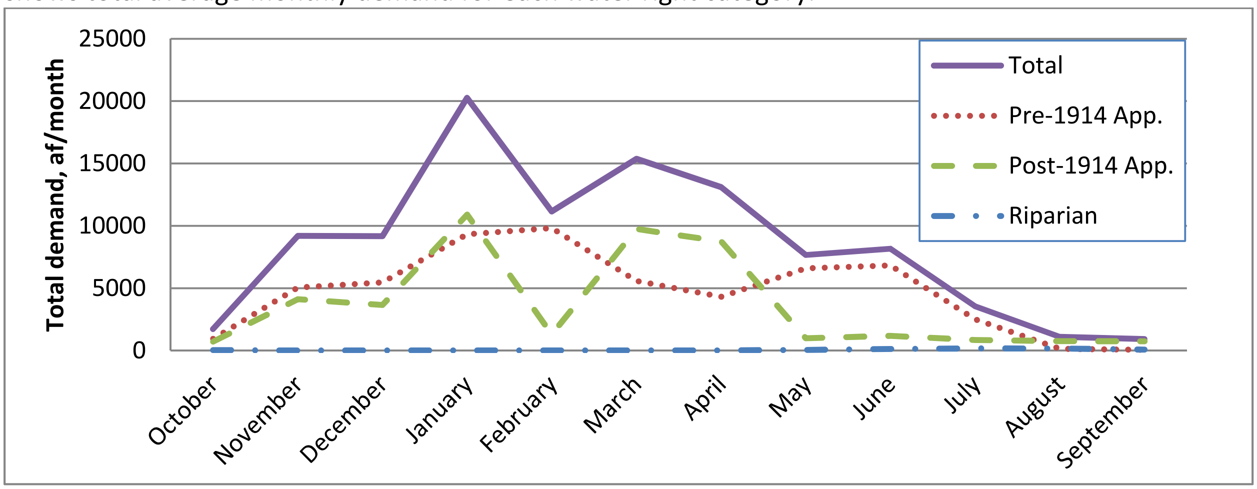

Figure 8 – Monthly water demand in the Eel River basin. Source: SWRCB

June 30, 2014, curtailments

On June 30, 2014, the SWRCB announced curtailments for all post-1914 water rights in the North Fork Eel River, Main Stem Eel River, and the Van Duzen tributary, with some exceptions. Curtailments could only be lifted once the SWRCB determined that "water is legally available for diversion under [a user's] priority of right" (SWRCB, 2014).

Table 7 summarizes the demand, by user group, for June 30. Of the 683 rights, 419 have non-zero demand for the day and are considered "active." The remaining 264 "inactive" rights have zero demand are excluded from the model. Pre-1914 appropriative rights are most use by volume, followed by post-1914 rights and riparian rights. Figure 9 shows the June 30 cumulative demand for all rights in the Eel River.

Table 7. Eel River water demand, June 30

Right Type	Number of active users, % of total	Demand, af/d (% of total)
Riparian	158 (38%)	4.6 (2%)
Pre 1914 App.	25 (6%)	228.0 (84%)
Post 1914 App.	236 (56%)	39.5 (14%)
Total:	419 (100%)	272.2 (100%)

