Water Right Curtailment Analysis for California's Sacramento River: Effects of Return Flows

By

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Abstract

California's recent drought has brought economic hardship and attention to long-standing weaknesses in California's water management. One weakness is assessment of surface water shortages and resulting needs to curtail water diversions. This thesis presents an integrated method that mathematically combines basin hydrology with legally defined water right priorities and regulations in a spreadsheet model with an open source solver to suggest a legally-optimized water allocation for a network of sub-basins within a watershed. The resulting Drought Water Rights Allocation Tool (DWRAT) allocates water to every water right holder in a watershed according to riparian and appropriative water law and can be modified for any watershed with hydrologic and water use data. This method is applied here to the Sacramento River basin. DWRAT currently employs a statistical hydrologic model developed by the U.S. Geological Survey (USGS) to disaggregate estimated unimpaired flows from points with gaged streamflow to regions of unknown streamflow. To ensure water right priorities are maintained, DWRAT uses linear programs to apply riparian and appropriative water law doctrines. The hydrologic representation and linear programming are combined with monthly water use data for water right holders to create a DWRAT model for a basin. This report focuses on the Sacramento application and the effects of different representations of return flows. Current model results show that for the critically dry water year October 2014 - September 2015, there would be 13.2 million acre-feet of water shortage (63% of normal water diversions/use) in the Sacramento basin, with 65% of that shortage during the irrigation season. Including return flows decreased annual water shortage by 1 maf (from 65% to 60% of normal use). DWRAT provides a transparent accessible framework for integrating legal doctrines, water use, and hydrologic knowledge of a basin for water use curtailment during drought.

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Chapter 1 – Introduction and Background

For over three decades, California avoided formal curtailment of water rights. This changed abruptly in the summer of 2014, the third consecutive year of drought in California, when the State Water Resources Control Board (SWRCB, Board, or State Board) determined—for the first time since 1977 and only the second time in the State's history—there was not enough water in the Scott, Sacramento, San Joaquin, Eel, and Russian river basins to meet the demands of all water right holders in these regions (2016.a). This left the Board with a difficult decision. It was clear there was not enough water for everyone, but how great was the shortage and which right holders should be curtailed? This thesis reports on the development of an analytical tool to suggest a set of drought water right curtailments for sub-watersheds within a watershed that comply with riparian and appropriative water right priorities given what is understood of the watershed's surface water hydrology and water uses. This framework is applied to California's Sacramento River basin, with special examination of approaches to represent return flows.

California Water Law

Most water rights in California are riparian or appropriative. Riparian rights originate from English common law and belong to individuals who own land adjacent to a stream or river. Water diverted under a riparian right is connected to riparian land, cannot be used on land not directly connected to the stream, and cannot be stored. Riparian rights are the most senior water rights in California, but are equal in priority amongst each other, with shortages allocated proportionally (Mooney and Burch, 2003).

Appropriative rights in California originate from the state's mining era. Mining operations required water far from the streams. Unlike riparian rights, water held under an appropriative right can be diverted to land away from the stream and can be stored. Also unlike riparian water rights, appropriative rights are given a strict priority based on when the water was first used or applied for, summed up by the phrase, "first in time, first in right". There is no shared priority among appropriative users. If farmer A owns a water right dating one day before neighboring, farmer B, and there is not enough water to supply both rights, farmer B is required to forego all water use before farmer A is required to take any cutbacks. Appropriative rights established before 1914—when California began requiring permits for appropriative rights—define seniority by the date of first use and are referred to as pre-1914 or senior rights. The priority of appropriative rights established after 1914 depends on the date a water right permit was applied for and are referred to as post-1914 or junior rights (Mooney and Burch, 2003). California is unusual in having both riparian and appropriative rights. Several other western states, such as Oregon and Texas, once had riparian and appropriative rights but converted most riparian rights to appropriative rights in the early 1900s because of difficulty managing them together (Escriva-Bou et al., 2016). In California, riparian water rights, as a class, are given priority over appropriative rights.

Another aspect of appropriative water rights is the "use it or lose it" principle. If appropriative water right holders do not divert water for five consecutive years, the right is lost (California Water Code, § 1241).

