Drought Curtailment of Water Rights – Problems and Technical Solutions

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Summary

The current drought has focused and renewed discussion about how California curtails water rights when water availability is insufficient. Prior to the 2013-14 water year, the most recent curtailment effort dates back almost 40 years to 1976-77. Since then, many changes and advances have occurred in water use, policies, and technology. New complicating issues include the growth of environmental and water quality requirements. Given the likely growing frequency of the need for water right curtailments and the centrality of curtailments to overall drought management, the State Water Resources Control Board needs a comprehensive, quantitative water rights curtailment program. Preliminary phases of such a program have already been developed and applied in the Eel and Russian River basins, including a Drought Water Right Allocation Tool (DWRAT) that estimates ideal curtailments given data sets on water rights and water availability. Extending this program to other basins, including the Sacramento-San Joaquin Delta watershed, will require decisions on water rights and water availability quantification and resolution of several ambiguous or conflicting policies. Supporting the development of DWRAT as the basis for water rights curtailment decisions will provide a long-term approach that brings structure, quantification, and transparency to a complex and difficult administrative process.

Introduction

The 2013-14 water year was the driest since 1976-77, and the first water year since then to require extensive administrative water right curtailments by the State Water Resources Control Board. Preparation for such administrative curtailments was not extensive. The procedures and documentation from the last curtailments, more than a third of a century ago, provide only imperfect and potentially outdated guidance.

The 2013-14 water year was dry, but should not be seen as exceptionally dry when preparing for the future. In terms of precipitation, this drought year is only the 8th driest in the 106-year historical record. Water demands have grown since 1976-77, particularly with expanding environmental requirements and hardening urban and agricultural water uses. Climate change is likely to increase the frequency of extremes. So the need for administrative water right curtailments is likely to become more frequent, increasing from once in 37 years in the recent past to perhaps once every 5-10 years (from perhaps a 50% chance over the span of a professional career to several times in a professional career). Water right curtailments will go from rare to almost routine, justifying more investments in developing and exercising more routine and transparent administrative procedures, methods, and data for protecting senior water right holders and other state responsibilities, with additional benefits for the transparency and reliability of California's water right and water management systems.

This short report summarizes a range of ideas for improving any administrative water right curtailments needed for the ongoing 2014-15 water year and for improving the practical effectiveness of California's water rights system for the longer term.

Like almost everyone reading this document, we have only written and some oral experience passed down from the 1976-77 drought. We rely here on our experience trying to quickly develop more formal water right curtailment procedures that follow water rights law in 2014, and our broader experience with water management and modeling in California.

Brief Review of 2014 Water Right Curtailments

The 2014 administrative water right curtailments were done largely based on procedures (gleaned from documents and recollections) used in the now-remote 1976-77 drought year. State agencies (SWRCB, DWR, DFW, and CDPH) had made little preparation for implementing broad administrative water right curtailments. However, greater demands and shifting types of demands for water in 2014 meant that potential economic and environmental damages from misallocating water are much greater now than in 1976-77. Under these conditions, administrative curtailments were necessarily somewhat crude, based on broad priority dates, and applied uniformly over large basins for many months.

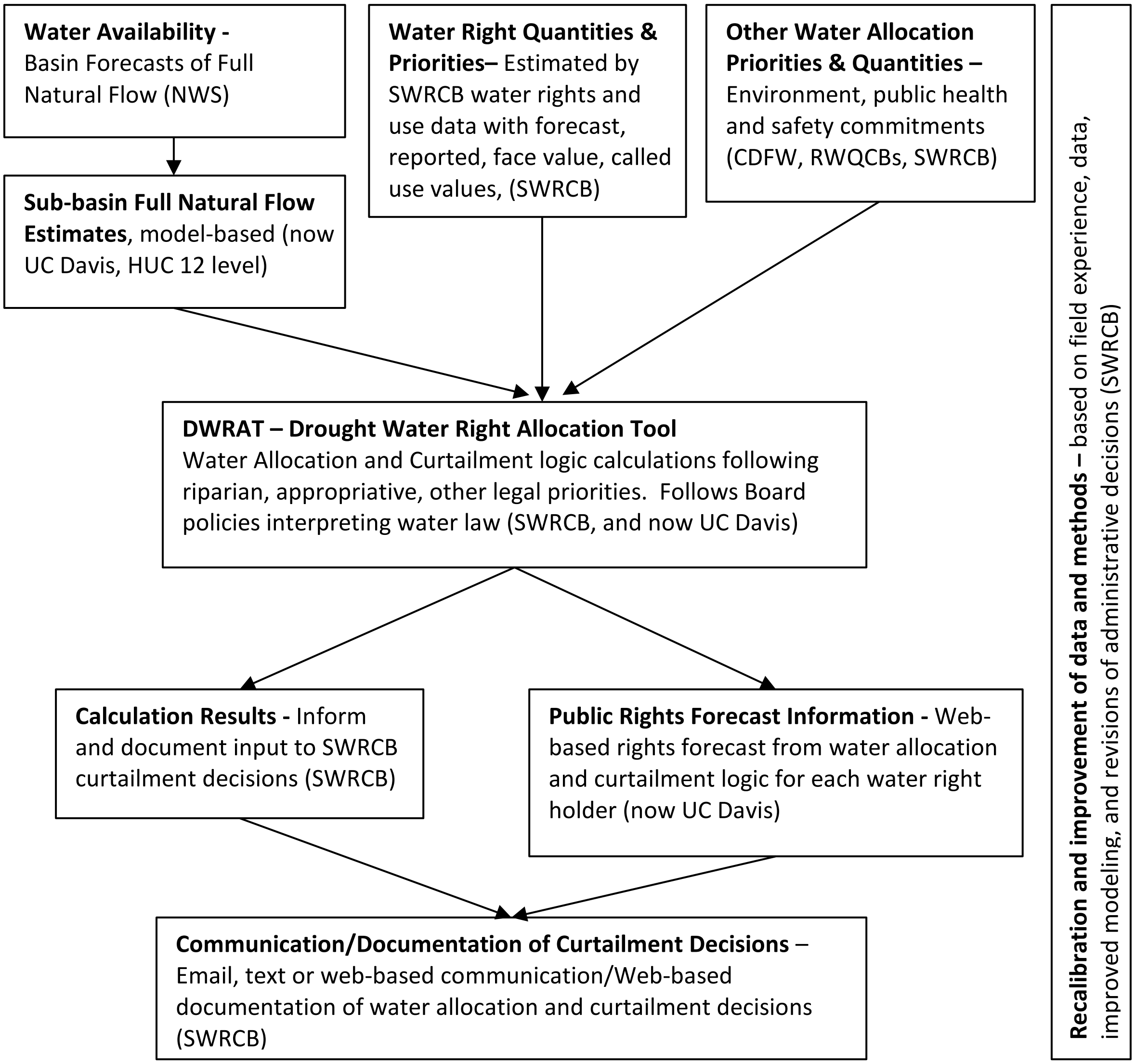
In addition to the coarse approach applied to the 1976-77 curtailments, little formal incorporation of environmental and water quality flows occurred, and few exceptions were made for public health and safety responsibilities. The lack of preparation for managing for environmental purposes during drought seemed especially pronounced. Finally, the interaction with drought-stressed groundwater systems (a difficult technical and policy issue) was generally neglected.