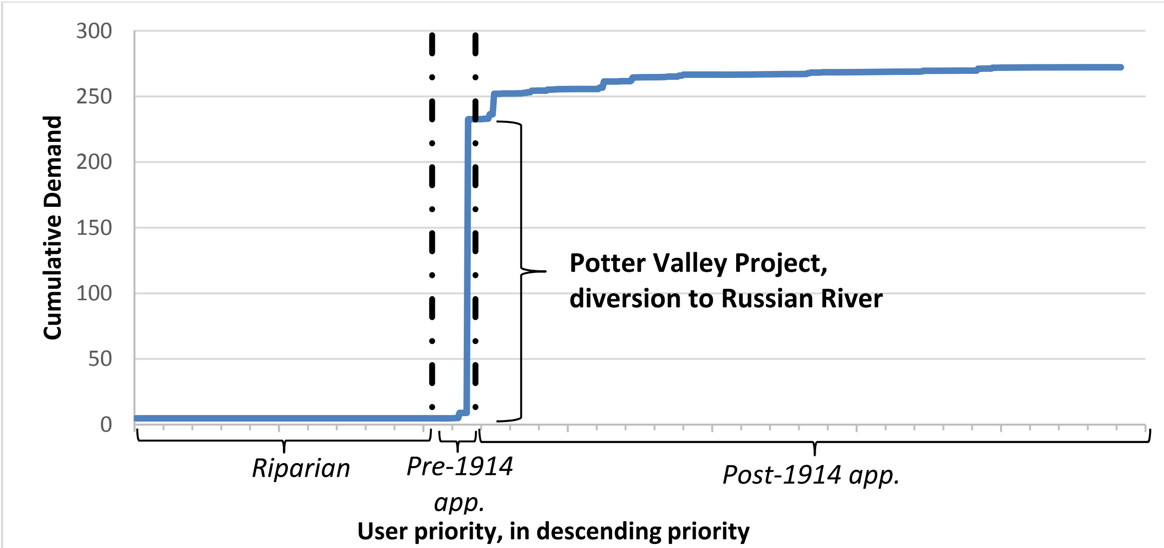

Figure 9 – June 30 cumulative water demand

Water use volume for June 30 in the Eel River is dominated by a few rights owned by the Pacific Gas and Electric Company (PG&E) for the Potter Valley Project (PVP), which transfers water from the Eel's headwaters to the Russian River's East Fork for hydroelectric power. The two largest rights are application numbers S001010 (231st in priority, first use in 1905 with June 30 estimated demand of 223.8 acre-feet/day—82% of total demand) and A006594 (249th in priority, first use in 1930 with June 30 estimated demand of 15.5 acre-feet/day).

DWRAT was used to estimate optimal curtailments for June 30, 2014 in the Eel River, with no buffer or environmental flows. 126 rights were curtailed (30% of all users). Curtailments included 46 riparian rights (29% of riparians), 6 pre-1914 rights (24% of pre-1914s), and 120 post-1914 rights (31% of post-1914s). In total, 24.9 acre-feet of water were allocated. Most curtailments were in HUC12 basins where supply is calculated using the NWS gage at Lake Pillsbury, which had an unimpaired flow of zero. This resulted in zero water available for allocation in all dependent HUC12s. About 75% of curtailed rights are in this part of the watershed, including the large Potter Valley Project diversions.

The SWRCB curtailed diversions for all post-1914 appropriative users, regardless of location in the watershed. The curtailments proposed in DWRAT incorporate spatial variability of flow and limit allocations where supplies are lowest. Many post-1914 appropriative users received full allocations using DWRAT, particularly in downstream locations. Shortage was allocated nearly proportionately among user classes and depended more on location than priority of right.

Extended DWRAT Application

DWRAT was used to calculate June 30 curtailments in the Eel River for previous historical years. The NWS only began providing unimpaired gage flow estimates in 2014, so an alternative source of unimpaired flows was developed. Three USGS impaired flow gages near the NWS sites were selected. The gage at Scotia has the longest record, dating to 1911. The other two stations, at Fort Seward and Lake Pillsbury, have much shorter records. Regression analysis was used to develop a trend for the overlapping records between these two stations and the Scotia gage. The trend was extended over the entire historical record to generate the synthetic impaired flows, with estimated diversions then returned to estimate 102 years of unimpaired flows (Lord 2015). DWRAT was then used to estimate curtailments for June 30 of each year using the synthetic unimpaired flows from 1911 to 2014.

Of the 102-year synthetic unimpaired streamflow record, 88 years would have some curtailments on June 30. By comparison, the SWRCB has only issued curtailments once before 2014. The more frequent curtailments of DWRAT are caused by several factors. DWRAT evaluated curtailments with average 2010-2013 monthly demand over the entire period. Historical water use rates may have been much less. Also, DWRAT omits surface water return flows, resulting in decreased availability. However, most of the large appropriative rights are fully consumptive to the basin and most other water use is in the northern part of the basin near the outlet where supplies are plentiful, reducing the potential benefit from return flows. The high frequency of curtailments also is affected by DWRAT's exclusion of water released from storage, underestimating flow availability for appropriative right-holders. Errors also occur in gage flow estimates and the spatial distribution of flows.

