Water rights curtailments for drought in California: Method and Eel River Application

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Abstract

Water users in California's water right systems have different priorities to available water during drought. An integrated set of water right allocation models was developed to determine optimize water allocation under drought conditions according to riparian and appropriative water right principles, with spatially varying water availability. Linear programming formulations are developed and applied for both cases. The models were extended to determine reliability of curtailment and factors of safety during the water right curtailment process. Alternate methods for issuing curtailments are discussed. Curtailments from the models are compared to actual curtailments issued in the Eel River, California for June 30, 2014. By implementing water right laws as an algorithm, the allocation models offer a more transparent and precise vision for water rights curtailments in California.

Contents

List of figures

Chapter 1 - Introduction

This report presents the formulation and example applications of the Drought Water Rights Allocation Tool (DWRAT). This approach uses formal optimization methods to most fully allocate limited water supplies, employing mathematical representations of the logic of riparian and appropriative water law doctrines across a basin with spatially varying supply and demand. By implementing California water rights law as an algorithm, DWRAT provides a precise and transparent framework for the complicated and often controversial process of curtailing water rights use during drought, implemented in spreadsheet form.

Overview of California's water rights

California's water rights system dates back to when the state was part of Mexico. After ceding California to the United States under the treaty of Guadalupe-Hidalgo in 1848, the American government recognized existing pueblo water rights, which remain today. However, these rights are few in number and have little effect on California's larger right system.

The California Constitution, adopted in 1849, initially contained no explicit references to water rights. However, the state Legislature adopted "the common law of England, so far as it is not repugnant to or inconsistent with the Constitution of the United States or the Constitution or laws of this State." (California Civil Code §22-22.2) By adopting English common law, California introduced the doctrine of riparian water rights.

In 1849, gold was discovered at Sutter's Mill in the foothills of the Sierra Nevada mountains. During the ensuing California Gold Rush, miners would divert water for use at a site far from the point of diversion. As more miners arrived, more diversions occurred and conflicts over water arose. An *ad hoc* legal system was established to resolve these disputing claims. The principal of "first in time, first in right" was used to determine priority; early diverters had a higher priority than later diverters.

Riparian water rights (riparians) are rooted in English common law. These rights are directly tied to land adjacent to water bodies. Right-holders are entitled to the full natural flow of the water body, so long as downstream users are not "unreasonably affected" and the diverted water is used and not stored on the adjacent land parcel. Generally, riparian rights are more suitable for areas with humid climates and plentiful rainfall. Riparian rights are correlative; there is no prioritization of rights and shortage is shared proportionately by all.

When California became a state in 1850, neither riparian nor appropriative water rights had been explicitly recognized by the courts or legislature. Conflicts over water rights in the ensuing decades prompted legal confrontation of these principals. In the 1855 decision *Irwin v. Phillips*, the California Supreme Court recognized appropriative water rights as a distinct doctrine, independent of common law and riparian rights. In the decision of *Lux v. Haggin* in 1886, the California Supreme Court ruled that appropriative rights were secondary to riparian rights.

The 1913 California Water Commission Act, which became effective in 1914, established an agency to manage water rights and codified statutory procedure for the appropriation of unclaimed waters. The new agency, a predecessor of today's State Water Resource Control Board (SWRCB), organized all new appropriations of water. All appropriative water right claims after the law came into action are prioritized by application date. These "Post-1914" appropriative water rights are the only new type of water right available in California today. All appropriative rights with dates of first use before January 1, 1914 are referred to as "Pre-1914" rights and have extremely high priority.

California is one of the few western states to recognize both riparian and appropriative water rights. Riparian rights are highest in priority and correlative, followed by appropriative rights ranked by seniority. Generally, disputes over water allocation are handled by courts in legal disagreements between right-holders. Despite having the legal authority, the SWRCB has only issued curtailments (a mandate for an individual or group of water right holders to cease diversions) once before the current drought, in 1977.

California's current drought

California has an extremely variable climate. Extensive water infrastructure in the state has been developed to buffer the unpredictable cycle of flood and drought. 2014 was the third year of abnormally low precipitation in California, prompting a declaration of drought emergency by Governor Jerry Brown after dry water years beginning in 2012. Reservoirs reached extremely low levels and greatly reduced deliveries for downstream users were predicted. Low precipitation in addition to warmer temperatures has diminished snowpack, which normally provide additional supply in spring and early summer.

As the state's water supplies approached critically low levels in 2014, the California State Water Resources Control board (SWRCB) considered issuing mandatory curtailments to water right holders in the state. Once active, these would be the first curtailments issued since the 1977 drought (which were the first ever issued).

The Scott river was the first watershed to have curtailments, beginning on May 16, 2014. In the following months, junior right-holders in the Sacramento, San Joaquin, Russian, and Eel rivers were curtailed as well.

Water allocation modelling

Previous water allocation models have used water rights as a framework for prioritizing users and demands. The Texas Water Availability Modelling (WAM) system (Wurbs, 2005) allocates natural streamflow and reservoir storage among water right-holders under the doctrine of prior appropriation. The WAM system was developed under mandate by the Texas legislature to provide comprehensive water management for the state. Water is allocated through an iterative loop that steps through each right in priority order, meeting targets where local supply is available. Many models represent priority-based water operations with different delivery, flow and storage objectives having different objectives, such as Calsim (Draper et. al. 2004) and Modsim (Fredericks et. al. 1998). Linear or network flow optimization is used in various ways to enforce such priority-based operations.

Network flow programming (NFP) is an optimization method well-suited for water allocation modelling. A type of linear program, NFP distributes flow throughout a network of nodes and links. Nodes represent locations in the system where flows merge or split. Links connect nodes and represent water conveyance structures, such as river channels or pipelines, as well as external inflows to nodes in the system, and water demands. A cost coefficient is assigned to each link, and the NFP allocates flow to minimize cost.

Appropriative water right priorities can be represented in NFP through the cost coefficient, with junior lower-priority rights having lower penalties for shortage. Israel and Lund (1999) extended the method by introducing an algorithm for determining cost coefficients with inclusion of return flows. This method was developed further by Ferreira (2007) and Chou and Wu (2014) for more precise calculation of coefficients and application to linear program formulations.

Despite the extensive literature on water allocation under the appropriative doctrine, very little exists on allocation under the riparian doctrine. DWRAT allocates water for rights under both doctrines, using spreadsheets and a free and open source solver platform.

The second chapter of this thesis presents the linear programming formulation for DWRAT and an illustrative curtailment example. The third chapter extends the methods presented in Chapter 2. Methods for estimating curtailment reliability and managing uncertainty in hydrologic forecasts are explored. Chapter 4 applies DWRAT in the Eel River and compares calculated curtailments to actual curtailments issued by the California State Water Resources Control Board.

Chapter 1 references

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Chapter 2 – Drought water rights allocation tool (DWRAT) formulation

The Drought Water Rights Allocation Tool (DWRAT operates in two phases. In California, riparian water right-holders (riparians), are equal in priority among each other, but categorically have a higher absolute priority than appropriative water right-holders (appropriators). The first phase of water allocation distributes available water proportionally among correlative riparian right-holders. A second phase allocates the remaining available water by strict priority among appropriative right-holders. In both phases, water users are scattered over a network of sub-basins, facing different hydrologic water availabilities within each sub-basin and the larger basin.

Each water rights allocation model is implemented as a linear program, with known flows at each sub-basin inlet and no return flows (for now) from water users. Total flow into catchment k is represented by v_k. Each user i receives water allocation A_i with a use demand of u_i. Appropriative users have a given priority in allocation determined by water right seniority, reflected in the unit shortage penalty p_i, which increases with seniority of right. Riparian users have equal priority and no ranking is given to users. Shortage among riparians is determined by limiting diversions to a set proportion of normal reported use for each user in a sub-basin. These proportions are assigned to each sub-basin as P_k, with a weighted penalty coefficient of w_k. The penalty coefficient w_k increases with the number of upstream basins u_k to properly balance proportions across sub-basins. The overall approach represents the logic of each water law doctrine mathematically, so it can be implemented in software. Figure 2-1 illustrates the data flow of DWRAT.

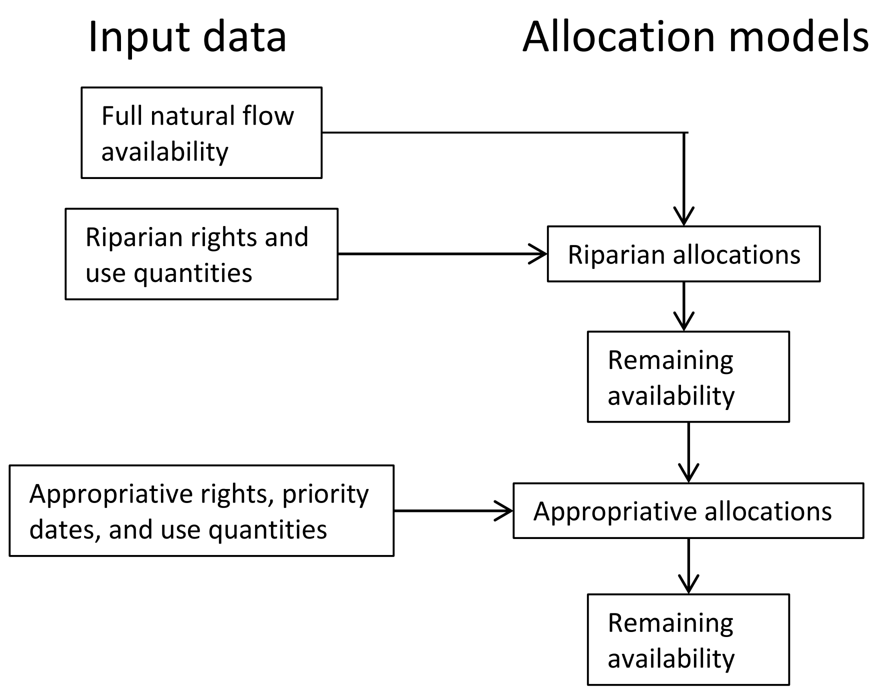

Figure 2-1 – DWRAT data flow. Boxes on the left indicate required input data. Boxes on the right indicate phases of the allocation model and reductions in availability.

Riparian allocation phase formulation

Riparian right-holders are equal in right, so shortage is distributed by restricting water use proportionally across all users in a basin. However, varying local availability allows differing degrees of proportional shortage. The following equations represent the logic of riparian water allocation.

Defining allocations

The allocation, A_i for a riparian user *i,* is defined below in equation 2-1. All users in a sub-basin *k*, receive the same allocation proportion P_k of demand u_i, where P_k is the decision variable.

$$A_i = P_k u_i, \forall i, i \in k \quad (2-1)$$

The allocation proportion, P_k is constrained between zero and 1 as shown in equation 2-2. This defines a minimum allocation of zero and a maximum allocation equal to normal use.

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

Mass balance

The sum of all allocations upstream of a sub-basin outlet can not exceed the total availability of water leaving the sub-basin. Total availability is represented by the difference in sub-basin inlet flow v_k, environmental flow requirement e_k, and "buffer" flow b_k as represented in equation 3. Environmental flows can be specified by the user. By implementing this value in the constraint, flows for the environment are reserved. Alternatively, environmental flows could be represented as a water right with a relative priority to other uses in the system. Buffer flow is used as a factor of safety to represent error or uncertainty in water availability and actual uses.

$$\sum_{i \in k} A_i \leq v_k - e_k - b_k, \forall k \qquad (2-3)$$

Objective Function

The riparian objective function, represented in equation 2-4, maximizes total allocations, with a weighting term to enforce allocation proportionally across water users.

$$Minimize\ z = \alpha \sum_k w_k P_k - \sum_i A_i \quad (2-4)$$

In drought, simply maximizing total allocations for all riparian users yields a range of multiple optima. In some situations, this could result in upstream users receiving zero allocations despite local availability, while downstream users would receive full allocations. Alternatively, water available in upstream reaches could be allocated completely to upstream users, resulting in large shortages downstream. Both of these situations fail to distribute water proportionally among riparian users. Because riparian users have equal priority, weight is given to enforce equitable allocation of shortage. The following constraints define how this equal proportionality of shortage with full allocation of available water objective is met.