Recent advances have improved the state's ability to curtail water rights since the 1976-77 experience. Fortunately, 2014 was the first year for which monthly water use data were available for an entire prior year (2011), submission of which was required of all water right holders (including riparian and pre-1914 appropriative users). These water use data, with all their substantial imperfections, are on the whole far more reliable indicators of water use than the face value of each water right. Utilizing these self-reported water usage numbers doubtlessly improved the accuracy of curtailments, compared to using the registered quantity of each water right.

Overall, agencies responded with deliberation and unusual flexibility during the event. Water right curtailments have not, and cannot, function in perfect accordance with the intent of current water law given imperfections in the availability and accuracy of water use and hydrologic data, water rights enforcement, and delays in issuing, implementing and communicating curtailments. Nevertheless, several technical steps could significantly improve the administrative water right curtailment process during droughts.

In 2014, the SWRCB experimented with developing a more formal and analytical approach to curtailing individual water rights during drought in collaboration with the authors of this text and others at UC Davis. The general approach that resulted from this effort was applied for the Eel River and is summarized in Figure 1, with details in Appendix A. The approach shows considerable promise and is the basis for many of our suggestions for near-term and long-term state water right curtailments. A demonstration link for results of this work is available for the Eel River at http://watershed.ice.ucdavis.edu/drought/#date=2014-04-28&river=EEL%20RIVER&zoom=9&ll=39.95291166179976%2C-122.49618530273438

Figure 1 - A Water Right Curtailment Calculation Process (Details in Appendix A)



The problem for 2015

Without sufficient precipitation in the coming months, administrative water right curtailments will be required (continued, renewed, or expanded) to effectively enforce water rights. Diminished reservoir and aquifer storage means that more precipitation would be needed to have an equivalent overall water availability to 2014. Statistically, there is about a 50% chance that the new water year will be dry or critically dry. It is prudent to prepare for continued or additional water right curtailments for the new water year.

Last year's water right curtailments were based on necessarily coarse calculations and judgments. To base water right curtailments on more precise calculations will require the SWRCB to make interim policies using the most suitable available data (detailed below) on some ambiguous and important aspects of water allocations and curtailment priorities. Even with such interim policies for calculation purposes, it would be prudent for final allocation and curtailment decisions to be coarser than these calculations to reflect the judgment of the SWRCB.

Although a comprehensive approach to curtailing water rights will involve work beyond 2015, several issues will need to be resolved more quickly. Some interim method or policy judgments are needed to support near-term curtailment calculations. These include:

1. **Quantifying water use by water right holders.** The face value of a water right often substantially exceeds actual water use. So using face values of water right quantities would usually lead to extensive and unnecessary curtailments of junior right-holders, and underutilization of total water available to the water rights system. In the curtailment calculations, it seems most important that these water right quantities represent the actual quantity that each user is expected to use, so fuller use of available water can be made. Options for quantifying water use for curtailment calculations include: a) historically reported monthly use, b) face value quantity of water right, c) a formal "call" on the right by the right-holder (especially larger right-holders), or d) some other forecasted amount of water use.

Of these options, implementing a "call" system is recommended. If the largest senior water users can "call" use of their rights in advance, it should help make fuller and more reliable use of the available water. Having users "call" their rights during times of shortage is a common expectation in traditional appropriative water rights systems (such as Colorado and Utah). Sometimes a senior right-holder "call" instigates an administrative water rights curtailment on a basin over the course of the season. In other cases, the call can indicate the amount of water a senior water right holder intends to use, in advance, so that water flows and uses can be more tightly coordinated. Both senses of "call" could be used. If "calls" are made electronically for major water users, perhaps up to several days in advance, it should be possible to administratively tighten water allocations considerably, and provide much more timely information and adaptability for water users.

2. **Use of "buffer", reliability, or safety factor flow quantities to account for uncertainties inherent in flow and use estimates.** Physical reality will always deviate somewhat from water right calculations. Requiring that higher "buffer" flows remain after allocations and curtailments are calculated increases the reliability of senior allocations and priorities. However, including higher "buffer" flows also increases the likelihood that junior water right holders will receive less water in some cases than may be physically possible. With time and experience, it should be possible to reduce this safety factor in the calculations. Some numerical experiments using Monte Carlo modeling can help guide selection of proper buffer flows in the meantime. (Buffer flows need to be larger if "calls" are not made in advance, and might be negative where large return flows exist from senior water right holders.)

3. **Quantifying available water resources at the basin and sub-basin scales.** Full natural flow estimates are uncertain during drought, particularly for smaller and higher-elevation sub-basins. A host of technical decisions regarding the appropriate size of sub-basins, methods and models for estimating full natural flows at basin and sub-basin scales, groundwater interactions, and return flows and locations from water diversions will need to be made or explicitly neglected. The National Weather Service can provide estimates of full natural flow for some

locations, but mathematical models (bases on a combination of physical processes and field data) are needed to disaggregate such natural flow estimates to smaller sub-basins. UC Davis currently uses a USGS model to disaggregate such flows to the HUC 12 level (Appendix B, Section 2).

4. **Establishing methods and policies to estimate and prioritize environmental, water quality, and public health and safety uses during drought.** Legal priorities for allocating water during drought might include more than water right priorities for water allocation. The State Board would probably initially judge the priority balance of these and other water uses, but estimates of these quantities and locations might involve CDFW (for fish and ecosystem flows), RWQCBs (for water quality flows), and CDPH (for public health and safety).

In the absence of clear estimates of alternative water objectives. Short-term options sometimes include expanding using 1707 dedications to add flexibility to water use within the existing water rights framework. In Siskiyou County, two water rights holders with primarily agricultural use, successfully petitioned to add environmental objectives to their beneficial use (SWRCB 2014a, SWRCB 2014b, CA Superior Court Decree No. 7035). Through water transfers, this water was transported instream for environmental objectives; it also had the potential to transfer to more junior water rights holders located downstream of high-value aquatic habitat who might not have otherwise received water during a curtailment. This is an important longer-term option as well.

Different public health and safety and environmental flows might have different legal or policy priorities and quantities in the context of drought emergency authority and administration. Different priorities might be assigned to different environmental flows, based on their legal basis. Some potential categories of environmental flows might include:

- Biological opinions pursuant to the Endangered Species Act
- Clean Water Act flows for water quality
- Migratory bird treaty requirements for wetlands
- Fish and Game Code 5937, requiring fish flows downstream of dams

These quantities might have conditional values during drought to balance interests under the general authorities of the California constitution, Article X, Section 2, and the Public Trust Doctrine.