The State Board mandated water right curtailments again in 2015 for the Scott, San Joaquin, and Sacramento River watersheds. While the 2014 curtailments in these basins affected nearly all post-1914 appropriative users, more severe drought conditions occurred in 2015 with some regions of the San Joaquin basin receiving zero water for even the most senior appropriators (SWRCB, 2014a; 2016a).

Water use curtailment decisions cannot be based directly on stream gage readings impaired by upstream diversions and reservoir releases. Appropriative water right holders are entitled to unimpaired streamflow. Unimpaired flow is what the flow would be given present-day stream channels (with levees) without upstream diversions and releases (Chung and Ejeta, 2011; Kadir and Huang, 2015).

Riparian right holders are entitled to natural flow, defined as the flow available given pre-human conditions (Chung and Ejeta, 2011; Mooney and Burch, 2003). Natural flow is more difficult to calculate and more uncertain, as it requires unimpairment of gage flows from diversions and releases, plus corrections for changes in basin evaporation from changes in vegetation, wetlands, floodplains, and other basin characteristics with development (Chung and Ejeta, 2011; Kadir and Huang, 2015).

Unimpaired and full natural flow (FNF) are often confused and used interchangeably (Chung and Ejeta, 2011). Several agencies (e.g. National Weather Service, U.S. Geologic Survey, California Department of Water Resources) report FNF estimates at locations along California rivers, but these values are calculated using present-day stream channels and therefore represent unimpaired flow as per the definitions above. For accuracy and clarity, the streamflow data reported as full natural flow from various agencies are called unimpaired flow in this thesis. For simplicity, both riparian and appropriative water right holders in DWRAT models are allocated water based on unimpaired flow availability.

Currently, the Board determines when curtailments are needed by comparing unimpaired flow estimates at the outlet of a major watershed to total reported recent demand upstream of those outlets. When the unimpaired flow estimate is less than the total demand, SWRCB determines the necessary number of water rights to curtail to bring allocated demand in balance with the estimated unimpaired flow supply. Online, the Board provides examples of the supply and demand graphs used to determine curtailment decisions (SWRCB, 2016b). One such graph is shown in Fig 1-1. Figure 1-1 portrays how and when the SWRCB made curtailment decisions in 2015 by comparing estimated water supply and demand for the Sacramento River Basin. Supply is the unimpaired flow (labeled Daily FNF in the figure) and demand is separated into pre-1914 and riparian demand. Post-1914 demand is not identified on this graph, but all post-1914 right holders were curtailed on May 1st in 2015. The shaded areas show the level of demand based on 2014 available data. In 2015, the State Board issued an Information Order to pre-1914 and riparian right holders in the Sacramento and San Joaquin basins to better assess true demand from senior users (SWRCB, 2015a). The solid green line in Fig. 1-1 reflects the combined demand of riparian and pre-1914 (i.e. senior) users adjusted for reports from the 2015 Information Order (SWRCB, 2015b).

When unimpaired streamflow and adjusted senior demand intersected in mid-June, the Board determined it was necessary to begin curtailing pre-1914 rights. On June 12th, the Board curtailed all appropriative users with a 1903 priority date or later to balance allocated water and unimpaired supply (SWRCB, 2016a).

2015 Sacramento River Basin Supply/Demand Analysis with Proportional Delta Demand
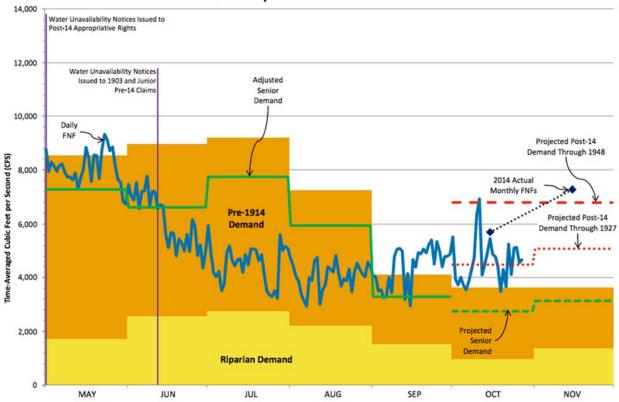
Figure 1-1: SWRCB curtailments in 2015 and estimated supply and demand for the Sacramento River Basin. Graph compares unimpaired water supply (referenced as Daily FNF in the figure) to demand of Pre-1914 and Riparian rights. Graph was created on October 30, 2015 by the SWRCB.