Most curtailments occur in sub-basins dependent on the Lake Pillsbury gage flow for flow extrapolation. 2014 is the only year with zero flow at this gage but is also the only year with a NWS unimpaired flow value. The PVP is in this group of basins. The combination of low predicted flows and a nearby extremely large, senior water right results in consistent curtailments for this part of the watershed. If the highly senior PVP right is curtailed, almost all other appropriative water rights in this region also will be curtailed.

Implicit stochastic optimization

The method developed above to estimate curtailment thresholds was applied to the Eel River. To simplify analysis, flows at Fort Seward and Lake Pillsbury were calculated as a function of flow at Scotia, using regression equations, and assuming constant proportionality of flow in all sub-basins, making flow in all HUC12 sub-basins a function of Scotia flow (Lord 2015). Optimal curtailments were calculated for a range of flows at Scotia. Figure 10 shows the number of users curtailed over the range of flows.

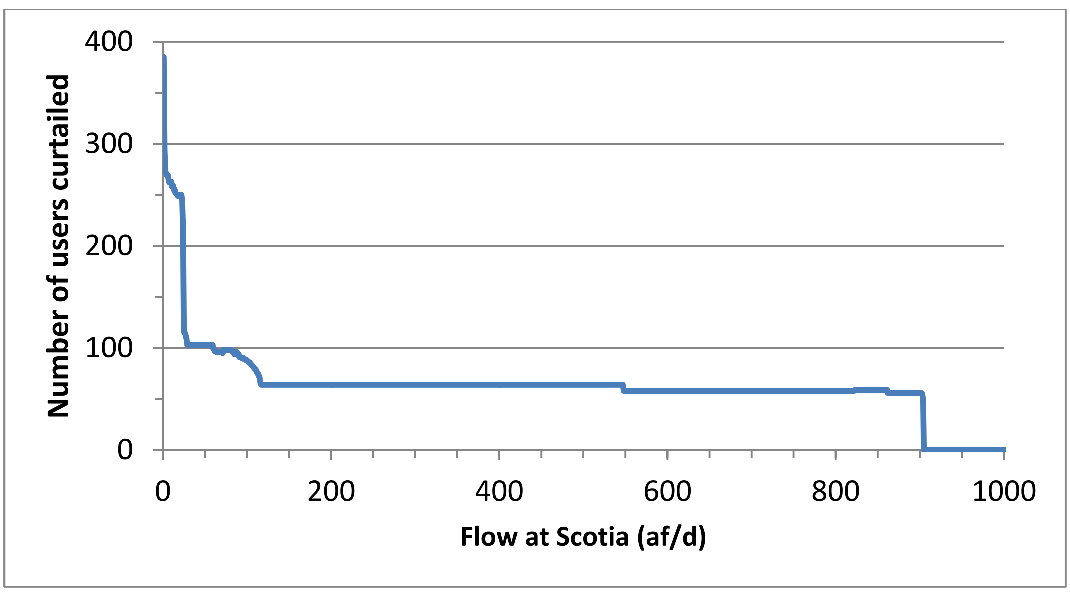

Figure 10 – Number of users curtailed by flow at Scotia, June 30

The function shown in Figure 10 was expected to decrease monotonically, with the total number of curtailed users never increasing with additional supply. While the curtailments predominantly decrease with increasing unimpaired flow at Scotia, the number of curtailed users increases slightly at twelve points. This behavior occurs at flows ranging from 50 to 100 and 800 to 850. However, the total volume of curtailed water (the difference between total demand and total allocations) always decreases monotonically. The cause of the rising curtailments with increased supply is unclear. Rights experiencing this curtailment with increased water availability are mostly appropriative. Further work is needed to determine why curtailment numbers (but not volumes) sometimes increase slightly with increased water availability.