Another difficulty in balancing environmental flows during drought is the possible consequence of low environmental flows. Additional endangered species listings may result from drought conditions, as happened following the 1988-92 drought, which could further reduce water availability to water right holders.

5. **Public reporting of water right curtailment information.** In basins where detailed calculations have provided most of the justification for curtailment and allocation decisions by the Board, these calculations can be made public. To do so would require interim policies or decisions for making data and calculations public. Transparent calculation and decision methods build credibility to the water right curtailment process and help water right holders anticipate and prepare for curtailments. If the process is extended to include forecasted curtailment estimates, similar issues would apply, although existing data might make curtailment forecasts fairly crude in the near term.

These actions, as well as long-term considerations, are summarized in Table 1 in this document's conclusions section.

State Board calculations for water right curtailments, using methods from 1976-77, are inherently coarse. If the State Board would like to use more detailed calculations for identifying legally appropriate curtailments and allocations across many more basins in 2015, it would be necessary to enlist a broader range of state and local expertise to gather, organize, and appropriately employ existing data for more detailed water right curtailments. This might involve district offices of the Department of Water Resources and some of the larger county or other regional water agencies, perhaps with some RWQCB staff, where suitable staff are available. With proper motivation, leadership, resources, and authority, many more basin curtailment calculations could be formalized in 2015, but such an effort would have to begin almost immediately.

At the end of 2015, or perhaps at the end of the drought, a formal assessment should occur of technical, legal, and institutional issues that have arisen, along with options for making improvements for the future.

Beyond 2015 - Modernizing technical aspects of water right administration

While the previous suggestions may address short-term needs in the water right curtailment process, additional measures are needed to develop a practical and systematic long-term approach. In the longer term, California's water right curtailment system is likely to see more frequent use. Increased frequency in administrative curtailments with growing water demands from most sectors will increase the economic, legal, and environmental importance of making curtailments consistently, reliably, and timely, so that water users can better make alternative advance arrangements for water supply and demand reductions. Water right curtailments also will need to more explicitly fit with other legal and social water management objectives, particularly environmental and urgent public health and safety demands. Anticipating its routine implementation as drier conditions occur more frequently, a water rights curtailment system for droughts also should take advantage of more modern data, computation, and communications technology to make more complete and appropriate allocations of available water, with greater transparency and forewarning to water right holders and other interests.

At the UC Davis Center for Watershed Sciences, we have been thinking about what such a water right curtailment system might look like. This is represented schematically in Figure 1. At the center of this system is a Drought Water Right Allocation Tool (DWRAT), a mathematical model to estimate the most appropriate legal curtailments of water rights. Based on the decisions made regarding the critical interim issues identified above, these curtailments integrate information about local hydrology, regulatory policies, individual water use, and water right and use priorities. This explicit approach, which is being experimentally applied to the Eel River and developed for the Russian River, provides a framework for making fuller use of available water during a drought with a more timely response to changing hydrologic conditions. A summary description of this process and current data and methods used in each step is in Appendix A.

This approach brings together fundamental data on water availability, water rights, and other water management concerns from various local, state, and federal agencies. Reducing the calculation of water right curtailments to mathematical logic requires explicit interpretations of water rights law by the SWRCB in cases of ambiguity, and would accommodate future modifications as such issues are resolved. This type of framework should allow for a far more transparent, precise, and minimal curtailment of water rights, with benefits for legal justification as well as timeliness of proceedings, and improved ability to forecast the duration of curtailments. Such a framework also would allow for the more precise and increasingly accurate quantification of water availability, rights, and uses with time and experience.

Such a framework for water right curtailments during drought will initially identify gaps and problems with data. In the future, remote sensing, groundwater interactions, return flows, and gage data can be more explicitly integrated to update and improve water availability accounting. In terms of policy, such a framework would allow for more explicit and transparent representation of water rights and other related law, regulations, and policies, and the more timely implementation and enforcement of the law.

It is reasonable to expect that early applications of these more formal methods will be more to inform existing water right curtailment administrative judgments than presenting exact prescriptions for curtailments. However, these methods and their results, when compared with field and other data, would be improved to make more reliable and direct estimates of legally ideal water right curtailments. On-going studies have already begun to explore these issues; Appendix B to this report includes some technical descriptions of this work so far.

Some additional suggestions

The process to develop a comprehensive, quantitative, and transparent curtailment process would benefit from additional information in several areas. Recommendations for next steps include:

1. **Build on existing experiences elsewhere.** California is not unique as a dry part of the world with a large agricultural sector and population that faces occasional or frequent drought. It would be useful to commission a comparison of California with other Western States and other developed semi-arid and arid regions in terms of technical, institutional, and legal procedures for curtailing water rights during periods of shortage. These states and regions might include:
   - Arizona, Colorado, Idaho, Kansas, Nebraska, Nevada, New Mexico, Oregon, Utah, and Washington State
   - Australia, Spain, Italy, southern France, South Africa, Chile, etc.

The 1874 plan for irrigating the Central Valley benefitted immensely from such a global survey; such a survey should be updated.

2. **Water use reporting.** As water right curtailment becomes more frequent, the quality of reported water use data becomes more important. If reported use is a frequent basis for water right curtailment calculations, then over-estimates of use detracts from junior right-holders, and vice-versa. Additional quality control and enforcement on reported water use, particularly for larger users, will be useful. Return flow estimates, timing, and locations also will be needed to further reduce uncertainties in net water use, particularly for large water users with substantial return flows to streams. For some uses, it might be possible to replace, supplement, or cross-

check reports with remotely sensed measurements of evapotranspiration. This is done in Idaho, for example, economically and apparently to good effect.

3. **Refine estimates of "buffer" flow quantities.** Efforts to quantify error should be included in programs to systematically improve data and estimation methods, particularly for estimates of full natural flows at basin and sub-basin scales. This would likely involve the NWS and DWR as well as agencies with local hydrologic expertise and pragmatic hydrology experts.

4. **Policies for quality control and documentation of data, calculations, and decisions.** These will be useful for improving the transparency, calculations, and quality of more routine water right curtailment decisions.

5. **"Dry runs" –** Having drought curtailment exercises each year or in alternating years would better ensure that State Water Board staff are prepared for more intensive periods of drought water right curtailment, prepare collaborating agencies (such as DWR and CDFW and local agencies) for providing data needed for effective water right administration during drought, and establish public and water right-holder expectations, procedures, and advance feedback for how water right curtailments would proceed during droughts. Such exercises would be similar to flood, earthquake, fire and other emergency exercises commonly used to prepare agencies and stakeholders for rare and common times of critical decisions. These exercises might be held for different basins around the state in each year, to foster better collaboration and information sharing with local agencies and water users.

6. **Incorporate forecasting capabilities.** Forecasts of curtailments might have considerable benefit for water right holders with economic needs that could benefit from buying and selling water or making alternations to water demands during a drought. Ideally, the drought curtailment system would interface well with the administration of temporary water market transfers or temporary changes in diversion location, perhaps partially automating approval of water transfer agreements or even allowing identification of promising water transfers. These processes require similar data, and could provide broader functionality. This should be explored.