Throughout the summer, unimpaired flow remained below senior demand and all post-1903 right holders remained curtailed. In September, senior demand levels dipped below unimpaired flow estimates and on September 18th, the Board released pre-1914 users who did not make the 1903 cutoff in select regions of the Sacramento Basin with greater water supply. The remaining curtailed users were released from curtailment through following releases on October 30th and November 2nd (SWRCB, 2016a).

A shortcoming of this method is it does not account for spatial variability and the hydrologic connectivity of users within the basin. Consider two water users (a senior and junior user) in a basin with only the mainstem and one tributary, as in Fig. 1-2. The senior user has a demand of 11 units and is upstream on the tributary where only 1 unit of unimpaired flow is available. The junior user demands 10 units and is downstream on the mainstem where 11 units of unimpaired flow are available. Curtailment decisions based on only unimpaired flow available at the outlet of the basin will curtail all use by the junior user to meet the senior user's 11 units of demand with the 11 units of flow available at the outlet. However, the senior user lacks access to the 11 units of flow at the outlet, and only has access to 1 unit of flow on the tributary, meaning the senior user can only take one unit and the junior user must allow 10 units of water to flow by unused. A more disaggregated approach would make more legally and hydrologically appropriate curtailments within a watershed's sub-basins.
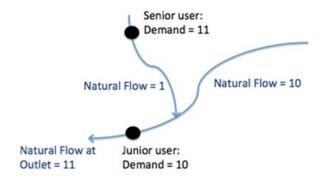
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Figure 1-2: Example of where a simple basin curtailment decision method leads to misguided curtailments.

Introduction to DWRAT

The harsh drought in 2014 and resulting water right curtailments sparked controversy between the State Board and water right stakeholders. Some stakeholders questioned the Board's authority to curtail water rights and the Board imposed fines up to $1,000 per day on right holders who failed to comply with curtailment decisions (SWRCB, 2014a). With great conflict around water curtailments, the Board saw need to improve the speed and transparency of curtailment decisions. The Drought Water Rights Allocation Tool (DWRAT) is a step in that direction. DWRAT is an Excel spreadsheet model that combines simplified hydrologic representation of a watershed, unimpaired streamflow estimates, water user demand and priority data, and linear programming to minimize water shortages according to a mathematical representation of the legal framework of California's water rights. Results output by DWRAT can be exported as a .csv file and uploaded to an interactive, online mapping tool to display curtailments decisions (Lord, 2015). Examples of water allocation models for appropriative-ruled systems already exist and are in practice in Texas (Wurbs, 2001; WRAP model), Idaho (Olenichak, 2015; Water District #1), and Utah (Walker, 1991; Sevier River Water Allocation Model), but allocation models to handle both appropriative and riparian water rights have yet to be developed or documented.

The flowchart in Fig. 1-3 shows how unimpaired streamflow, hydrology and water user data are input into two linear programs for DWRAT to optimally allocate available water in a watershed.
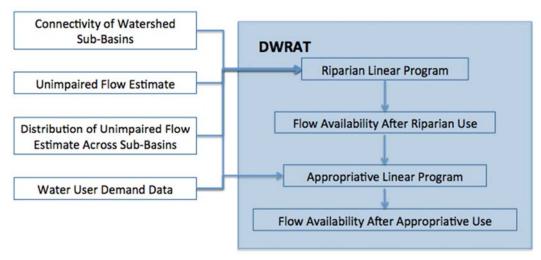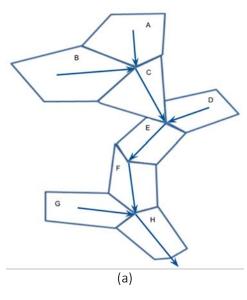

Figure 1-3: Flowchart of DWRAT

Define Hydrologic Connectivity

The first step in developing a DWRAT model is to represent the basin as a network of smaller sub-basins. This defines the hydrologic connectivity of users (i.e. who is upstream of who) and inflows. The USGS's HUC (Hydrologic Unit Code) system is used. The smallest sub-basins defined by the HUC system are HUC-12 basins, which range from 3 to 300 square miles, and are used in DWRAT. With sufficient additional hydrologic data, this could also be done at the user level.