Upstream users can not have less shortage (a higher P_k) than downstream users. If upstream users do have less shortage than downstream users, some of the upstream water could be allocated downstream so both sets of users experience the same proportion of shortage. This constraint is implemented in equation 2-5, where the allocation proportion in any basin *j* can not exceed the proportion of any downstream basin k.

$$P_j \leq \ P_k, \forall k, j \in k \ (2-5)$$

This constraint assumes full natural flow in a downstream basin will always exceed flow available in an upstream tributary. This implies no major net losses of flow downstream (to ground water or lake evaporation, for example).

All 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 2-6. The downstream penalty, w_k, increases with the number of basins upstream of basin *k*'s outlet.

$$w_k = \frac{n_k}{n_{k,system\ outlet}} \quad (2-6)$$

The sum of the products of these weights and allocation proportions is further weighted in the objective function to balance the multiple objectives. To prioritize allocating all water the equality terms are given significantly less weight. The weighing term coefficient, α,must be less than the minimum ratio of the downstream penalty to total upstream demand for a basin *k* as shown in equation 2-7.

$$\alpha < Min\left(\frac{w_k}{u_k}\right) \forall \ k \quad (2-7)$$

Equations 2-5, 2-6, and 2-7 provide counteracting weights to distribute shortage equally across a watershed while maximizing total allocations to riparian users.

Riparian allocation example

An example watershed, illustrated in figure 2-1, was created to test and demonstrate the riparian allocation linear program. The basin has 8 sub-basins (A-H) with local inflows occurring in each. Unimpaired streamflow is given for the outlet of each sub-basin, with a certain fraction allocated for environmental flows. Flow characteristics for each sub-basin are shown in table 2-1 and demand by user is shown in table 2-2.

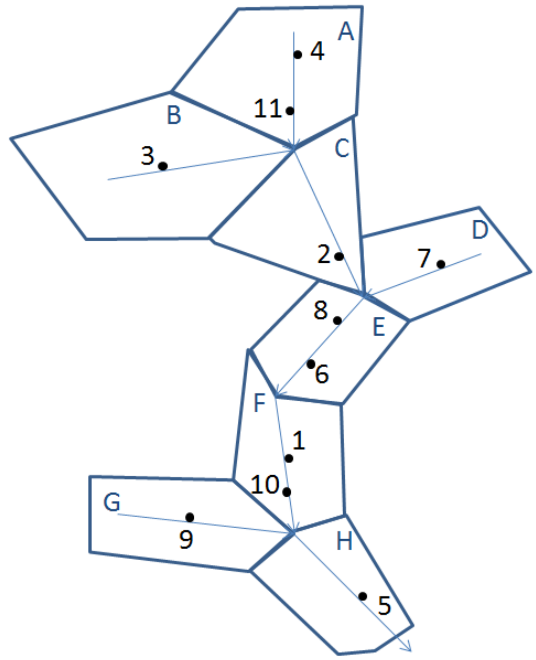

Figure 2-1 – Example watershed. Sub-basins are outlined and labelled A-H. Users are represented by black dots and labelled 1-11. Arrows indicate direction of flow

Table 2-1 – Subbasin hydrology. All flow values are in units of flow/time

Sub-basin	A	B	C	D	E	F	G	H
Local inflow	7	7	7	7	7	7	7	7
Available flow:	7	7	21	7	35	42	7	56
Environmental flow:	1.4	1.4	4.2	1.4	7	8.4	1.4	11.2
Total flow available to allocate:	5.6	5.6	16.8	5.6	28	33.6	5.6	44.8

Table 2-2 – Riparian user characteristics

User:	1	2	3	4	5	6	7	8	9	10	11
Demand:	7	4	8	8	8	4	3	9	9	7	10

Riparian allocation results

Tables 2-3 and 2-4 show user and basin results from the riparian water rights allocation model, respectively. Basin results are represented by shading in figure 2-2.

Table 2-3 – Riparian model results by user. All flow values are in units of flow/time

User:	1	2	3	4	5	6	7	8	9	10	11
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

Comparing the allocations in basins A and B can yield insight into the riparian allocation mechanics. Basin A has a total upstream demand of 18 and a local availability of 5.59. 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 5.59 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 shortage downstream. There are no greater shortages downstream of Basin A, so all available flow is allocated locally. Unallocated flow can serve as a rough approximation of local shortage. If unallocated flow is zero, the upstream shortage exceeds potential downstream shortages. Availability directly limits upstream allocation and equation 3 is a binding constraint. If unallocated flow is greater than zero, water is retained to lessen the more severe shortages downstream.

Table 2- 4 – Riparian model results by basin. All flow values are in units of flow/time

Basin	Allocation Proportion	Availability	Upstream demand sum	Upstream Allocation sum	Unallocated flow
A	0.31	5.59	18.00	5.59	0.00
B	0.67	5.59	8.00	5.33	0.27
C	0.67	16.78	30.00	13.58	3.20
D	0.67	5.59	3.00	2.00	3.60
E	0.67	27.97	46.00	24.24	3.73
F	0.67	33.56	60.00	33.56	0.00
G	0.62	5.59	9.00	5.59	0.00
H	0.70	44.74	77.00	44.74	0.00

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

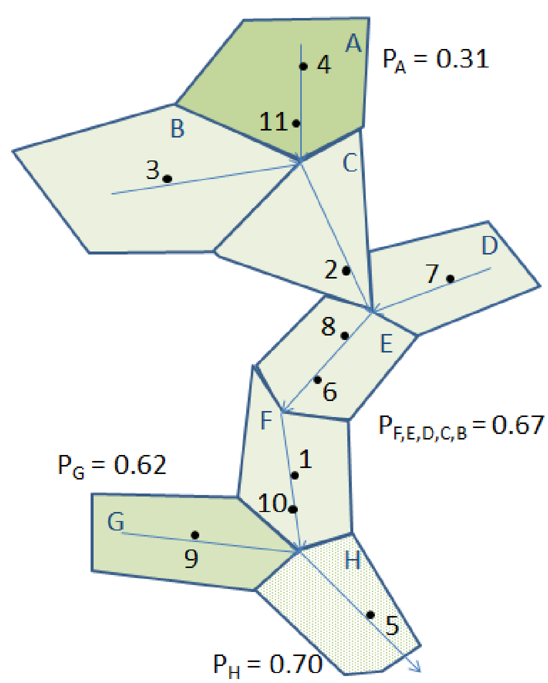

Figure 2-2 – Example riparian allocation results. Basins are shaded by allocation proportion. Darker shades indicate lower proportions and higher degrees of shortage.

Appropriative allocation phase formulation

After riparian water rights receive allocations, the remaining water is allocated to appropriative right-holders by strict priority according to the following formulation. This mathematical formulation represents the logic of priority-based appropriative consumptive water rights, without return flows.

Defining allocations

Allocation for a user *i* is represented by the decision variable A_i. Allocations for any user have a maximum of use u_i and a minimum of zero.

$$0 \leq A_i \leq u_i, \forall i \qquad (2-8)$$

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

Mass Balance

Similar to the mass balance for riparian users (equation 2-3), the sum of all allocations upstream of a basin outlet can not exceed the total water availability remaining after riparian allocations.

$$\sum_{i \in k} A_i \leq v_k - e_k - b_k - \sum_{i \in k} A_{upstream\ riparian\ users\ i}, \forall\ k \ (2-9)$$

Prioritizing users

Unlike riparian rights, appropriative water rights are curtailed by strict individual priority. Rights are ranked by date of first use. The earliest right in a basin has the highest priority, and the most recent right has the lowest ("First in time, first in right"). Priority is used to establish 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 defined as the difference between demand u_i and allocation A_i.

Objective function

The objective function minimizes total shortage penalty for all users. Senior users with high priority have more weight in the objective function and are more likely to receive a full allocation. Likewise, junior users have low priority and are less likely to receive an allocation.

$$Minimize\ z = \sum_i p_i(u_i - A_i) \qquad (2-10)$$

Appropriative allocation example

An appropriative allocation model was developed for the example watershed used above (Figure 2-1), with the same user and basin characteristics (Tables 2-1 and 2-2). In this application, all users have appropriative rights and the user label corresponds to priority, with user 1 having the highest priority and 11 the lowest.

User and basin results from the appropriative water rights allocation model are shown in Tables 2-5 and 2-6, respectively. User 1, located on the main stem of the stream and with the highest priority, receives a full allocation. User 3 has a relatively high priority but is located in the upper reaches of the watershed where less flow is available. Thus, User 3 receives all of the available flow in subcatchment B, yet still experiences shortage. User 4 has a similar allocation in catchment A, receiving all available flow. User 11, also 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 2-5 – Appropriative model results by user. All flow values are in units of flow/time

User:	1	2	3	4	5	6	7	8	9	10	11
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	0.0
Shortage:	0.0	0.0	2.4	2.4	0.0	0.0	0.0	4.6	5.8	7.0	10.0

Table 2-6 – Appropriative model results by basin. All flow values are in units of flow/time

Basin	Availability	Upstream demand sum	Upstream allocation sum	Unallocated flow
A	5.59	18.00	5.59	0.00
B	5.59	8.00	5.59	0.00
C	16.78	30.00	15.19	1.59
D	5.59	3.00	3.00	2.59
E	27.97	46.00	26.56	1.41
F	33.56	60.00	33.56	0.00
G	5.59	9.00	3.19	2.41
H	44.74	77.00	44.74	0.00

Combining the allocation methods

To issue allocations for a basin with both riparian and appropriative water rights, the riparian linear program is run first, followed by the appropriative LP. Riparians, with a higher priority in right overall, are much less likely to be curtailed than appropriators. Due to the method of shortage distribution for riparians, right-holders in upper portions 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 the upstream portions of watersheds are also extremely vulnerable to shortage, due to low water availabilities and being curtailed to help meet downstream riparian demands.

Conclusions and limitations

All users within a subcatchment *k* are assumed to have equal access to total flow (v_k). This is not necessarily true, as some local basin inflows can enter downstream of some subcatchment users. Error from this assumption is reduced by increasing the spatial resolution of the model and implementing a finer subcatchment grid. Error also could be reduced by restricting allocations for each user to the percentage of total sub-basin outflow available at the user's point of diversion. Ideally one would define sub-basins for each user, but this would make the problem much larger, for solving and hydrologic estimation.

While the maximum allocation for each user is their previous reported use u_i, these values are reported under historic flow circumstances and may not be relevant under drought conditions, particularly for riparian right-holders. Ideally, water users would "call" their right each time period so water right administrators could make more accurate and timely full allocations of available water

In times of drought, curtailed water users replace lost surface water allocations with groundwater. However, DWRAT only develops surface water allocations and does not incorporate groundwater depletion effects on surface water availability. This may overestimate water availability, especially in longer droughts.

DWRAT does not include the effects of return flows. This assumption results in artificially low availabilities, particularly for downstream users. Water uses such as hydropower and flood irrigation have high return flow values, so systems with large amounts of these users could have significant error. Israel and Lund (1999) present a method for developing priority-based penalty coefficients for network flow programming models of water resources system with return flows and appropriative rights. This method is extended to riparian users by Ferreira (2007) and applied in Chou and Wu (2014). These algorithms could serve as pre-processors for the above models to account for return flows while preserving the priority ranking of water rights.