7. **Public communication and outreach.** Communications with the public and water right holders could likely be made more useful, informative, and effective using a web interface, perhaps with email or text messages, and including forecasts of curtailments. A demonstration link for such a website is available for the Eel River at http://watershed.ice.ucdavis.edu/drought/#date=2014-04-28&river=EEL%20RIVER&zoom=9&ll=39.95291166179976%2C-122.49618530273438

Overall conclusions and recommendations

Drought water right curtailments are likely to become more frequent and consequential to California. It behooves the state to develop a more formal and routine framework for assembling the data, policies, procedures, and authorities needed to implement water right curtailments in a timely, transparent, and reliable way. This approach will take advantage of more modern analytical, data management, and communications methods, and if properly done, will provide many additional benefits to water users and state agencies during droughts, and in preparing for droughts.

Specific recommendations have been identified to move the state in this direction in the near term and in the longer term. These recommendations are summarized in Table 1.

Table 1. Some actions worth considering

Near-term Actions (2015)
Administrative
• Expand use of formal water right curtailment calculations • Develop an explicit interim standard method for estimating water right holder use and full natural flows for water right curtailment calculation purposes • Develop explicit interim methods under existing state authorities and policies to estimate and prioritize environmental, water quality, and public health and safety uses in drought • Develop an explicit interim method or policy for the use of a buffer or safety factor quantity for water right curtailment calculation purposes • Have large water users "call" use of their water rights to tighten water allocations. • Develop online mechanisms to publically report and gather curtailment and use information • Gather local, state, and federal expertise and data to better quantify drought water availability in major basins
Scientific
• Improve quantification of water use, available water resources, and "buffer" flows to account for inherent uncertainty, to improve allocation reliability • Monte Carlo numerical study to estimate trade-offs water right and full utilization reliabilities for different "buffer" flow values • Multi-agency review of accretions and depletions estimates in large watersheds
Legislative
• No legislation seems needed unless for confirmation of authorities or for funding
Long-term Actions (becoming effective after 2015, but often started sooner)
Administrative
• Refine water use reporting and enforcement to improve estimates of actual use • Implement "dry run" training to prepare for curtailment periods • Develop and implement policies for quality control and documentation of data, calculations, and decisions • Establish a communication network with public and water right holders using a web-interface, e-mail, or text message • Expand forecasting capabilities and reporting for water right holders for finer time scales • Explore expanding water right curtailment forecasting system to support water transfer permitting and promising water transfer identification • Manage the surface water system conjunctively with the local groundwater system • Expand water right curtailment calculations to additional basins
Scientific
• Identify potential strategies through a review of curtailment methods elsewhere • Collaborate with partnering agencies to reduce errors in data and estimation methods • Assess forecast potential for curtailment decisions • Investigate use of remote sensed ET for consumptive use estimation • Develop methods to quantify return flow locations, quantities, and timing for larges water rights • Improve disaggregation of basin flow forecasts to sub-basins • Refine full natural flow calculations to better account for groundwater interactions
Legislative
• Expand routine data collection and information sharing on water use and return flows for large water right holders.

Appendix A – Components and data sources for formal water right curtailment (from Figure 1)

1. Basin Forecasts of Full Natural Flow

The National Weather Service (NWS) operates a network of river flow monitoring and flood forecast stations throughout the nation. Ensemble forecast models of natural (unimpaired) surface flows are available for some of these stations. These natural surface flow forecasts provide the input to the spatial disaggregation model for estimating water availability in sub-basins, described in Appendix B, Section 2.

2. **Sub-basin Full Natural Flow Estimates**

To date, full natural flows for each HUC12 sub-basin have been estimated with a spatial disaggregation model developed at UC Davis. This model applies data mining techniques to geospatial data to distribute flows throughout a basin. This process is described in Appendix B, Section 2.

3. **Water Right Quantities and Priorities**

Data for water rights, including water right type (riparian or appropriative) and priority, face value, 2013 monthly reported use, filing date, and point-of-diversion location, are provided by the State Water Resources Control Board (SWRCB).

4. **Other Water Allocation Priorities and Quantities**

To date, priorities and quantities for environmental flows, public health and safety, and flows necessary to maintain water quality standards have not been defined, but are available for use in the data and modeling framework.

5. **Drought Water Right Allocation Tool (DWRAT)**

This tool mathematically estimates the legally-required curtailment of water rights, given explicit interpretations of water law and data on water availability, uses, and legal priorities. UC Davis has developed such a tool to maximize water allocations to right-holders in a basin while following riparian, appropriative, and other legal priorities as interpreted by the SWRCB. Appendix B, Section 1 describes the initial version of this tool, which has been applied to the Eel River.

6. **Calculation Results**

DWRAT results are used to inform and document input for SWRCB curtailment decisions. The SWRCB will verify the results and check for anomalous allocations or model behavior and make final water right curtailment judgments given model results and their agency judgment given uncertainties in data and conditions.

7. **Public Rights Forecast Information**

The curtailment model (DWRAT) can be run in advance with full natural flow forecasts from the NWS, allowing the SWRCB to forewarn users of curtailments before they go into effect.

8. **Communication of Curtailment Decisions**

UC Davis has developed a web-based map interface for communicating curtailment decisions. Each water right is displayed, along with the corresponding demand, priority date, and allocation. A demonstration link for this website is available for the Eel River at http://watershed.ice.ucdavis.edu/drought/#date=2014-04-28&river=EEL%20RIVER&zoom=9&ll=39.95291166179976%2C-122.49618530273438

Appendix B, Section 1: Drought water rights allocation tool formulation

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Abstract: Within California's water rights system, water users have different priorities to water that is naturally available during drought. Higher priority users are less likely to face shortage due to the demands of other users, but may be limited by reduced availability of water. An integrated set of water right allocation models was developed to determine optimal allocation of shortage for riparian and appropriative water right holders, which also allows for including required flows for the environment and public health and safety, and operational reliability for senior water right-holders. Riparian water right holders have equal priority, with water shortage allocated as an equal proportion of normal diversions for all riparian users within each sub-basin. These proportions are determined by water availability, with downstream users likely to receive higher proportions due to downstream accumulations of streamflow. Appropriative users as a class have a lower priority than riparian users. Shortages allocated among appropriative water right holders are made strictly by water right seniority.

Introduction

In droughts, water availability is reduced and water users face shortages. A set of linear programs is presented to allocate water between users with riparian and appropriative water rights with restricted flow availability throughout a basin. Shortage is allocated among riparian water right holders by restricting withdrawals to a certain proportion of normal usage in a basin. With appropriative water right holders, water supply is allocated by seniority of right. Senior appropriative right holders have a higher priority in access to water, but may experience shortages due to reduced flow. Junior right holders have a lower priority in water access, and may experience shortage in order to preserve access for senior users. Other factors of interest in allocating water include environmental flow requirements, allowance for public health and safety, and, in light of uncertainties in flow estimation, allowing some reliability flow buffer so allocated water use can be available with greater reliability.