A connectivity matrix summarizes and defines the upstream/downstream relationships of the sub-basins. This information is used by the linear programs to create mass-balances and other constraints. The matrix is built so a "1" indicates that the column sub-basin is upstream of, or the same as the row sub-basin and a "0" indicates the column sub-basin is downstream of the row sub-basin. An example basin and corresponding connectivity matrix is given in Fig. 1-4 a&b to clarify.

(a)

Upstream: Downstream	A	B	C	D	E	F	G	H
A	1	0	0	0	0	0	0	0
B	0	1	0	0	0	0	0	0
C	1	1	1	0	0	0	0	0
D	0	0	0	1	0	0	0	0
E	1	1	1	1	1	0	0	0
F	1	1	1	1	1	1	0	0
G	0	0	0	0	0	0	1	0
H	1	1	1	1	1	1	1	1

(b)

Figures 1-4 a&b: Example basin (a) with eight sub-basins (A through H) and corresponding connectivity matrix (b). In the matrix, a "1" indicates that the column sub-basin is upstream of or the same as the row sub-basin. A "0" indicates the column sub-basin is downstream of the row sub-basin.

In the above connectivity matrix, rows A, B, D, and G have a single "1" value because no sub-basins are upstream of them and the single "1" value is found when the column sub-basin is the same as the row sub-basin. By contrast, row C contains three "1" values. Two are in columns A and B because sub-basins A and B are both upstream of sub-basin C. The third "1" is in column C because the column basin matches the row basin. A "1" indicates that water from the column sub-basin is available to the row sub-basin.

Estimate Unimpaired Flow

Once sub-basins are defined, unimpaired flow available to each sub-basin is estimated by taking unimpaired flow estimates for particular reference locations in the basin and scaling these reference flow estimates to estimate unimpaired outlet flows of each sub-basin in the model. The scaling is done through a statistical model developed by the USGS that combines 20 hydrologic and geographic indicators (e.g. precipitation, soil, elevation) with historical streamflow data (Grantham and Fleenor, 2014; Falcone, 2011). More detail on the statistical model is found in Grantham and Fleenor (2014), Carlisle et al. (2010), Falcone (2011), and Moriasi et al. (2007). The statistical model is then used to calculate ratios of streamflow between sub-basins.

Define User Demand and Priority Data

The next step for setting up a DWRAT model is to specify user demand and priority data. Demand data comes from reported monthly use collected by the State Board for 2010 to 2013. Prior to 2009, riparian and senior appropriative users were exempt from reporting their use and only junior appropriative users were required to report. Legislation passed in 2009 requires riparian and senior appropriative users to report their monthly use every three years. Junior users are required to annually report monthly use. The reported use data is compiled into the Water Rights User Database System (WRUDS), which contains 2010 – 2013 reported use from all water right holders and calculates their average monthly demand. The WRUDS database also includes water right priorities, which are taken from the State's online water rights database, eWRIMS (SWRCB, 2014b).

Direct diversions by hydropower users (i.e. not diversions to storage) are considered non-consumptive, so reported direct diversions do not add to a hydropower user's overall demand in WRUDS. The database has also undergone some quality control to identify and correct misreported values. For example, reported use is compared to irrigated acreage to see if the water volume diverted per acre is reasonable. The WRUDS database is continually under modification as improved data becomes available. In February of 2015, the State Board sent an information order to the top 90% of riparian and pre-1914 appropriative right holders by volume in the Sacramento and San Joaquin Watersheds requesting 2014 monthly use and anticipated monthly use in 2015. The order required reports to be submitted one month later (SWRCB, 2015a). Rights are considered active if annual demand in WRUDS exceeds zero. Demand for users who responded to the 2015 information order is calculated in WRUDS solely from the recent report and not from 2010 – 2013 data.