Calculated curtailment thresholds had little correlation with cumulative demand or priority, particularly for appropriative users. Optimal curtailments in the Eel are largely determined by location in the watershed rather than priority of right. Water rights for the PVP dominate allocations. Users downstream of the PVP have low curtailment thresholds and low probabilities of curtailment. Users upstream of the PVP are much more likely to be curtailed to preserve flow for senior downstream users. Basin-wide curtailments by priority date will not allocate the most water possible due to spatial variability in water availability, priority, and demand in the Eel. To ensure maximum allocations, curtailments could be issued at a finer spatial scale by priority date. The presented methods could locate areas of large basins likely to face shortage, minimizing the likelihood of downstream false curtailments.

This representation of the Eel River's hydrology is greatly simplified. Flow for the entire river is calculated from availability at Scotia. A better hydrologic model could improve calculations of optimal curtailments and probabilities. Also, return flows should be incorporated. Assuming all use is consumptive artificially reduces availability and increases curtailments. Using past reported water use as a basis for estimated water demands is also a source of error, as noted by Gratham and Viers (2014).

Conclusions, limitations, and further research

DWRAT enables precise calculation of water right curtailments during drought by incorporating spatial variability of flow, demand, and priority into a mathematical framework representing the logic of California water law. While the 2014 drought was significant, more dry years will occur. DWRAT provides an explicit, transparent, mechanistic, and rigorous method for calculating water right curtailments in a mixed water right system using public data and software. It can help support more transparent curtailments and prepare water right administrators for future dry conditions. The "curtailment threshold" method may be an alternative timely means for issuing curtailments. All users in smaller basins could be told of a specified "curtailment threshold" value for a nearby gauge. When gage flow falls below that value, a user will know not to withdraw water to preserve downstream supply.

DWRAT is structured for any temporal or spatial scale large enough where dynamics and hydraulic routing are unimportant. However, curtailments calculated by DWRAT are only as good as the data used. Improvements can be made in both water supply and demand data.

Currently, only monthly withdrawals are available through the SWRCB's databases. Daily demand is estimated in DWRAT by dividing the monthly demand by number of days. This may be reasonable for some users, such as municipalities, but it can be unreliable. Irrigation is rarely distributed evenly across a month. However, asking right-holders to report daily use is unrealistic today. Instead, large users could "call" use of their rights in advance of an expected curtailment date during extreme dry periods. DWRAT could estimate curtailments based on the updated demand data. Both the SWRCB and users would benefit from this arrangement. Users would benefit from the ability to plan water use in advance and fuller basin water use. The SWRCB would benefit from a transparent and flexible system with explicit and timely water right holder input.

Few data exist on return flows. Rights associated with in-stream hydropower uses have zero consumptive demand in DWRAT, but nonconsumptive use from other sources is not yet considered. For rights with return flows re-joining the basin near the point of diversion, allocations could be based on consumptive use rather than total withdrawal. Rights where return flows return to supply far from the point of diversion, such as interbasin transfers through hydropower, present a larger challenge, but might just be considered as fully consumptive from surface water availability. Several studies (Israel and

Lund, 1999; Ferriera, 2004; Chou and Wu, 2014) present methods for adjusting penalty coefficients for appropriative users to address this problem, but the method may be too complex for large systems and data on return flow locations may be difficult to acquire.

Water availability is estimated statistically, using discrete NWS full natural flow forecasts and a spatial extrapolation model. DWRAT does not include water released from reservoirs, which is available for appropriative right-holders. In large systems with multiple reservoirs, such as the Sacramento River, this can be an important supply source. Current versions of DWRAT lack this capability, but reservoir releases could be added to appropriative availability.

DWRAT is an algorithm for implementation of water rights law in California. By accounting for spatial variability in demand, supply, and priority, curtailments can be suggested with greater precision. As California faces future droughts, tighter water rights administration will be necessary. Tools such as DWRAT can add transparency, rigor, and accuracy to better address the needs in future dry years.

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