Model formulation

The water rights allocation tool developed allocates water for all these types of uses and rights in two phases. The first phase allocates available water proportionally among riparian water users. The second phase allocates any remaining water availability by strict priority among appropriative water right holders. In both phases, water users are scattered over a network of sub-basins, facing different water availability within the larger basin.

Each water rights allocation model assumes all users were either riparian or appropriative, with no return flows and known inflows to each sub-basin. Flow is modelled in the system with total water availability in a catchment k represented by v_k, with environmental flow e_k. Environmental flows are assumed to be a fraction of total availability v_k. Each user i receives water allocation A_i. Appropriative users have a certain priority in allocation determined by water right seniority, reflected in the unit shortage penalty p_i, which increases with seniority. Riparian users have equal priority and no ranking is given to users. Shortage is allocated by limiting diversions to a set proportion of normal reported usage 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.

Riparian water right allocation
The following equations characterize the riparian user allocation model:

Minimize:

1) $z = \alpha \sum_k w_k P_k - \sum_i A_i$ [Minimize weighted sum of basin allocation proportions minus total allocations for the overall basin]

Subject to:

2) $A_i = P_k u_i, \forall i, i \in k$ [Each riparian user's allocation is defined as the proportion of normal use for its upstream-most sub-basin]

3) $P_j \leq P_k, \forall k, j \in k$ [Riparian use proportion for tributary basins cannot exceed downstream basins]

4) $\sum_{i \in k} A_i \leq v_k - e_k, \forall k$ [Cannot allocate more than is available per sub-basin, intermediate basin, and basin]

5) $0 \leq P_k \leq 1, \forall k$ [Each basin's allocation proportion is between 0 and 1]

6) $A_i \geq 0, \forall i$ [No negative allocations]

7) $A_i \geq u_{i,Public\ Health\ and\ Safety}, \forall i$ [Allocations must meet minimum public health and safety requirements]

8) $w_k = \frac{n_k}{n_{k,system\ outlet}}$ [Proportion penalty weights for a basin increase downstream]

9) $\alpha < Min\left(\frac{w_k}{d_k}\right) \forall k$ [This weight makes water allocation more important than reducing the proportion allocation, so allocations occur in sub-basins with little water use

Where z = total system penalty; α = weight applied to all weighted proportions; A_i = water allocation for user i, P_k = proportion of normal usage allowed for all users in sub-basin k, w_k = weighing factor of basin proportion for basin k;; v_k = flow in basin *k*; e_k = environmental flow requirement in basin *k*; u_i = normal usage (demand) for user *i;* n_k = number of basins upstream of basin k; and d_k = sum of usage upstream of basin *k*.

The objective function (equation 1) minimizes system outflow (maximizes total water allocation) while maintaining the proportionate multiplier for each subcatchment. Under ideal system operation, water availability (equation 4) is binding for all sub-basins where demand exceeds flow. When this constraint binds, P_k becomes less than 1 and equation 2 binds for all users in the sub-basin. If available flow exceeds total demand in a basin, P_k will be 1 and equation 2 will bind as each user in the basin will receive their full demand.

Appropriative water right allocation
The following equations represent the appropriative user model:

Minimize:

10) $z = \sum_i p_i(u_i - A_i)$	[Minimize sum of priority-weighted shortages, weight increases with priority]

Subject to:

11) $\sum_{i \in k} A_i \leq v_k - e_k - \sum_{i \in k} A_{upstream\ riparian\ users\ i}, \forall k$	[Cannot allocate more than is available in basin and upstream after riparian user allocations]
12) $A_i \leq u_i, \forall i$	[Allocations cannot exceed demand]
13) $A_i \geq 0, \forall i$	[No negative allocations]
14) $A_i \geq u_{i,Public\ Health\ and\ Safety}, \forall i$	[Allocations must meet minimum public health and safety requirements]

Where z = total system penalty; A_i = water allocation for user i, p_k = unit shortage penalty coefficient for user i; v_k = flow in basin k; e_k = environmental flow requirement in basin k; and u_i = normal usage (demand) for user *i.*

The appropriative model objective function minimizes the total shortage penalty in the watershed. The penalty coefficient p_i increases with water right seniority ranking for each user, with the most senior user having the highest penalty and the most junior user having the lowest. If demand exceeds availability in a sub-basin, water availability (equation 11) will be binding and junior users in the basin will likely be shorted.

All use in the models is assumed to be consumptive, with no return flows. This will result in users likely being allocated less water than is actually available. Israel and Lund (1999) present a method for developing priority-based penalty coefficients for network flow programming models of water resources system. This algorithm could serve as a pre-processor for the above models to account for return flows while preserving the priority ranking of water rights.

All users within a subcatchment *k* are assumed to have equal access to total flow (v_k). This may not necessarily be true, as some basin flows will have a spatial distribution within each subcatchment that may not allow users to receive their full allocation. While the maximum allocation for each user is their previous usage u_i, reflecting the hydrology within the sub-basin, these usages are reported under normal flow circumstances and may not be feasible under drought conditions. Error from this assumption could be minimized by increasing the spatial resolution of the model and implementing a finer subcatchment grid. Error could also be reduced by restricting allocations for each user to the percentage of total sub-basin outflow available at the user's point of diversion.

Model application

An example watershed, illustrated in figure 1, was created to test the model. The basin is made up of 8 sub-basins (A-H) with local inflows occurring in each. Unimpaired streamflow was calculated 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 1.

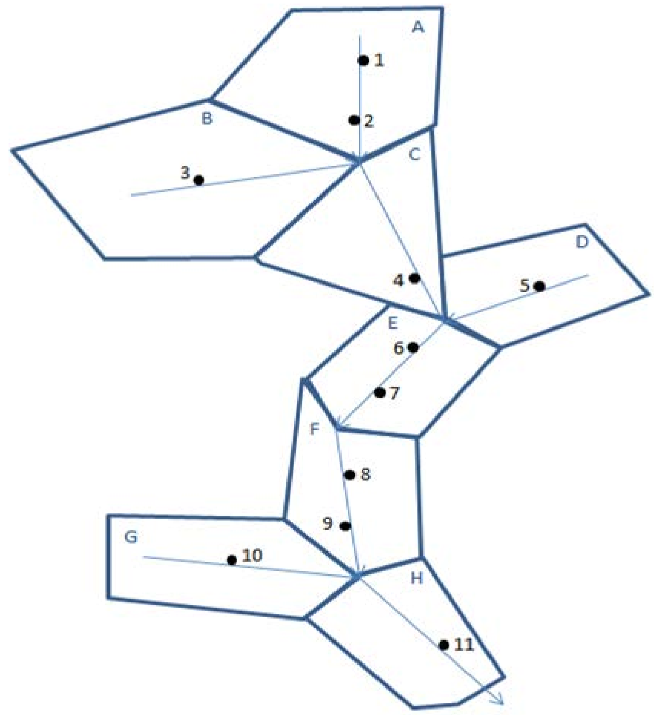

Figure 1 – Example watershed. Sub-basins are outlined and labelled A-H. Users are represented by black dots and labelled 1-11. Arrows indicate direction of flow

Table 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
Flow at outlet:	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 availability:	5.6	5.6	16.8	5.6	28	33.6	5.6	44.8

Each model was run independently assuming all users were either appropriative or riparian right holders. Table 2 shows demand and appropriative priority rank for each user. User 8 is the most senior right holder with a priority of 1, while user 2 is the most junior right holder with a priority of 11.