The methods here seek complete use of available water for water right-holders. However, estimates of water availability, use, and return flows are imperfect. Buffer flow, represented in the mass balances (equations 3 and 9) can account for some error by modifying availability. Any positive buffer flow value will decrease availability, resulting in more curtailments, but less likelihood of over-promising of water. Conversely, negative buffer values will result in fewer curtailments, but more over-promising of water and likelihood of senior right-holders being deprived of water. Errors cannot be entirely eliminated, or even entirely known without extensive monitoring. Varying buffer values largely affects the likelihood of false curtailments (when water is actually available) versus false promises (when water is not actually available for a non-curtailed right-holder). By varying the buffer flow to represent uncertainty, a range of curtailments could be generated for a given date. This capability allows much greater flexibility in predicting and accounting for uncertainty in DWRAT inputs. A method for estimating optimal buffer flows is presented in Chapter 3.

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Chapter 3 – Estimating water right reliability

The Drought Water Rights Allocation Tool formulation presented in Chapter 2 calculates the optimal set of water allocations according to legal priority and rules for a given set of flows throughout the basin. This method can be extended to find optimal water rights curtailments under a variety of hydrologic conditions. By varying the flow and conducting probabilistic analysis of results, the reliability of allocations can be estimated for a set of users. This chapter introduces a preliminary approach for estimating water supply reliability for individual water right holders given hydrologic variability.

Problem setup

For any unimpaired outlet flow Q_n with a distribution of local sub-basin inflows, there is 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 presented in Chapter 2. When $C_i = 1$, user *i* is curtailed and receives less than their full allocation of water. Conversely, a user is not curtailed when $C_i = 0$ and receives a full allocation. Two methods were used to calculate the probability of curtailment for each user; Monte Carlo analysis and implicit stochastic optimization.

<u>Monte Carlo analysis</u>

In Monte Carlo analysis, input parameters to a model 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 of occurence. Frequency analysis on the full set of model outputs can estimate the likelihood of any given solution (curtailment) over the range of possible input values.

For small or simple basins, to estimate water right reliability, inflow is varied using a given distribution. The optimal curtailment set $[C_n]$ is calculated for each outlet flow. The number of instances where user i is curtailed over the full group of curtailment sets divided by the total number of sets approximates the probability of curtailment for that user.

<u>Implicit Stochastic Optimization</u>

Operating water systems under uncertainty can be complex and computationally intensive. Estimation of uncertainty itself can be prohibitively complex. Implicit stochastic optimization (ISO) can reduce these problems by applying deterministic modelling methods 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 set occurring is the probability of the corresponding input set. Frequency analysis can be performed over the set of solutions to determine probabilities of occurrence. Alternatively, the full solution set can provide a set of rules for real-time system operation. Administrators could observe current conditions and look up the corresponding optimal operations from the ISO results without additional model runs.

ISO is most often employed in studies to identify operating rules for reservoirs faced with uncertain inflows (Young 1967, Draper 2001). Operations are optimized over a long representative time-series of inflows with perfect foresight using deterministic methods. The optimization process can be repeated over different inflow time-series to find operations under a variety of conditions. By simulating a representative range of inflow time-series, reservoir operations under stochastic inflows can be estimated.

For this application of ISO, stochastic operation of a water rights system is considered, both from administrator and user perspectives. To estimate water right reliability with ISO, a range of outlet flows Q_n is selected. Stepping through the range, DWRAT calculates $[C_n]$ for each outlet flow Q_n. The probability of a curtailment set occurring is the probability of the lowest Q_n for which the curtailment set occurred. This method can be further extended to estimate water right reliability for a user. For each user *i*, there is a corresponding "curtailment threshold flow" Q_{ti}, for simple or small systems. 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 LPs, Q_{ti} can be identified for each user as the minimum flow for which C_i is 0. The probability of a user receiving a curtailment is the probability of Q_{ti}.

Example basin

The example watershed used in Chapter 2 was extended to test and illustrate these methods. Both riparian and appropriative users are present. 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 (n_k) to total basin drainage area (Equation 3-1).

$$v_k = Q_n * \frac{n_k}{n_{k,outlet}} \quad (3-1)$$

Outlet flow error is assumed to be normally distributed with a mean of 60 and standard deviation of 30, representing error in forecast outlet flow. Local inflows to each sub-basin are assumed to be deterministic, given an unimpaired outlet flow. Sixteen water right holders occupy the basin. Users labelled R1 through R5 have riparian rights and have equal priority. Users labelled A1 through A11 have appropriative rights and with priority corresponding to the label number (A1 has the highest priority and A11 the lowest). Figure 3-1 shows the distribution of users in the basin and Table 3-1 shows demand for each user.

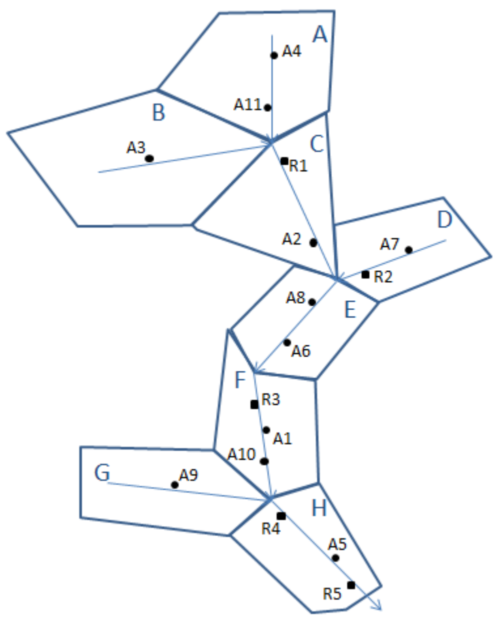

Figure 3-1 – Example basin with users

Table 3-1 – 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

An alternate way of representing the system is to view cumulative demand of users ranked by priority, as displayed in the bottom row of Table 3-1. For a riparian user, cumulative demand is the sum of all riparian demand. For an appropriative user, cumulative demand equals the sum of all demand by higher priority users.

If all users had equal access to the full outlet flow, cumulative demand for user *i* would be the total amount of water 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. The cumulative demand for all users, ordered by priority is illustrated in Figure 3-2 below.

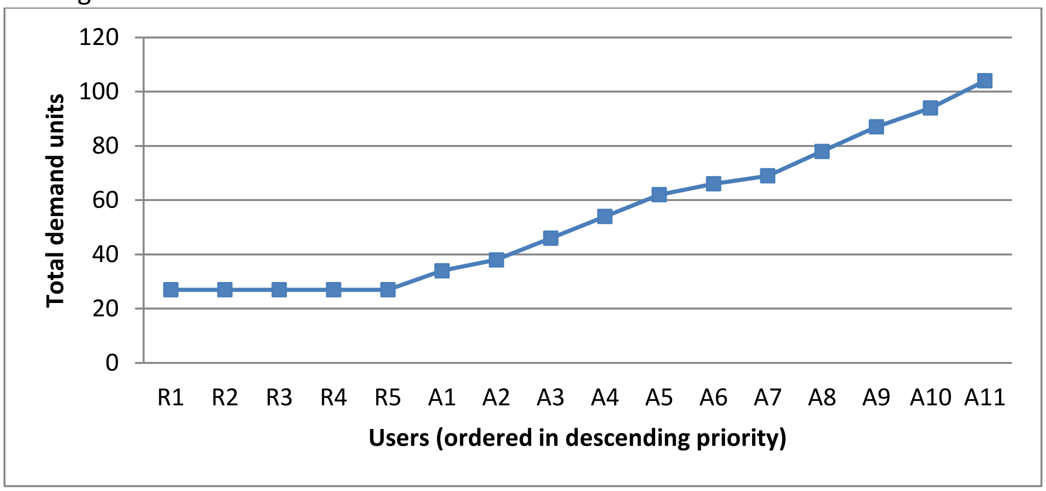

Figure 3-2 – Cumulative demand for example basin

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 $[C_n]$ to determine the reliability of water allocation for each user. The results of the frequency analysis are displayed in Figure 3-3 and Table 3-2. These are

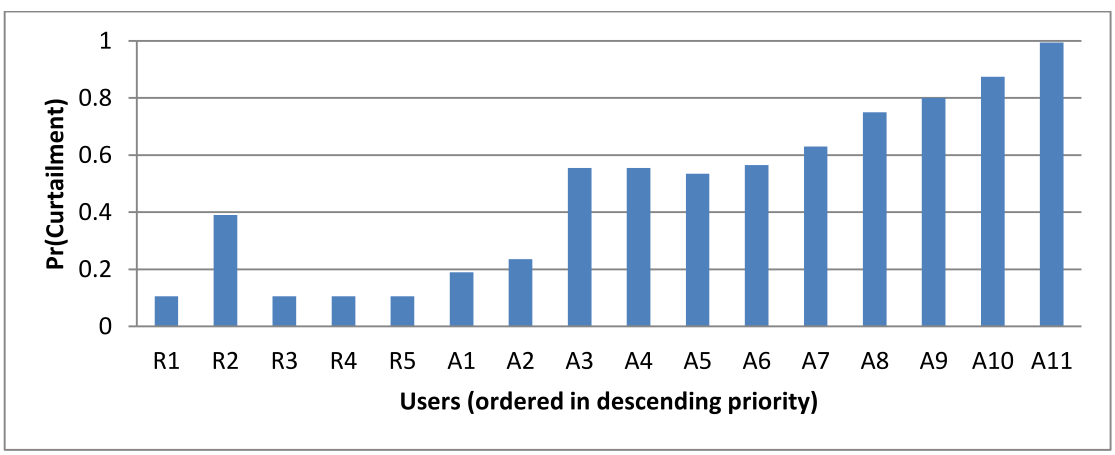

Figure 3-3 – Curtailment probability for each user from Monte Carlo analysis

Table 3-2 -- Probability each right should be curtailed, given forecast availability, Monte Carlo

User (ordered by priority)	R1	R2	R3	R4	R5	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Probability of curtailment, 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

Probability of curtailment increases as priority decreases, with some deviation. Riparian users, with the highest priority, have the lowest probability of curtailment in the basin. However, user R2 is on a tributary branch of the basin, and much more likely to face local shortages than the other riparian users, resulting in a higher curtailment probability. Similarly, users A3 and A4, located high in the watershed, have higher probabilities of shortage than A5, with lower priority but located on the main stem close to the outlet. Furthermore, users A3 and A4 have the same probability of shortage, despite the higher priority of A3. Both users are on separate tributaries with independent availabilities, so the availability in basin A is not affected by 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 Q_n in a representative set, ranging from an outlet flow of 0 to 150. As outlet flow increases, fewer users are likely to be curtailed, as illustrated in figure 3-4.

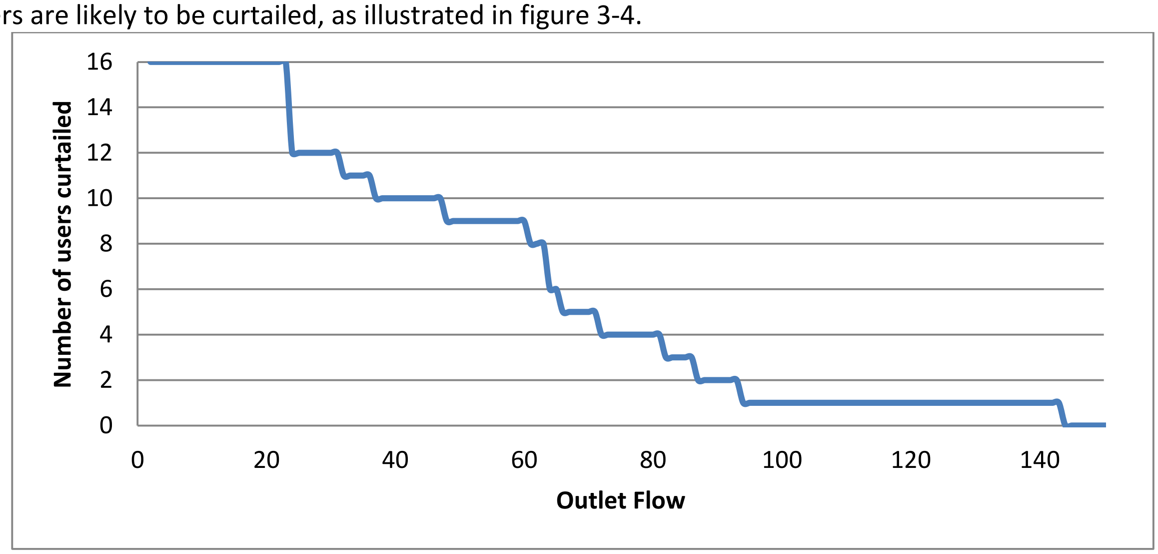

Figure 3- 4 – Total number of curtailed users by outlet flow value

Each "step" in Figure 3-4 corresponds to a user or set of users receiving a full allocation. The flow value corresponding the "step" at which a user receives a full allocation can be considered the "curtailment threshold flow" Q_{ti}. When the outlet flow is below Q_{ti}, user *i* is curtailed. Figure 3-5 displays the curtailment threshold for each user.