Periodically, the State Board updates WRUDS and makes a simplified version available to the public. On their website, 2010 – 2013 average demand and 2015 information order data are listed separately (SWRCB, 2016b). The version of WRUDS used for this thesis combines 2010 – 2013 data with the 2015 information order. Figure 2-4 in chapter 2 summarizes the monthly demand in WRUDS for the Sacramento Basin.

Most data in WRUDS is from 2010 to 2013, of which only 2012 and 2013 were drought years. During a drought, many right-holders likely use conservation methods and reduce use even if their rights are not curtailed. As the State Board processes water use reports from more recent (and dryer) years for post-1914 right holders—who account for 84% of demand— data will better reflect water demand during a drought and improve curtailment decisions from DWRAT.

Linear Programs and Their Equations

The DWRAT model uses two linear programs run in sequence to calculate a legally optimal allocation of water to minimize shortage, adhering to water right priorities given an understanding of basin and sub-basin hydrology. Each model run is for a representative single time-step, in this case average daily flows and demands representing monthly curtailments, since both user data and unimpaired flow data are reported for monthly periods.

The first linear program solves for allocations to riparian users and the second solves to allocate remaining water to appropriative users. Separate linear programs are needed because of the legal differences between riparian and appropriative rights and how they are curtailed. Riparian users are allocated water first because of their senior priority to appropriatives. DWRAT allocates riparian users a proportion of their 2010 - 2013 average demand. Proportions are equal for riparians within the same sub-basin, but vary from sub-basin to sub-basin. Appropriative users are allocated their water right in its entirety or none at all. Within a sub-basin, appropriative users will be curtailed before riparian users, but a riparian user in a drier sub-basin may be curtailed before an appropriative user in a sub-basin with greater water supply. This thesis summarizes the objective function and constraints for the Appropriative linear program. The Riparian linear program is more complex and explained elsewhere (Lord, 2015; Whittington, 2016).

Appropriative Linear Program

The priorities of the appropriative doctrine imply a fairly simple objective function and constraints for the appropriative linear program. The appropriative doctrine objective is to minimize the total weighted water shortage. Shortages are weighted to cause the optimization to meet all senior user demands —if possible— before meeting the demand of a hydrologically connected junior user. Decision variables in this model are the daily allocations to each user. The objective function is as follows.

$$Min \ Z = \sum_i p_i(d_i - A_i)$$
(1-1)

Where p_i is the unit penalty for shorting user *i* by one unit of water, d_i is the water demand for user *i*, and A_i is the allocation of water given to user *i*. The shortage unit penalties, p_i, increase with right holder seniority, so the objective function incentivizes DWRAT to allocate water to senior right holders before junior right holders. The decision variable in this linear program is A_i.

There are four constraints in the appropriative linear program. These constraints ensure the model follows conservation of mass and users are not allocated more than their demand of water, represented by their recent use.

The first constraint maintains mass-balances in the system and requires that the sum of all appropriative allocations upstream of and within a sub-basin cannot exceed the water available at the outlet of that sub-basin after environmental flows, buffer flows, and riparian diversions are removed.

$$\sum_{i \in K} A_i \leq v_k - e_k - b_k - \sum_{r \in K} A_r , \forall k \tag{1-2}$$

Where K is the set of users upstream of and within sub-basin k, v_k is the initial unimpaired flow available at the outlet of sub-basin k before any diversions, e_k is any flow reserved for the environment in sub-basin k, b_k is the buffer flow provided as a factor of safety for estimations of user demands and available water for sub-basin k, and the fourth term on the right-hand side of the equation is the sum of all allocations given to riparian users, A_r, upstream of and within sub-basin k (determined previously by the Riparian LP).

The second constraint ensures users are not allocated more than their demand for water.

$$A_i \leq d_i, \forall i \tag{1-3}$$

The third constraint ensures users are at least allocated enough water to meet public health and safety standards.

$$A_i \geq d_H, \forall i \tag{1-4}$$

Where d_H is the amount of water needed to meet the public health and safety standard.