Table 2 – User characteristics.

User:	1	2	3	4	5	6	7	8	9	10	11
Demand (flow unit/time):	8	10	8	4	3	9	4	7	7	9	8
Priority ranking (appropriative model only):	4	11	3	2	7	8	6	1	10	9	5

Model results

Tables 4 and 5 show user and basin results from the riparian water rights allocation model, respectively. The proportionate multiplier of 0.67 in the main stem catchments of C, E, and F is dictated by the binding flow availability in the lower catchment F, illustrating an even allocation of shortage across the larger drainage area. This proportionate multiplier value of 0.67 is extended to all upstream catchments where flow availability is not binding (catchments B and D). User allocations in sub-basins A and G are limited by availability at their respective outlets, leading to smaller proportionate multipliers in these basins. Basin H has a binding availability that dictates a proportionate multiplier of 0.7, but this does not extend upstream due to the binding flow in the immediate upstream basins F and G. All available flow was allocated to users with no non-environmental flow leaving the system; indicating optimal system performance.

Table 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
Allocation:	2.49	3.11	5.33	2.66	2	5.99	2.66	4.66	4.66	5.59	5.59
Demand:	8	10	8	4	3	9	4	7	7	9	8
Proportion:	0.31	0.31	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.62	0.7

Table 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 (0 indicates binding availability)
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

Note: significant figures are carried for demonstration, rather than applied, purposes.

User and basin results from the appropriative water rights allocation model are shown in Tables 5 and 6. The most senior users experience no shortage where flow is available. User 3, with a high priority of 3, receives a shortage of 2.4 due to low flow availability in the subcatchment. 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 5 – Appropriative model results by user. All flow values are in units of flow/time

Users:	1	2	3	4	5	6	7	8	9	10	11
Allocation:	5.59	0.00	5.59	4.00	3.00	4.37	4.00	7.00	0.00	3.19	8.00
Demand:	8	10	8	4	3	9	4	7	7	9	8
Priority:	4	11	3	2	7	8	6	1	10	9	5
Shortage:	2.41	10.00	2.41	0.00	0.00	4.63	0.00	0.00	7.00	5.81	0.00

Table 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 (0 indicates binding availability)
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

Conclusions

The linear program approach presented above allocates water between users in riparian and appropriative water right systems. Shortage between riparian users is allocated by limiting withdrawals to a certain proportion of normal usage in a sub-basin. This proportion varies throughout the larger basin but is primarily dictated by downstream flow availability. Appropriative users are allocated water based on seniority of right. Both models allocated all available flow in the system, indicating optimal performance.

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Appendix B, Section 2 -Drought Water Rights Allocation Tool Supply Estimation

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The Drought Water Rights Allocation Tool requires estimates of natural, unimpaired surface water supplies at the 12-Degree Hydrologic Unit Code (HUC12) catchment-scale. Because stream flows in most HUC12 catchments are not measured, we developed a modeling approach to predict flows (i.e., water supply) at these ungaged locations. Briefly, the approach relies on National Weather Service (NWS) river flood gages to quantify daily flows at discrete locations in the catchment of interest. Daily flows are then disaggregated to ungaged locations using a statistical model that estimates historical monthly flows across all subcatchments. Rather than using drainage area as a scaling factor, the ratio of modeled historical monthly flows at gaged and ungaged catchments is used to scale daily flows from NWS gages to ungaged locations. The approach is described in detail in an example for the Russian River basin in northern California.

Step 1. Identify NWS 'full natural flow' river flow observation and forecast sites

The National Weather Service operates a network of river flow monitoring and flood forecast stations throughout the nation (NWS 2014). Ensemble forecast models of natural (unimpaired) surface flows are available for a subset of these stations, which are indicated by an 'F' and the end of their site identification code. For example, HEAC1 (at the City of Healdsburg) is the only station in the Russian River basin with predictions for unimpaired flows, designated as HEAC1F (Figure 1)

Figure 1. National Weather Service flow monitoring and flood forecast stations in the Russian River basin. The Healdsburg site (HEAC1F) includes ensemble predictions of unimpaired, natural flows.

Step 2. Define station scaling catchments within study area

Station 'scaling catchments' are the set of HUC12 watersheds to which flows from each station will be extrapolated. The Russian River basin contains 43 HUC12 watersheds and one station (HEAC1F) with natural flow data, so all HUC12 will be scaled from that station. Basins with two or more stations with natural flow predictions can be partitioned into subcatchments associated with each station. The designation of each HUC12 to a station scaling catchment is user-defined, based on spatial proximity to a station and degree to which flows at the station reflect conditions in the HUC12 watershed.

Step 3. Model historical monthly flows

Hydrologic models for predicting mean monthly flows at HUC12 catchments were developed using Random Forests (RF) (Breiman 2001), a statistical modeling technique used for prediction and classification (e.g., Cutler et al. 2007). The RF modeling approach is described in detail in Carlisle et al. 2010 and applied here to predict expected, unimpaired monthly flows at the HUC12-catchment scale. RF are a model-averaging technique that produces thousands of regression trees, each with a bootstrapped sample of 70% of observations and a randomly selected subset of predictor variables considered at each branch. The remaining 30% of observations are withheld to evaluate model predictive performance. RF models are implemented in R with the randomForest package (Liaw and Wiener 2002).