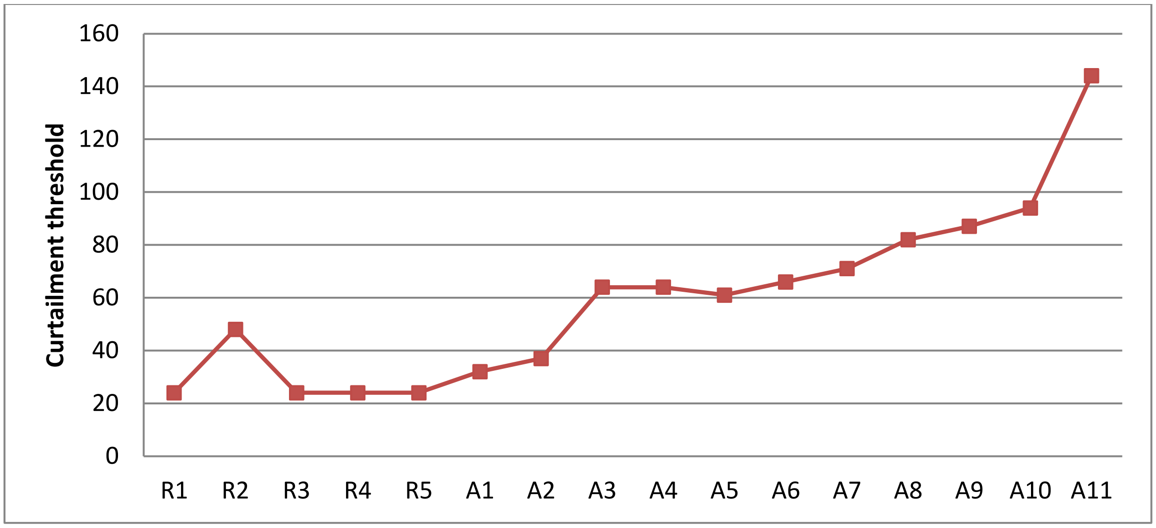

Figure 3-5– Curtailment threshold by user. If outlet flow is below curtailment threshold for a user, the user will be curtailed.

The probability of curtailment for a user *i* can then be calculated as the probability that Q_n is less than or equal to Q_{ti}, which can be found in the cumulative probability distribution function for Q. Figure 3-6 shows the probability of curtailment for each user calculated through the ISO method.

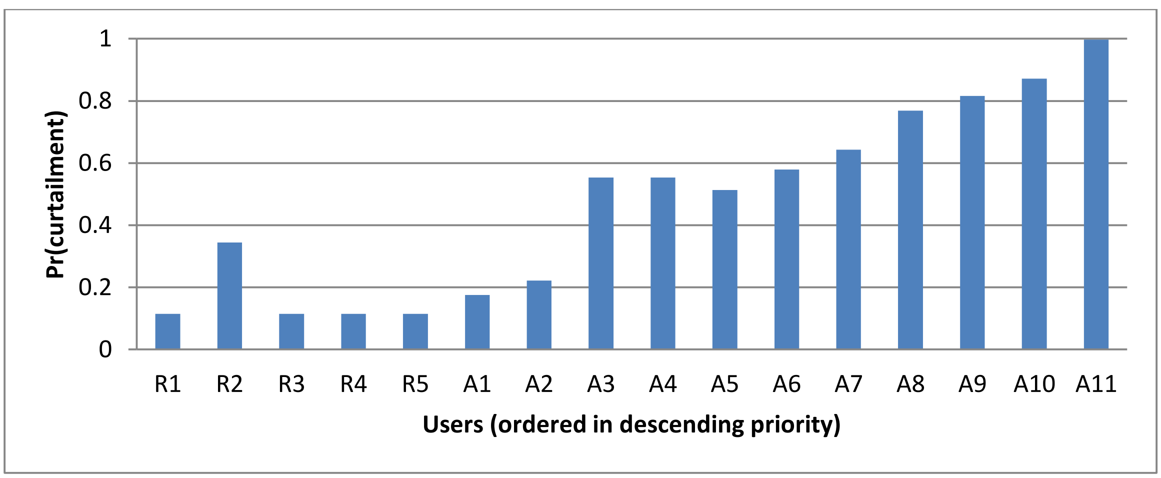

Figure 3-6 – Probability of curtailment for each user from implicit stochastic optimization (ISO) method

The Monte Carlo and ISO methods yield nearly identical curtailment probabilities as displayed in Figure 3-7. With a higher number of iterations in the Monte Carlo analysis, the results would likely converge.

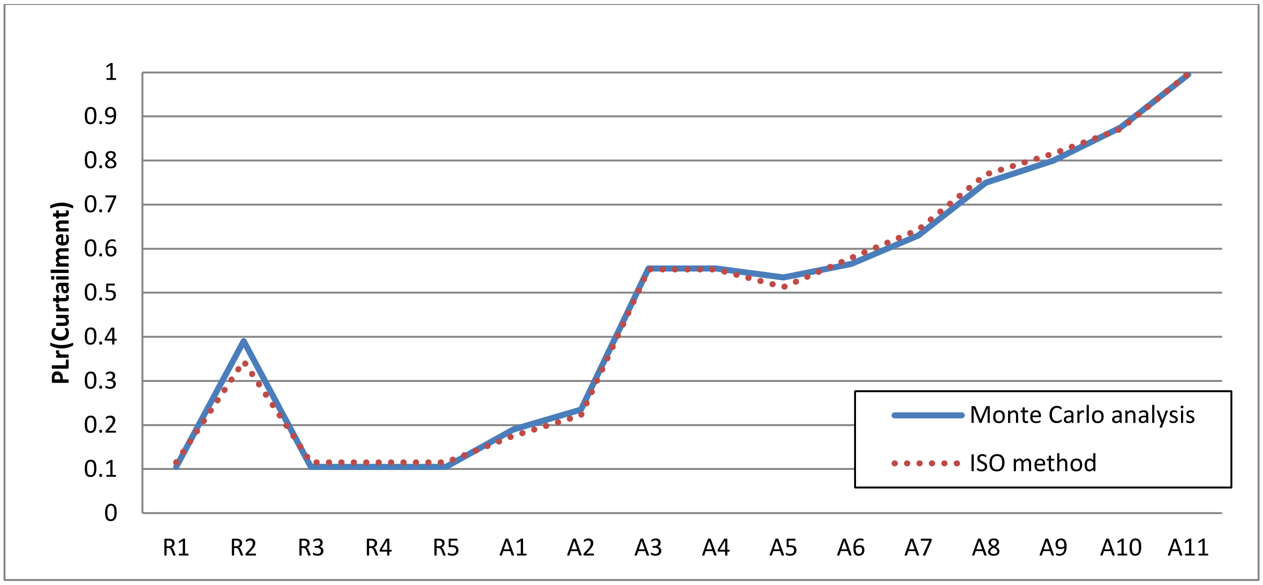

Figure 3-7 – Comparison of curtailment probability determination methods

Discussion of results

The probability of curtailment for a right-holder primarily depends their priority and location in watershed. The effects of these factors can be seen by plotting cumulative demand and curtailment threshold for all users as illustrated in Figure 3-8.

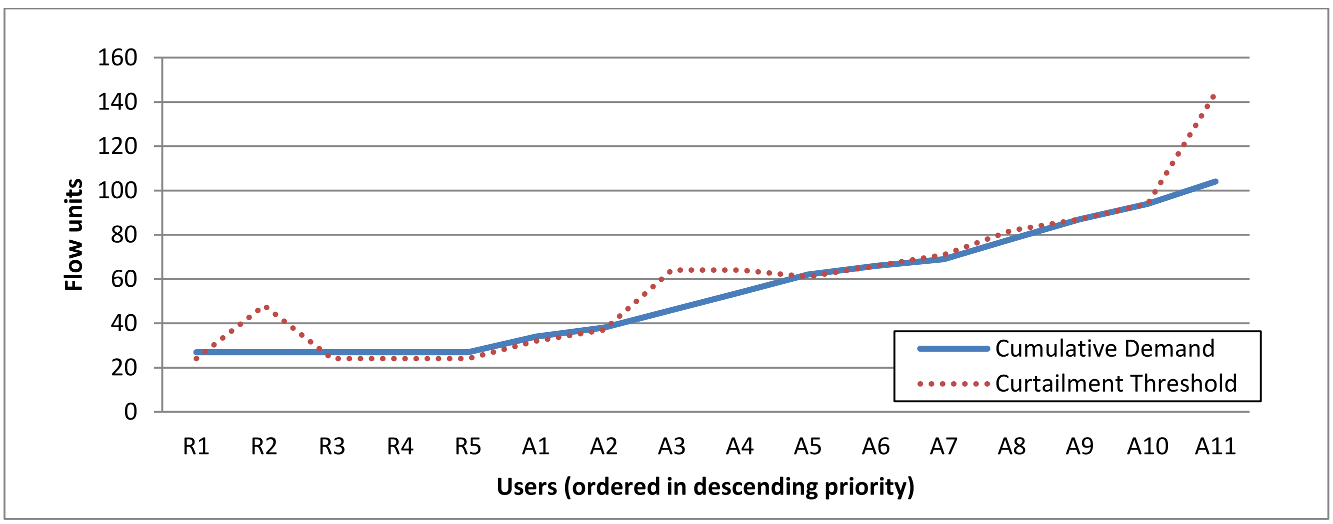

Figure 3-8 – Cumulative demand and curtailment threshold for all users

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 greater access to flow and are less likely to be subject to local supply shortages. Curtailment for these users is generally dictated by priority. In figure 3-8, cumulative demand and curtailment threshold values for these users are approximately equal. Users in the upper portions of the basin (subcatchments A, B, D, and G) are more likely to be subject to curtailment due to local flow shortages. This effect is seen in

Figure 3-7 for users R2, A3, and A11, for whom curtailment threshold significantly exceeds cumulative demand. The upstream locations of these users makes them more vulnerable to curtailment than those of similar priority downstream.

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 due to errors in estimating error distribution, water demands, and overall water availability and its spatial distribution.

Buffer Flows

Uncertainty in hydrologic forecasting can lead to curtailment errors, compared to curtailments under fully-known conditions. Curtailments are likely to be calculated in advance based on a forecasted full natural flow and anticipated user withdrawals. However, actual flow and user diversions may differ significantly from forecasted flow, leading to errors in allocations. Buffer flow, presented in chapter 2, is a means to adjust curtailments for forecasting uncertainty by artificially reducing water availability. A higher buffer flow is a safety factor for senior (uncurtailed) 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 the types of error caused by uncertainty and provide a framework for selecting buffer flow values.

False promises

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

$$E(FP) = \int_0^\infty P(Q_{act}) FP\left(Q_{for}, Q_{act}, B\right) dQ_{act} \quad (3-2)$$

where:

$$FP\left(Q_{for}, Q_{act}, B\right) = Maximum \begin{cases} C(Q_{act}) - C(Q_{for} - B) \\ 0 \end{cases} \quad (3-3)$$

Equation 3-2 yields the expected number of false promises over all possible actual outlet flows Q_{act}, given a forecasted outlet flow Q_{for} and buffer flow *B.* False promises are defined in equation 3-3 as the difference between number of curtailments with the actual flow and number of curtailments with the forecast flow minus the buffer. Evaluated in the example basin above, the values for C correspond to the series shown in figure 4.

False curtailments

Buffer flows result in some users receiving curtailments due to the artificially reduced water availability. These *false curtailments* increase with buffer flow values. Given the nomenclature above, the expected false curtailments, *E(FC),* can be defined as:

$$E(FC) = \int_0^\infty P(Q_{act}) FC\left(Q_{for}, Q_{act}, B\right) dQ_{act} \quad (3-4)$$

where:

$$FC\left(Q_{for}, Q_{act}, B\right) = Maximum \begin{cases} C\left(Q_{for} - B\right) - C(Q_{act}) \\ 0 \end{cases} \quad (3-5)$$

Equation 3-5 defines false curtailments as the difference between forecasted curtailments including buffer flow, and the optimal curtailments with the actual outlet flow. Given uncertainty in water availability (as well as other aspects of water right calculations) there is always a likelihood that false promises and false curtailments will occur, the balance of which is a policy implicit in curtailment administration methods.

<u>Example basin application</u>

Equations 3-2 and 3-4 were applied to the example basin above with varying buffer flows and a forecast outlet flow of 60. Figure 3-9 illustrates the effect of increasing buffer flows

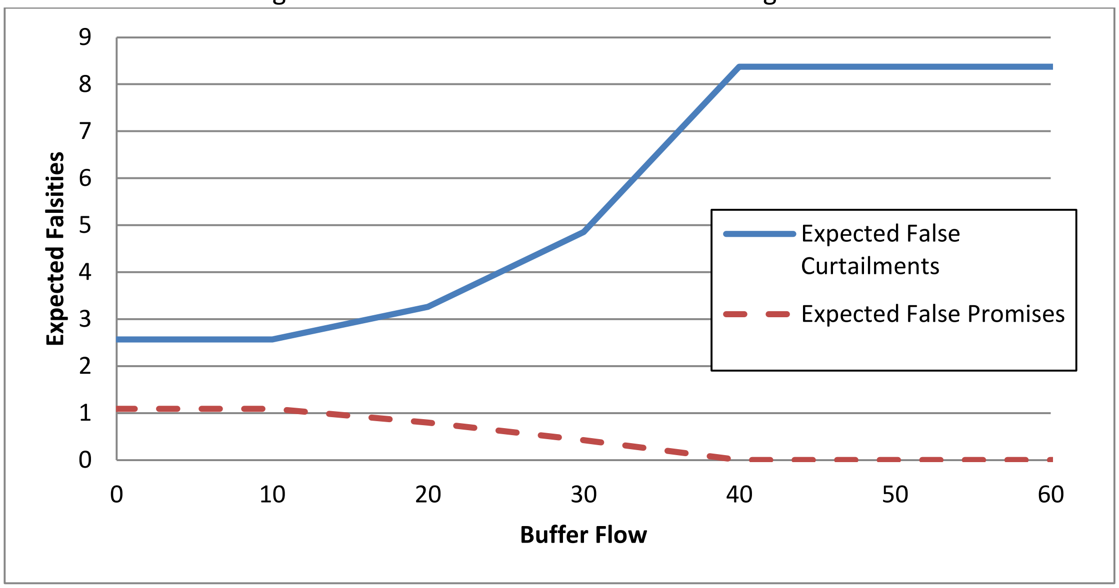

Figure 3-9 – Expected false promises and curtailments with varying buffer flow

With no buffer low, 1.1 false promises can be expected, whereas 2.6 false curtailments can be expected. As the buffer is increased, more false curtailments become likely and false promises become less. At a buffer flow of 40, only 20 units of flow are available for allocation and the number of false promises and curtailments stabilizes as all users are curtailed (as seen in figure 4).

Selecting the 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 the different falsities may not have equal weights. False promises may be more damaging than false curtailments. 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.

Conclusions and limitations

The presented methods are effective for estimating the probability of water right curtailment in a basin given an uncertain basin outflow hydrology. Uncertainty also will exist in actual water user withdrawals and return flows, and the spatial distribution of water availability within the basin.

Increasing the number of input parameters increases the complexity of the estimation method results. For each independent uncertain parameter, the calculations increase exponentially. In Monte Carlo analysis, this complexity can be overcome by simply increasing the number of iterations. In implicit stochastic optimization, enumeration of all possible parameter combinations leads to an extremely large set of results. For an individual user, the curtailment threshold would be calculated from a combination of independent variables, presenting a much murkier method for estimating reliability. With the more spatially complex flow model described in the above paragraph, user A5's curtailment threshold and probability of curtailment would depend on flow in basins C and H.

Implicit stochastic optimization can provide more in-depth analysis to water right reliability, specifically with the curtailment threshold calculation. However, the solution method grows exponentially more intensive with each additional uncertain hydrologic or water use input variable. Monte Carlo analysis can handle these larger systems, but only generates the probability of curtailment.

The presented methods may be useful for administrators of water right systems. The curtailment threshold could provide a simple method for communicating when a user is curtailed. A user would be told that when flow at a nearby stream gage is below a certain value, they are not allowed to divert water. This method of issuing curtailments has several advantages. DWRAT would no longer need to be run every time period for an entire basin; flow rates could be communicated daily (a system which already exists in many basins) and users with lower curtailment thresholds would cease diversions. Users would benefit from knowing the probability of curtailment, which would allow for better planning of diversions.

Further work

The representation of flow above is greatly simplified. Flow at every point in the basin is assumed to be a proportion of known flow at a single point (the outlet). In larger systems, flow may be much more spatially variable and depend on other factors. One way to decrease this error would be to consider flow at multiple points in the watershed to increase the spatial resolution. For example, in the above basin, flow in basins A and B would be a function of flow in C, whereas flow in lower basins would be a proportion of flow in H.

In the presented example, only uncertainty in flow is examined. Other sources of uncertainty should be explored, such as water demand.

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 expects to minimize falsities, a range of buffer flow values should be explored.

The methods for identifying probability of curtailment could be extended further. Using Monte Carlo analysis, users who are likely to face false curtailments or false promises could be identified. False promises could result from upstream users withdrawing more than allocated, resulting in a physical absence of water for downstream users.

Chapter 4 – Applying DWRAT in the Eel River

Overview of DWRAT in the Eel River

The Eel River is the first basin for which DWRAT has been developed for application. Located on California's Northwestern Pacific coast, the Eel watershed has a rugged terrain and a low population density. Much of the land is undeveloped, with logging having a major role in the local economy. The basin has an average annual precipitation of 60 inches, largely from November through March. Lake Pillsbury, and its forebay, Van Arsdale Reservoir, are the only significant storage projects in the basin. At Van Arsdale Reservoir, flow is diverted to the Russian River watershed via the interbasin Potter Valley Project (PVP).

<u>Water availability in the Eel River</u>

The United States Geological Survey (USGS) operates 11 gages in the Eel. The lowest gage, located at Scotia, has a record dating back to 1911. The Scotia gage has recorded a mean annual flow of 28,800 acre-feet/day (af/d). Average impaired monthly discharge is plotted below in figure 4-1.

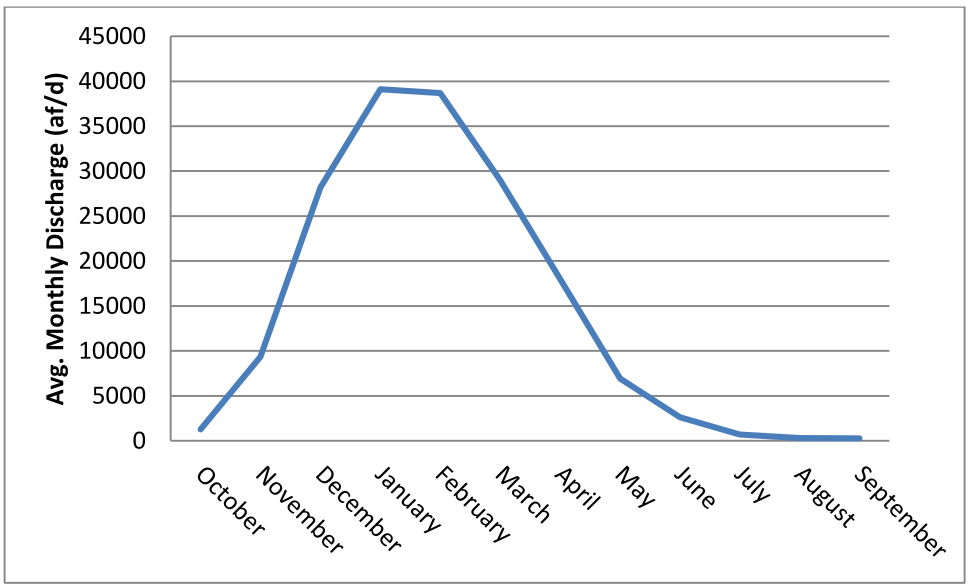

Figure 4-1: Eel River mean monthly flow at Scotia, California. Source: USGS gage 11477000

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

A statistical model developed by Grantham and Fleenor (2014) is used to disaggregate these unimpaired NWS flows to all ungaged HUC12 outlets using ratios of gaged to ungaged flow. The statistical model employs the Random Forests prediction method and the USGS Gages-II database to predict historical monthly flows at all ungaged locations (Carliele 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. The data flow of the model is illustrated in Figure 4-2.

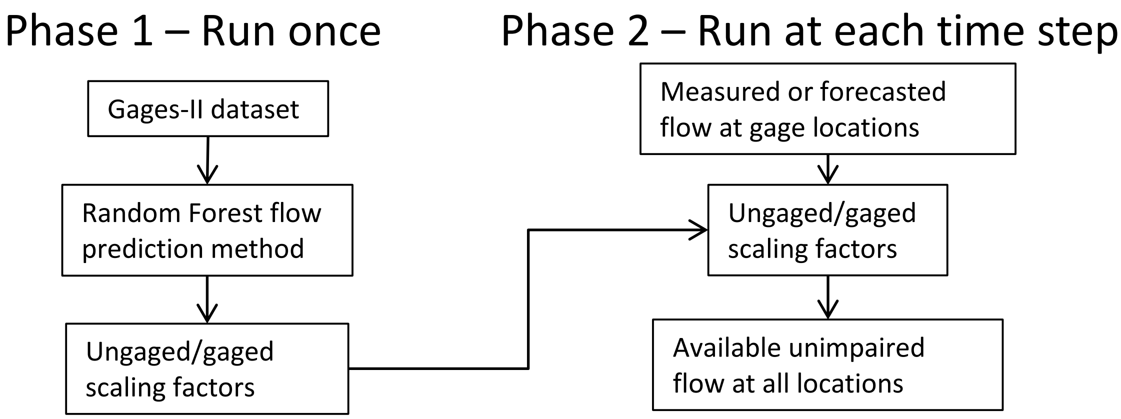

Figure 4-2 Data flow of water availability model.

<u>Water demand in the Eel River</u>

Water rights information for the Eel River is available from the California State Water Resources Control Board (SWRCB) Electronic Water Rights Information System. This dataset contains water right information such as type of right, date of first use, and monthly reported withdrawals from 2010-2013. The dataset lists 683 water active rights in the basin. Of these, 206 are riparian, 30 are Pre-1914 appropriative, and 447 are 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. Figure 4-3 shows the total average monthly demand for each water right category.