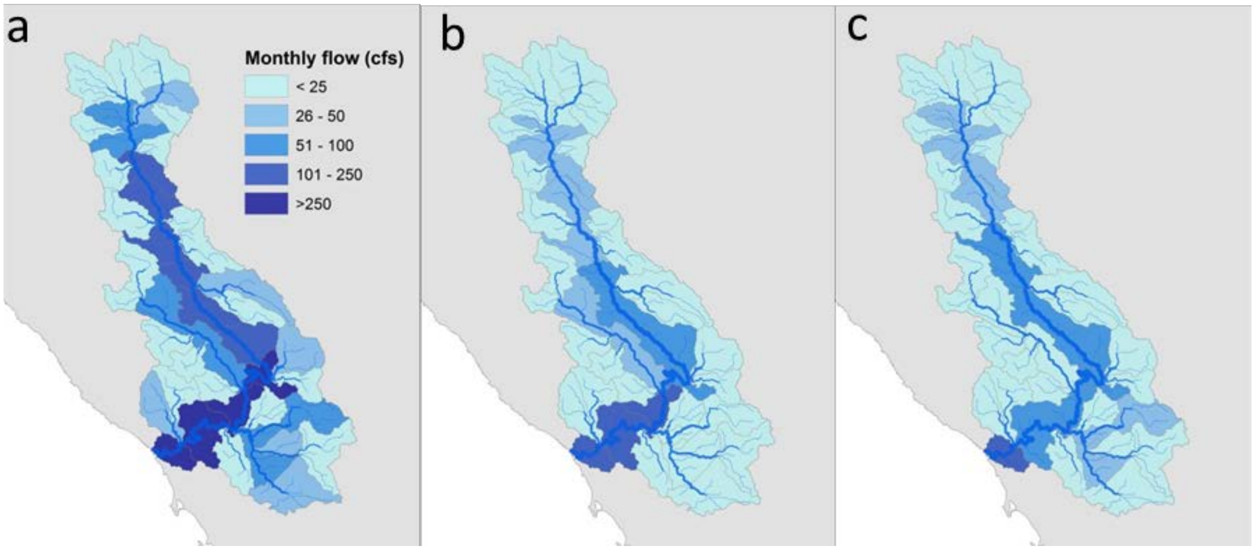
For predicting monthly flows at HUC12 catchments, the RF models used data USGS reference gages (e.g., those minimally affected by land- and water-management activities) and catchment predictor variables (e.g., climate, topography, soils and geology) in the Gages-II database (Falcone et al. 2011; Figure 3). Model predictions were compared with randomized subsets observed data withheld during RF model development to calculate several model performance metrics (Moriasi et al. 2007), including the coefficient of determination (r^2), Nash–Sutcliffe coefficient, and percent bias. In addition, predictive performance was assessed by sequentially excluding individual reference gages and re-running the models to evaluate observed against predicted (O/E) values at the omitted site. To improve predictive performance, separate models were developed for three subregions of California, which encompass the state's interior mountain, coastal mountain, and xeric regions.

Figure 3. USGS reference gages used to train the monthly flow models for California. Source: Falcone et al. 2011.

Coastal mountain region models were used to predict monthly flows in the Russian River basin. For the coastal mountain region, 32 reference gages were used to train the models, using over 100 catchment predictor variables derived from public geospatial datasets (Attachment A) to estimate observed monthly flows over the period of record for each gage. Overall, model performance was good for most months ($r^2 > 0.80$, percent bias less than 10%, NSE > 0.85 and O/E >0.9; Attachment B), indicating that a substantial proportion of monthly variation in flows was explained by catchment variables used in the models.

To predict monthly flows, the same set of catchment predictor variables used in model training (Attachment A), were calculated for all HUC12 catchments (including upstream drainage area). The "trained" RF models were then used to predict expected natural mean monthly flows in each catchment for all months between 1950 and 2010 (see example in Figure 3).

Figure 4. Predicted monthly flows in Russian River basin for (a) March, (b) April and (c) May 1977.



Step 4. Scale measured (or forecasted) daily flows to ungaged locations

To estimate daily flows at ungaged HUC12 locations, a series of scaling factors are applied to measured (or forecasted) daily flows at NWS stations. First, measured flows at NWS gages are extrapolated to the nearest HUC12 basin outlet by simple, drainage area scaling (Equation 1).

$$Q_{STA,HUC} = \frac{DA_{STA,HUC}}{DA_{STA}} * Q_{STA} \, , \tag{1}$$

where DA_{STA} and $DA_{STA,HUC}$ are the drainage areas of the station and HUC outlet closest to the station, respectively, Q_{STA} is the daily flow at the station, and $Q_{STA,HUC}$ is the predicted flow at the HUC oulet.

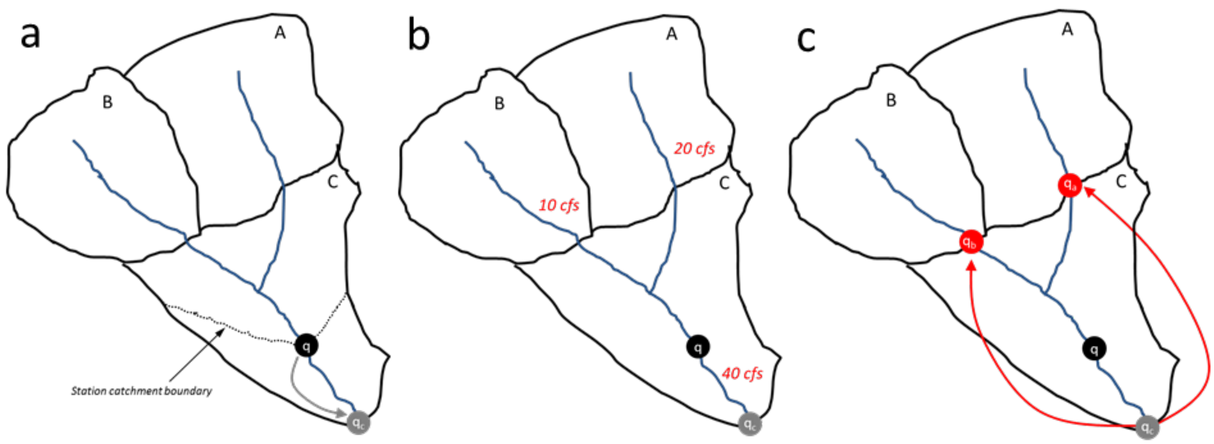
Next, the daily flows at all HUC12s are scaled based on the differences in modeled monthly flows at the reference NWS station(s) (Equation 2). For example, to estimate daily flows at ungaged HUC12 catchments during the current drought year, we used predicted monthly flows in 1977 as the reference.

$$Q_{HUC} = \frac{Q_{monthly,HUC}}{Q_{monthly,STA,HUC}} * Q_{STA,HUC} \, , \tag{2}$$

where Q_{HUC} is predicted daily flow at the ungaged HUC and $Q_{STA,HUC}$ is daily flow estimated at the HUC outlet nearest to the reference station (e.g., HEACC1F). $Q_{monthly,HUC}$ and $Q_{monthly,STA,HUC}$ are modeled monthly flows from an analogous historical water year at the ungaged HUC catchment and HUC nearest the gage station, respectively.

A hypothetical watershed with three HUC12 catchments (A, B, and C) is shown in Figure 4 to illustrate the scaling process. An NWS station with natural flow forecast data is located in the HUC12 catchment C, at the bottom of the watershed. First, flows at the station (q) are scaled to the outlet (q_c) by multiplying by the ratio of the catchment C area to the station catchment area (Figure 4a). Next model predictions of mean monthly flows are generated for each HUC12 catchment, based on a month and water year type similar to the current period of interest (e.g., under drought conditions). For example, the model could predict for March 1977 that catchment A has a mean monthly flow of 20 cfs, catchment B 10cfs, and catchment C 40 cfs (Figure 4b). Finally, the daily flows estimated at watershed outlet (q_c) is scaled to the outlets of basin A and B, using the scaling ratio of predicted mean monthly flows. In this example, daily outflows from catchment A (q_a) scaled by one-half relative to catchment C flows (q_c) while outflows from catchment B (q_b) would be scaled by one-quarter (Figure 4c).