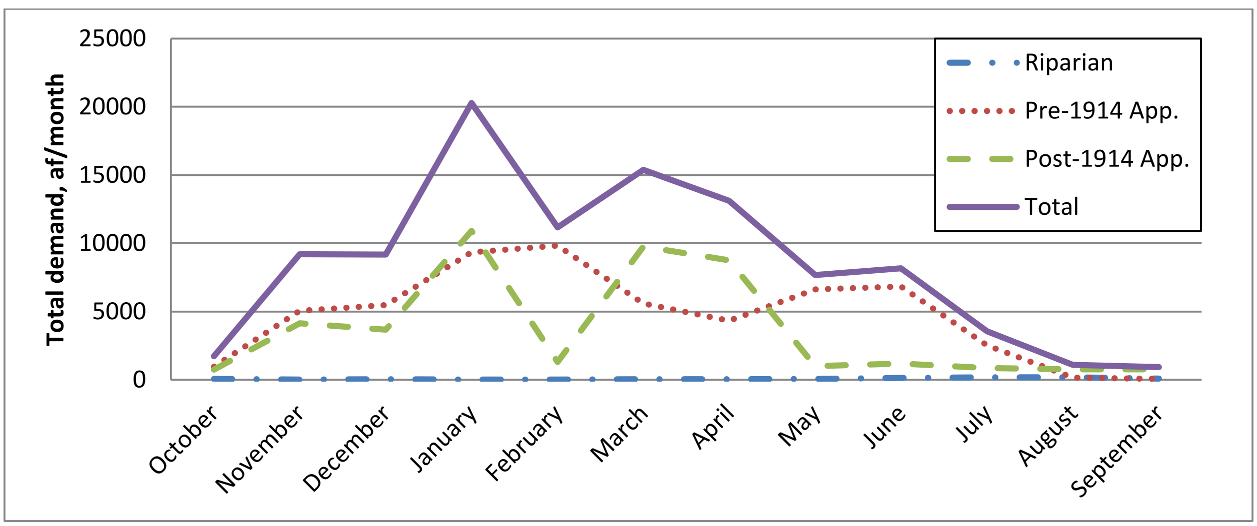

Figure 4-3: Total monthly water demand in the Eel River. Source: California State Water Resources Control Board

Demand is highest in the winter when the most water is available (Figure 4-1) and decreases through the spring and summer. Total demand is dominated by appropriative users, with Pre- and Post-1914 use alternating as category of largest use. Riparian rights are very little of demand overall. Many of the largest riparian uses are for in-stream hydropower, which is excluded from the demand database.

Daily demand is estimated in DWRAT by dividing the average monthly reported use by the number of days in the month. This assumption introduces some error, as water users rarely divert the same amount each day of a month.

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). Post-1914 diversions for public health and safety, and fully non-consumptive uses, such as hydroelectric generation, were exempted from the curtailments. Fines of $1,000 per day of violation and $2,500 per acre-foot diverted in excess of a water right were posted by the SWRCB.

June 30 demand

Table 4-1 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." Pre-1914 appropriative rights account for 6% of the active rights for the day, but are 84% of normal use. Post-1914 rights are the most numerous and account for 20% of total normal use. Riparian rights account for 38% of the total number of users, but only 2% of normal use.

Table 4-1. 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 4-4 shows the June 30 cumulative demand for all rights in the Eel river.

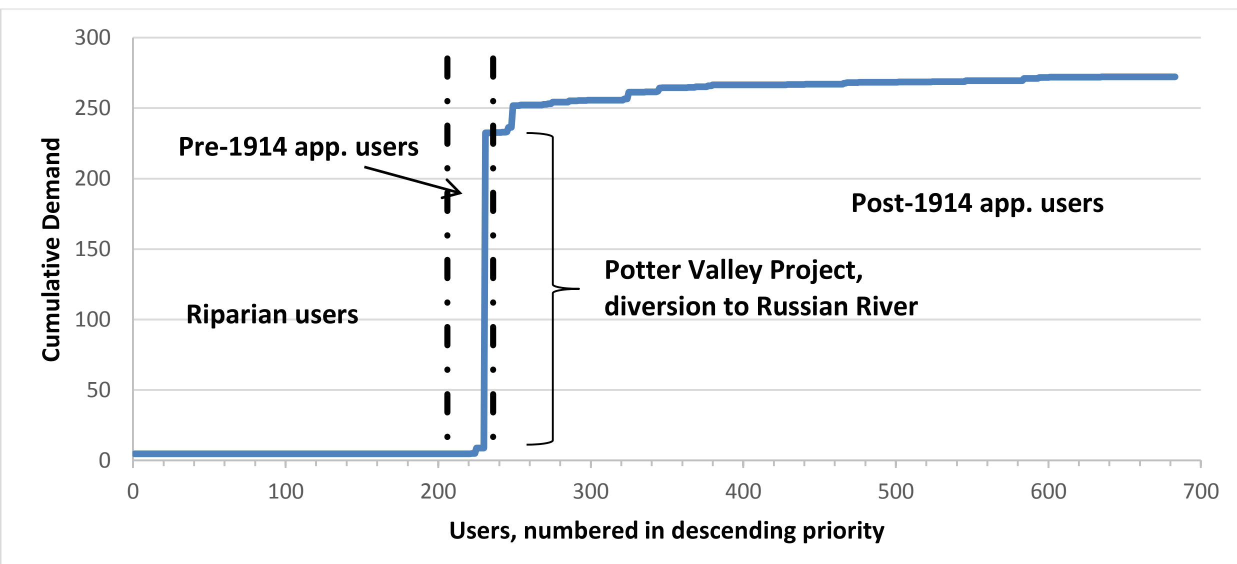

Figure 4-4 June 30 cumulative demand. Regions of the chart are labelled by type of right

Water use volume for June 30 in the Eel River is dominated by a handful of rights. The most notable of these is a Pre-1914 appropriative right with the application number S001010. This right, which corresponds to the largest step in cumulative demand shown in Figure 4-3, is 231st in priority with a year of first use in 1905. Estimated demand for this right on June 30 is 223.8 acre-feet, constituting 98% of Pre-1914 demand and 82% of total demand. The right is owned by the Pacific Gas and Electric company (PG&E) and is used for the Potter Valley Project (PVP), which transfers water from the headwaters of the Eel to the East Fork of the Russian River for producing hydroelectric power.

The second largest right by demand is a Post-1914 right with an application number of A006594, year of first use of 1930 (249th in priority), and estimated June 30 demand of 15.5 acre-feet. This right also is owned by PG&E and associated with the PVP.

June 30 curtailments in DWRAT

DWRAT was used to estimate optimal curtailments for June 30, 2014 in the Eel River. 126 rights were curtailed, or 30% of all users. By priority class, 46 riparian rights (29% of all riparians), 6 pre-1914 rights (24% of all pre-1914s), and 120 post-1914 rights (31% of all post-1914s) were curtailed. In total, 24.9 acre-feet of water was allocated.

Most curtailments occurred 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. Approximately 75% of curtailed rights are in this portion of the watershed, including the large diversions associated with the PVP. Figure 4-5 illustrates distribution of shortage in the watershed.

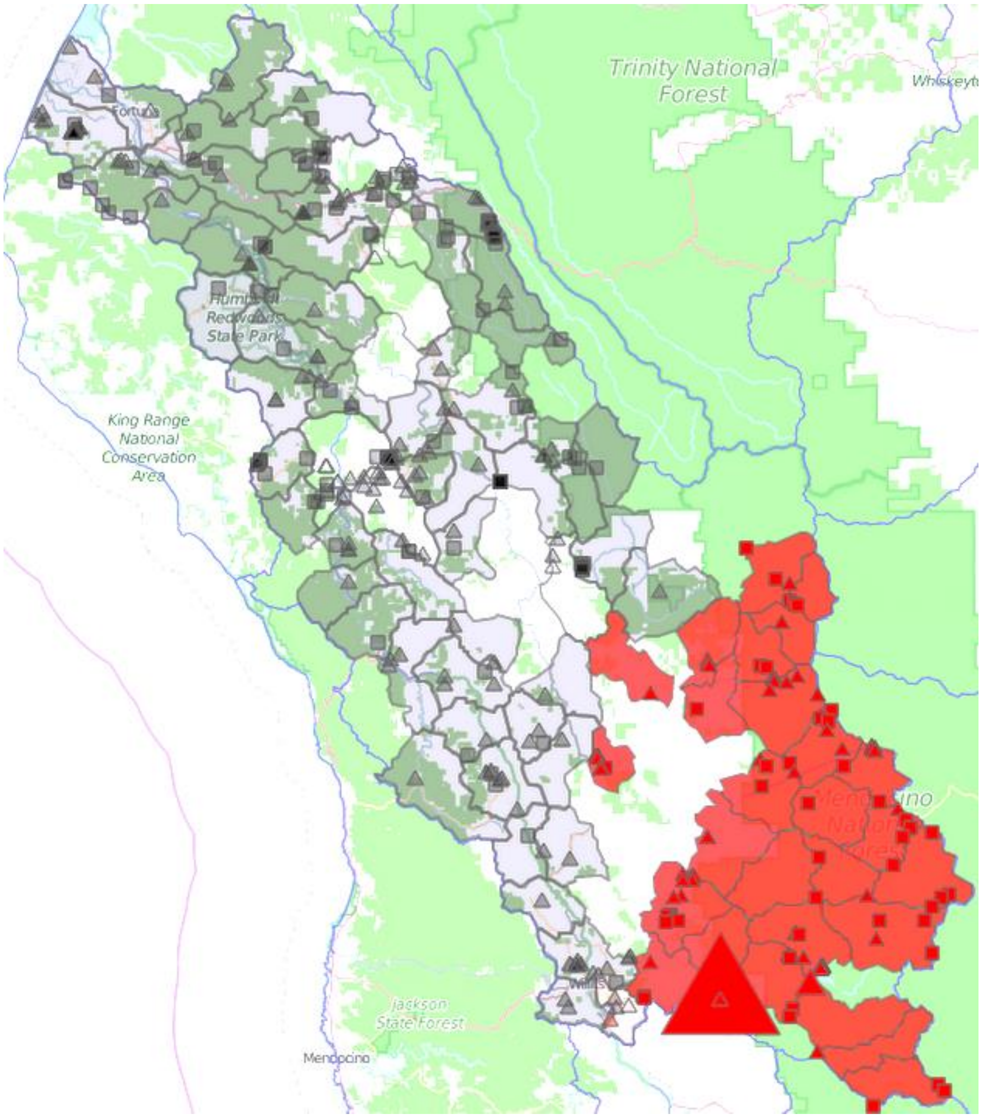

Figure 4-5: Shortage by HUC12 in the Eel River. Basins shaded in red indicate a high degree of shortage. Only HUC12 basins containing rights are shown. Points of diversion are shown as squares (riparian rights) and triangles (appropriative rights) and scaled in size according to quantity of normal use.

The Lake Pillsbury gage is used to calculate supply for the cluster of red HUC12s illustrated in the lower right of figure 4-5. The large triangle in the lower right is the water right for the PVP. Most of the remaining shortage occurs in the upper reaches of the South Fork Eel River, which is to the left of Lake Pillsbury gage cluster.

The curtailments issued by the SWRCB halt 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, particularly those in downstream locations. Shortage was allocated nearly proportionately among user classes, and was more dependent on location than priority of right.

DWRAT allocates full natural flow and does not account for water released from storage, which is available for diversion by appropriative right-holders. This results in lower supply estimations and more curtailments for appropriative rights.

Extending DWRAT in the Eel

<u>Historical analysis</u>

DWRAT was used to calculate June 30 curtailments in the Eel River for previous years. The NWS only began providing unimpaired gage flow in 2014, so an alternative source of unimpaired flows was developed. Three USGS impaired flow gages close to the NWS sites were selected. The gage at Scotia has the longest record, dating to 1911. Figure 4-6 shows a histogram of June 30 flow at Scotia, with a mean flow of 1250 acre-feet/day.

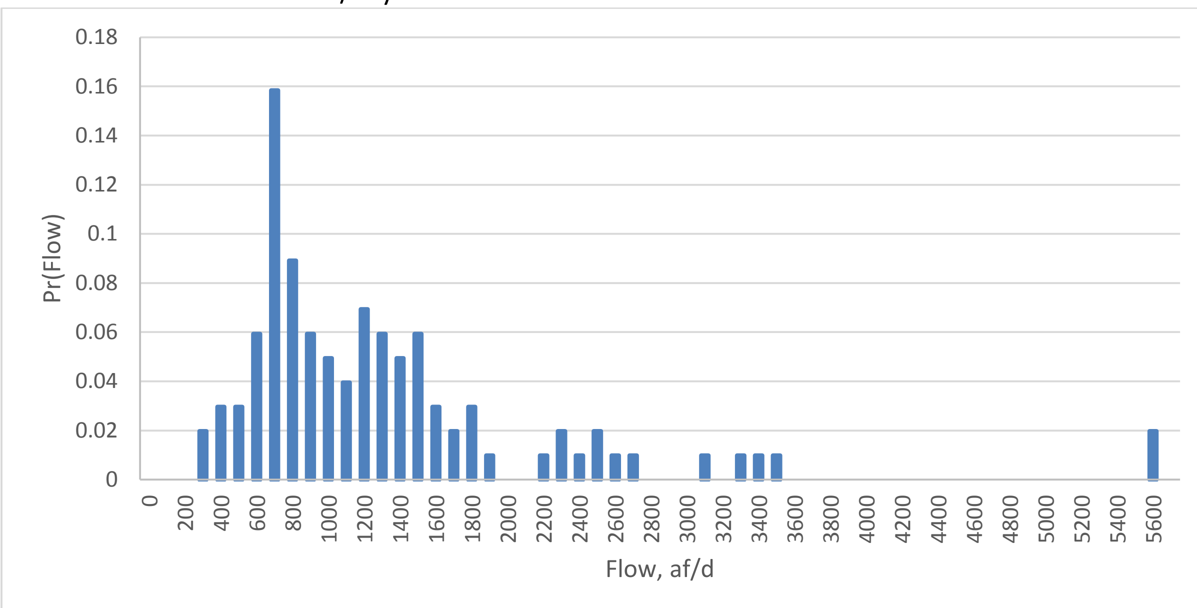

Figure 4-6: Histogram of June 30 impaired flows at Scotia. Source: USGS

The other two stations, at Fort Seward and Lake Pillsbury, have significantly shorter records. A regression analysis was used to develop a trend for the overlapping records between these two stations and the Scotia gage. The trend was then extended over the entire historical record to generate synthetic impaired flows as shown in Figure 4-7.

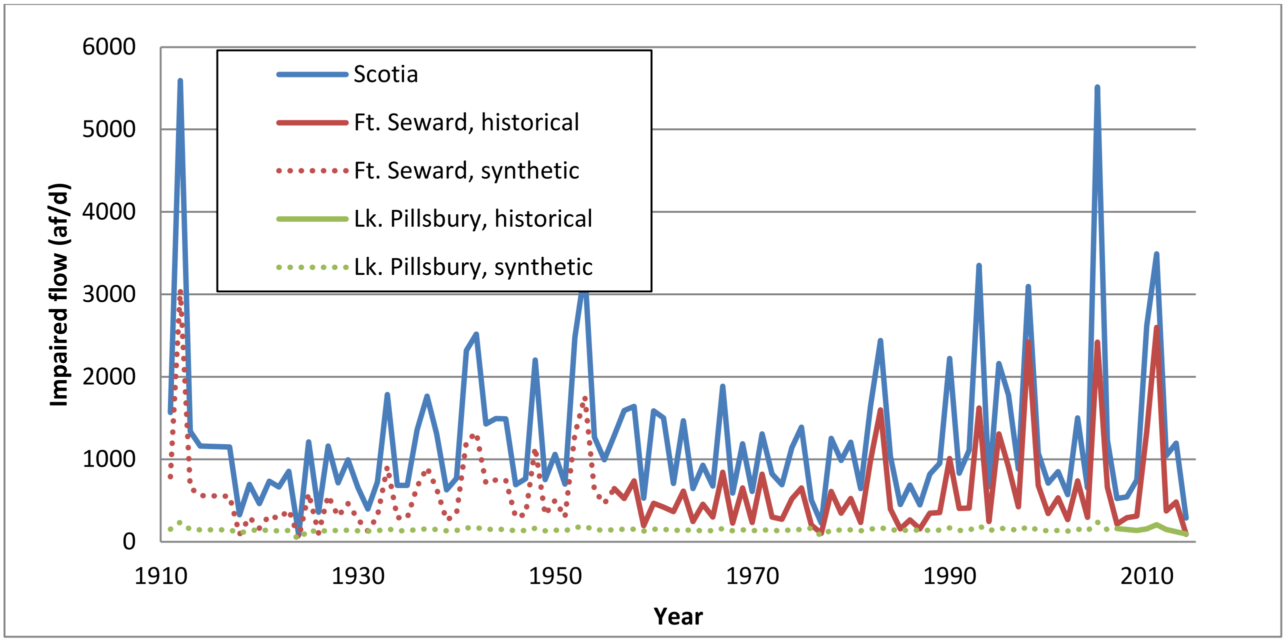

Figure 4-7: Impaired streamflow estimates for June 30 of each year. Solid lines are from USGS data. Dashed lines are generated from linear regression with of recorded flow at Scotia.

The Lake Pillsbury gage, located immediately downstream of a reservoir, has a highly regulated flow over the historical period. Only a very small flow increase occurs during the simultaneous high downstream flows of June 30, 2011. This results in a loose correlation between Scotia and Lake Pillsbury gage flow. Despite multiple downstream high flows in the record, the regression model predicted consistently little variation in flow at the Lake Pillsbury gage.

To estimate unimpaired flow, major consumptive water uses were added to the impaired flow values. The most notable consumptive use, the PVP, is upstream of Scotia and Fort Seward, so the associated June 30 diversion amount was added to these flow records.

DWRAT evaluated curtailments for June 30 of each year using synthetic unimpaired flows from 1911 to 2014. Figure 4-8 shows the number of curtailments for each year.

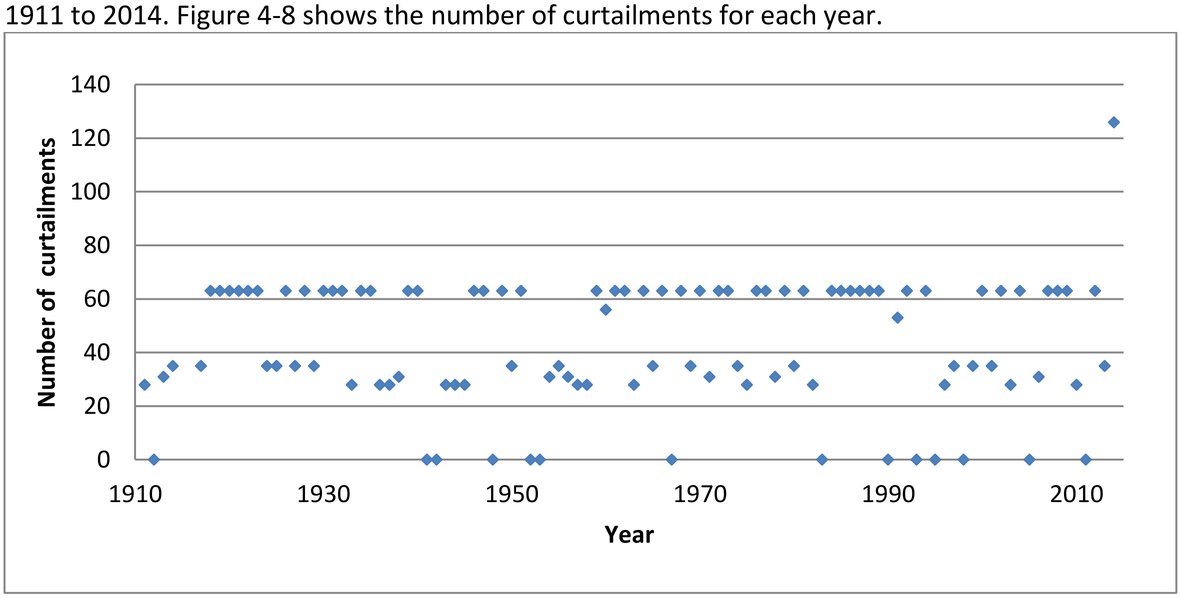

Figure 4-8: Number of curtailed users on June 30, by year, with 2010-2013 average water use

Over the 102-year synthetic 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 varied substantially. Further affecting demand, DWRAT does not include return flows, resulting in decreased availability.

Most curtailments occur in HUC12 basins dependent on the Lake Pillsbury gage flow for flow disaggregation. 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 Project is in this group of basins. The combination of low predicted flows and a nearby extremely large, senior water right result in consistent curtailments for this portion of the watershed. If the PVP is curtailed, almost every other appropriative water right in this region will be curtailed as well.

A representative group of rights was selected for more detailed analysis. Table 4-2 lists these rights and their associated type, date of first use, demand, cumulative demand, and historical probability of curtailment.

Table 4-2: Selected water rights in the Eel River

Water Right ID	Right Type	Year of first use	Demand (af/d)	Cumulative Demand (af/d)	Probability of curtailment
S019887	Riparian	n/a	1.9	48.8	0.00
S020088	Riparian	n/a	0.7	48.8	0.00
S001010	Pre-1914 App.	1905	223.7	288.9	0.64
S015419	Pre-1914 App.	1910	0.0	288.9	0.00
A005504	Post-1914 App.	1927	3.3	302.7	0.00
A006594	Post-1914 App.	1930	15.5	338.5	0.86
A019124	Post-1914 App.	1959	4.7	347.9	0.00
A023038	Post-1914 App.	1968	0.7	382.3	0.47
A031164	Post-1914 App.	2001	0.5	416.2	0.00

Water rights S001010 and A006594 are for the PVP and face the highest probability of curtailment over the historical record, despite having a fairly senior priority. This is likely because of their high demand and location in the upper reaches of the watershed. The selected riparian rights have zero probability of curtailment. Appropriative right A031164 has zero probability of shortage, despite a very junior year of first use. This right is in the lower section of the watershed downstream of Scotia, and is unlikely to face a local supply shortage.

The high frequency of curtailments is also affected by DWRAT's exclusion of water released from storage and return flows. Water released from storage, while only available to appropriative rights, can significantly increase local supplies. Lake Pillsbury and Van Arsdale reservoirs were both constructed to increase delivery reliabilities for the PVP, which releases into the Russian River. Excluding releases from these reservoirs drastically underestimates flow availability for appropriative right-holders. Return flows also would increase the amount of water available for all users. However, most of the large appropriative rights are fully consumptive, and most other water use occurs in the northern part of the basin close to the outlet where supplies are plentiful, reducing the potential benefit from return flows. Return flows may have a larger impact in more agricultural basins, such as the Russian and Sacramento rivers. Furthermore, the historical analysis above applies current water use patterns over the past 102 years.

Implicit stochastic optimization

The method developed in Chapter 3 to estimate curtailment threshold 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 the linear regression equations from the previous section, and assuming constant proportionality of flow in all sub-basins. This makes flow in all HUC12 basins a function of Scotia flow.

Optimal curtailments were calculated for a range of flows at the Scotia gage. Figure 4-9 displays the number of users curtailed over the range of flows.