Figure 4. Scaling daily flows at NWS stations to ungaged HUC12 catchments.



Step 6. Adjust water supply predictions based on water management and unique watershed features

The approach described above allows for estimation of surface water supplies based on natural watershed processes. It does not account for the effects of large water projects, such as dams and interbasin transfers, which may change the availability of water to water rights holders in affected water bodies. In addition, the model does not account for hydrologic processes other than surface flows. In watersheds where surface flows strongly influenced by subsurface hydrology, adjustments to the approach may be necessary to improve the accuracy of water supply predictions. Finally, uncertainty in introduced at all steps in the supply estimation process and results should be interpreted accordingly.

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Attachment A. Predictor variables for RF model training and prediction

All variables were calculated from publically available geospatial datasets. For additional information, see GagesII database (http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml).

Variable Name	**Variable Description**
ET	Climate: ET
PET	Climate: Mean annual potential evapotranspiration
PRECIP_SEAS	Climate: monthly precipitation variability
RH_BASIN	Climate: relative humidity
CaO_pct	Geology: composition
MgO_pct	Geology: composition
S_pct	Geology: composition
GEOL_REEDBUSH_DOM	Geology: dominate geologic formation
USC	Geology: strength
BFI	Hydrology: base flow index
PERHOR	Hydrology:overland flow
WB_JAN to WB_DEC	Hydrology: monthly runoff by water year (1950-2010)
WB5100_ANN_MM	Hydrology:runoff annual (1950-2000)
RUNAVE7100	Hydrology:runoff annual avg (1970-2000)
WB5100_JAN to WB5100_DEC	Hydrology: avg monthly runoff (1950-2000)
WD_BASIN	Precipitation: average annual wet days
PPTAVG	Precipitation: avg annual
JAN_AVG_PPT to DEC_AVG_PPT	Precipitation: longterm avg monthly (1970-2000)
JAN_PPT to DEC_PPT	Precipitation: monthly average by water year (1950-2010)
WD_JAN to WD_DEC	Precipitation: number of wet days
JAN_WB to DEC_WB	Runoff: monthly average
LPERM	Soil: Permeability
BDAVE	Soils: Average bulk density
OMAVE	Soils: Average organic content
PERMAVE	Soils: Average permeability
SILTAVE	Soils: Average silt content
ROCKDEPAVE	Soils: Average soil thickness
AWCAVE	Soils: Avg available water capacity
WTDEPAVE	Soils: Avg depth to water table
KFACT_UP	Soils: Avg K-factor value

SANDAVE	Soils: Avg sand content
NO10AVE	Soils: particle size
NO200AVE	Soils: particle size
NO4AVE	Soils: particle size
HG	Soils: Percent of soil in hydro group
RFACT	Soils: rainfall-runoff factor
CLAYAVE	Soils: texture
T_MAX	Temperature: longterm avg max annual (1970-2000)
T_MIN	Temperature: longterm avg min annual (1970-2000)
JAN_TMAX to DEC_TMAX	Temperature: longterm avg max monthly (1970-2000)
JAN_TMIN to DEC_TMIN	Temperature: longterm avg min monthly (1970-2000)
JAN_TEMP to DEC_TEMP	Temperature: monthly average by water year (1950-2010)
ASPECT	Topography: aspect
ELEV_MEAN	Topography: elevation
SLOPE_PCT	Topography: slope

Attachment B. Performance of monthly model for California Coastal Mountain Region

Monthly Model	r^2	Nash Sutcliffe	% Bias	Mean O/E	SD O/E
January	0.92	0.91	3.26	0.94	0.31
February	0.88	0.88	-1.38	0.97	0.31
March	0.93	0.93	0	0.95	0.29
April	0.92	0.92	5.17	0.96	0.3
May	0.84	0.83	9.23	0.94	0.34
June	0.81	0.8	10.04	0.93	0.38
July	0.81	0.75	12.38	0.93	0.31
August	0.85	0.8	12.05	0.85	0.31
September	0.83	0.76	15.47	0.9	0.31
October	0.84	0.84	2.78	0.97	0.4
November	0.88	0.88	-2.1	0.94	0.37
December	0.94	0.94	1.57	0.93	0.32

Appendix C – Some Water Right Curtailment Problems and Technical Solutions

General Data management needs:

- Existing water rights data has been essential to the curtailment process to date. Diligent database management practices, such as consistent formatting and thorough documentation, should help improve existing data.
- Existing databases should be surveyed to avoid redundant work, with realistic expectations set for acquiring further data.
- Databases should be checked periodically for consistency and updated as necessary. Preventative maintenance can solve many problems before they arise.
- Sources of error should be noted and efforts should be made to estimate uncertainty.
- Each curtailment process step should undergo careful scrutiny for quality control and improvement needs. This can be simplified with thorough documentation and maintaining transparency at all stages.
- Designated personnel responsibilities for each step of the curtailment process should be made clear to all involved.

Water Availability and Sub-Basin Flow estimates

1. Full natural flow forecasts are required for curtailments. The National Weather Service has a network of flood gages throughout California which have been used for this purpose. State and local agencies will likely play a role in refining these forecasts and their application for drought curtailments.
2. A spatial disaggregation model is used to estimate the full natural flow available in each HUC12 basin. Results from this model should be verified for accuracy with contribution from local agencies and stake-holders. Improvements, including perhaps development and state approval of substitute local and regional models, can occur with time.

Water Right Quantities and Priorities

1. Water use data for right-holders can be determined by historical reported monthly use, the face value of water rights, or remote sensing or water use forecast models. A consistent approach is needed to establish explicitly quantities of normal and drought water use for basin curtailment calculation purposes.
2. Users may hold both riparian and appropriative water rights with multiple points-of-diversion. These cases need to be identified and accounted for to avoid over-allocation of water to certain users.
3. Return flow quantities must be estimated or neglected. Currently, return flows are neglected, due to lack of data, which essentially becomes a safety factor to increase the reliability of water for senior water right holders.

Other Water Allocation Priorities and Quantities

1. Water allocations for environmental flows, public health and safety, and flows needed to maintain water quality standards are subject to legal priorities outside the doctrines of riparian and appropriative water rights. Specific quantities and locations for these uses must be established by the relevant agencies.

DWRAT – Drought Water Right Allocation Tool

- A factor of safety, or “buffer” flow, is introduced in the allocation model to account for error introduced in any of the above steps.
- This safety factor will increase reliability for right-holders at all levels and will likely become smaller with experience.
- The model also currently assumes that all water right use is entirely consumptive with no return flows to streams. Data is not generally available on return flow locations, volumes, or timing.
- Each right-holder currently has access to only its largest point of diversion. We expect to expand this.
- As the model is updated, a thorough update log must be maintained. All documentation explaining the curtailment model and process should be made public to increase transparency and trust.