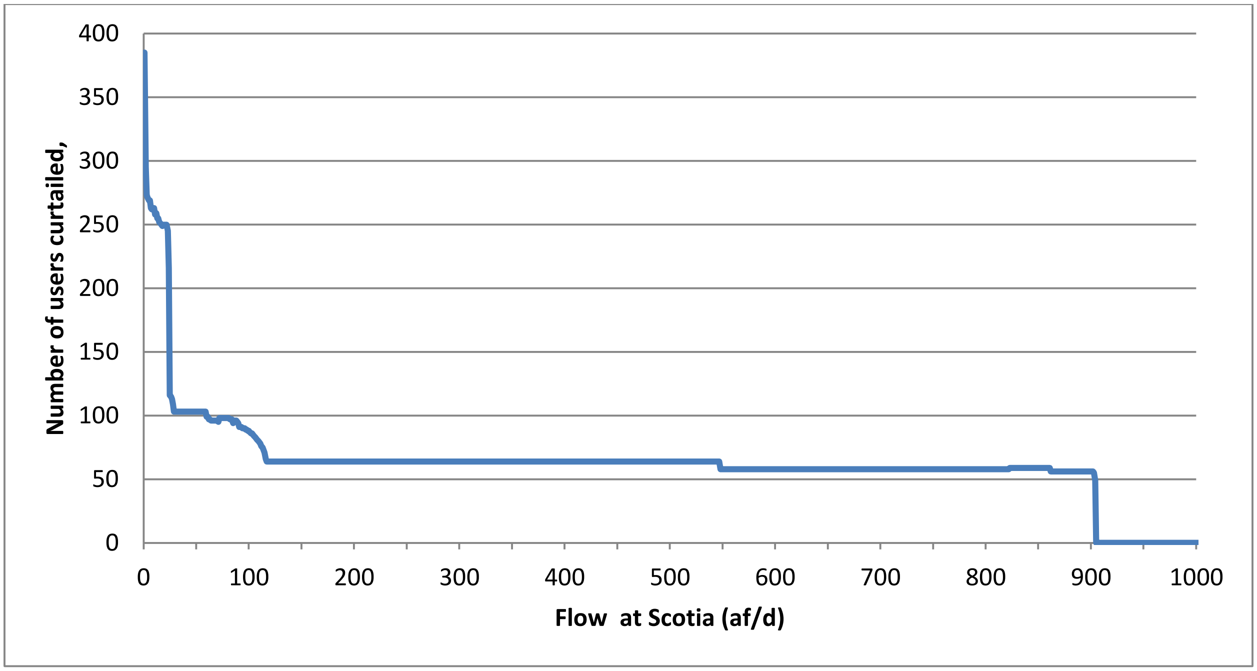

Figure 4-9: Number of users curtailed by flow at Scotia, June 30

The function shown in figure 4-9 was expected to be monotonic decreasing, with the total number of curtailed users never increasing with additional supply. While the function is largely dominated by decreasing and consistent behavior, the number of curtailed users increases slightly at twelve points. This behavior can be seen in Figure 4-9 at flows ranging from 50 to 100 and 800 to 850. Despite the number of curtailments increasing with certain flow availabilities, the total volume of curtailed water (the difference between total demand and total allocations) always decreases monotonically as shown in Figure 4-10.

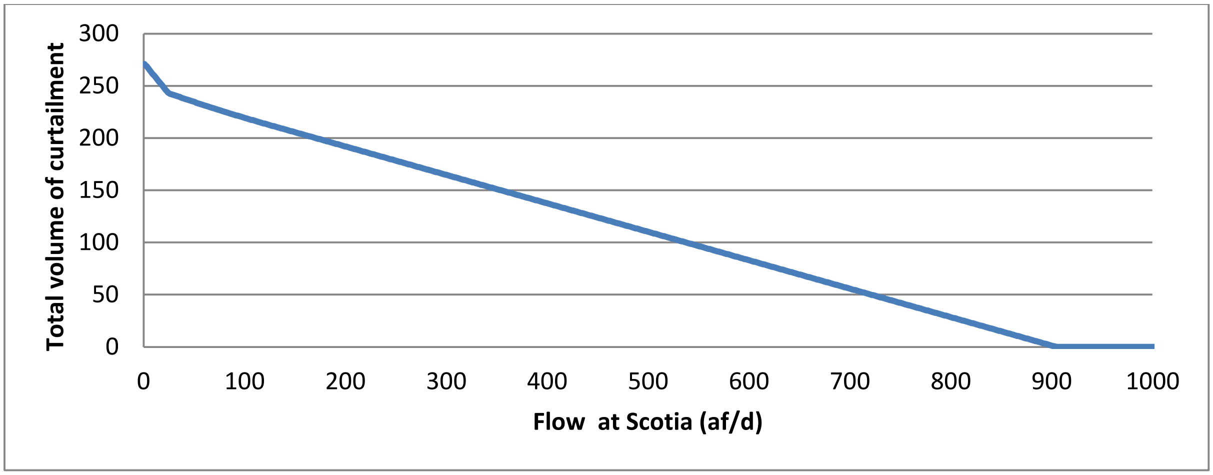

Figure 4-10: Total volume of curtailment for a range of outlet flows.

The cause of the rising curtailments with increased supply is unclear. Rights that experience this curtailment with increased supply are mostly appropriative, making an instance of multiple optima unlikely. The lack of return flows, also eliminates this as a cause. Further work is necessary to determine why curtailment numbers (but not volumes) can sometimes increase slightly with an increase in supply.

<u>Curtailment threshold</u>

Curtailment threshold for the above users is shown in table 4-3. When flow at Scotia is below the curtailment threshold value, the user is curtailed.

Table 4-3: User curtailment threshold for selected water rights

Water Right ID	Right Type	Year of first use	Demand (af/d)	Cumulative Demand (af/d)	Curtailment threshold
S019887	Riparian	n/a	1.9	48.8	1
S020088	Riparian	n/a	0.7	48.8	59
S001010	Pre-1914 App.	1905	223.7	288.9	814
S015419	Pre-1914 App.	1910	0	288.9	23
A005504	Post-1914 App.	1927	3.3	302.7	19
A006594	Post-1914 App.	1930	15.5	338.5	869
A019124	Post-1914 App.	1959	4.7	347.9	904
A023038	Post-1914 App.	1968	0.7	382.3	24
A031164	Post-1914 App.	2001	0.5	416.2	24

Cumulative demand and curtailment threshold are plotted for the selected users in figure 4-11.

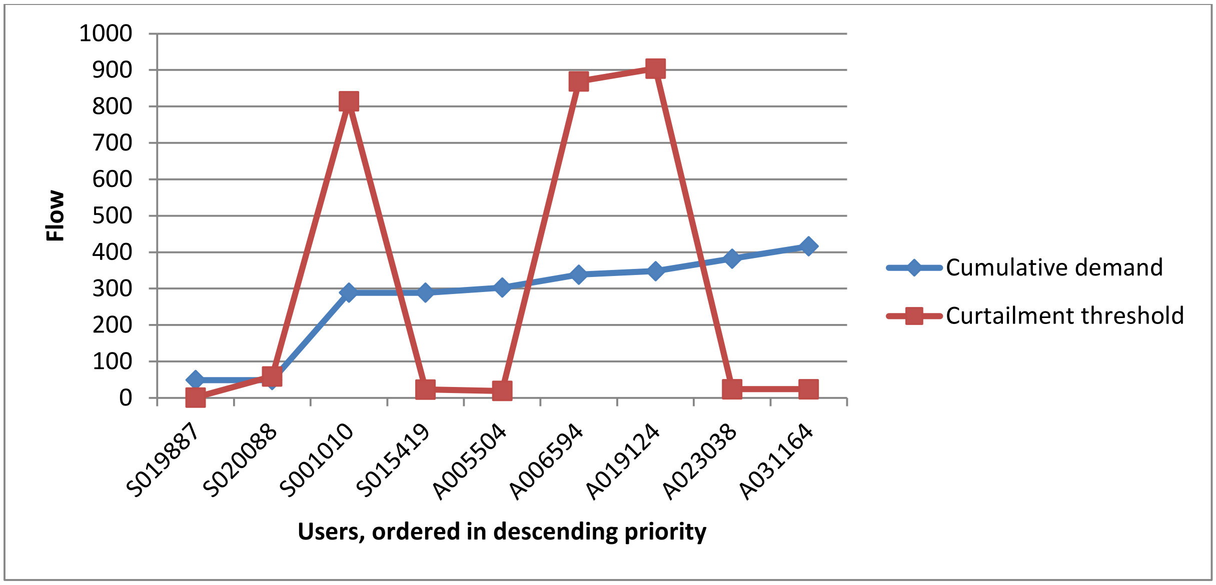

Figure 4-11: Cumulative demand and curtailment threshold for selected users in the Eel River.

Curtailment threshold has little correlation with cumulative demand or priority, particularly with appropriative users. User S001010 is the Potter Valley Project (PVP) and has the largest demand by far in the system. However, because the point-of-diversion for this right is in the upper watershed where less flow is available (figure 4-5), the curtailment threshold is much higher than cumulative demand.

Users S015419 and A005504 have lower priorities than the PVP, but are downstream. Allocations for these users do not affect water availability for any higher priority rights upstream. Curtailment threshold for these users is less than cumulative demand because of this combined priority and location.

By contrast, users A006594 and A019124 have higher curtailment thresholds than the PVP because of their upstream location. Allocations for these users would reduce availability for downstream senior right-holders, so they face a higher curtailment threshold.

Conclusions

Optimal curtailments in the Eel are largely determined by location in the watershed rather than priority of right. Water rights for the Potter Valley Project (PVP) dominate allocations. Users downstream of the PVP face very low curtailment thresholds and should have a low probability 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 the disjoint between 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.

Further work

The representation of hydrology in the Eel River is greatly simplified. Flow for the entire river is calculated from availability at a single point. A more rigorous hydrologic model would enable more precise calculations of optimal curtailments and probabilities.

As mentioned in previous chapters, return flows should be incorporated in the allocation model. Assuming all use is consumptive artificially reduces availability and increases curtailments. Using past reported use as a basis for estimated water demands is also a source of error. Having water right holders "call" their use of water in real time would provide a more accurate basis for fully utilizing available water during drought.

The non-monotonic decreasing of the curtailed users function illustrated in figure 4-9 should be investigated further. Growing curtailment numbers with increasing supply on occasion is counterintuitive and may represent errors in the allocation model or implicit stochastic optimization program, although total curtailment volumes appear to behave as expected.

Chapter 4 references

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Chapter 5 – Conclusions, limitations, and further research

DWRAT enables precise calculation of water right curtailments during drought by incorporating spatial variability of flow, demand, and priority int a mathematical framework representing the logic of California water law. While the 2014 drought is significant, more dry years will occur in the future. DWRAT is an example of an explicit, transparent, and rigorous method for calculating water right curtailments in a mixed water right system, using public data and software. It can help support a more transparent vision of water right curtailments during drought and prepare curtailment administration for future dry conditions. It could easily be used for training new water right administrators for drought conditions during wetter years as well.

DWRAT is structured to be compatible for any temporal or spatial scale. However, the curtailments issued by DWRAT are only as good as the data used for calculation. Improvements can be made in demand, supply, and spatial data.

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

Little data exists on return flows. Rights associated with in-stream hydropower uses have zero consumptive demand in DWRAT, but nonconsumptive use from other sources is not considered. For rights with return flows re-entering the supply close to the point of diversion, allocations could be based on consumptive use rather than total withdrawal. This could be estimated with a simple ratio of nonconsumptive use to withdrawals. Rights where return flows return to supply far from the point of diversion, such as interbasin transfers through hydropower, present a larger challenge. 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 hard to acquire.

The "curtailment threshold" presented in chapters 3 and 4 may present an alternative means for issuing allocations. All users in smaller basins could be told of a specified "curtailment threshold" value for a nearby gauge. When gage flow is below that value, a user will know not to withdraw water to preserve supply for downstream users. This method is most suited for appropriative users due to the clear prioritization among rights.

Water availability is estimated according to the methods described in Chapter 3, using discrete NWS full natural flow forecasts and a spatial disaggregation 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 are able to be administered with greater precision. As California faces future droughts, tighter water rights administration will be necessary.

Through the use of tools such as DWRAT, the SWRCB will be able to better address the needs of future dry years.

Chapter 5 references

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