The final non-negativity constraint ensures the model does not allocate negative amounts of water to users.

$$A_i \geq 0, \forall i \tag{1-5}$$

This approach has been applied preliminarily to the Eel River (Lord, 2015) and the Russian River Basins (Whittington, 2016). This thesis details how it has been applied to the much larger Sacramento River Basin.

Chapter 2 – Sacramento Basin DWRAT Model

Overview of Sacramento River Basin

The Sacramento River Basin sits between the Coast Ranges and the northern Sierra-Nevada mountain range in northern California. The watershed's southern border stretches to the Sacramento-San Joaquin Delta, which goes on to flow out into the San Francisco Bay. In the northern reaches, the basin crosses 30 miles over the Oregon border. At 27,000 square miles, it contains 31% of California's runoff and is the largest watershed in the state (Aalto, et al., 2010).

Figure 2-1: Map of Sacramento River Basin (Retrieved from wikipedia.org)

The basin is a primary source of water for California's $54 billion agriculture sector (CDFA, 2015) and both Northern and Southern California residents rely on the Sacramento for drinking water. Major tributaries include the Pit, McCloud, Feather, and American Rivers (Aalto, et al., 2010). Between the years of 1949 to 2013, the mean annual flow near the outlet of the Sacramento River Basin at Freeport was 17 million ac-ft, but ranged from 5.5 to 34 maf (USGS, 2013).

Unimpaired Flow

The Sacramento Basin DWRAT uses six reference streamgage locations for unimpaired flow estimates. Data for five of the stations are stored by the California Data Exchange Center (CDEC) and collected by a mixture of the California Department of Water Resources (DWR), the U.S. Geologic Survey, and the U.S. Bureau of Reclamation. The Department of Water Resources also estimates unimpaired flow near the outlet of the Sacramento River based on unimpaired flow at four upstream gages. This makes six reference streamgages in all. One drawback to these data is that they are mostly estimates of historical, not forecasted unimpaired flow. These are the same sources of unimpaired flow used by the State Board to help make curtailment decisions, but it would be more helpful to find a source of forecasted unimpaired flow so 1) the Board can assess future need for the upcoming irrigation season and 2) water right holders can plan for anticipated curtailment decisions. Forecasted streamflow data for several locations in this large basin would further the effectiveness of DWRAT in the Sacramento Basin.

A map of the six reference gages and the regions each gage represents appears in Fig. 2-2. The unimpaired flow from each gage is scaled to HUC-12 sub-basins within its respective region using flow scaling ratios as described by Grantham and Fleenor (2014). For this work, a slightly smaller Sacramento River Basin is used than pictured in Fig. 2-1. Roughly 60 miles of the northern-most section is removed because it is only part of the watershed when Goose Lake, on the California-Oregon border, overflows from extreme flooding. This last occurred in 1881, so these 60 miles have not been part of the watershed for over a century (Wikipedia, 2016).
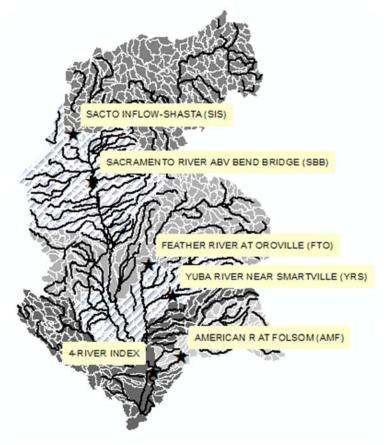

Figure 2-2: Map of Sacramento River Basin used in DWRAT. Stars indicate reference gage locations where unimpaired flow *is estimated. Shading indicates regions represented by each reference gage. Black lines indicate rivers/streams and white lines indicate borders of HUC-12 sub-basins.*

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At the location of the 4-River Index gage (noted above in Fig. 2-2), the California DWR made estimates of historical unimpaired monthly flow volumes for water years 1915 to 2015. A comparison between unimpaired monthly flow volumes during water year 2015 and averages over the past century is in Fig. 2-3. While water year 2015 had an especially wet December, the rest of the year was below average and March through June was well below average.
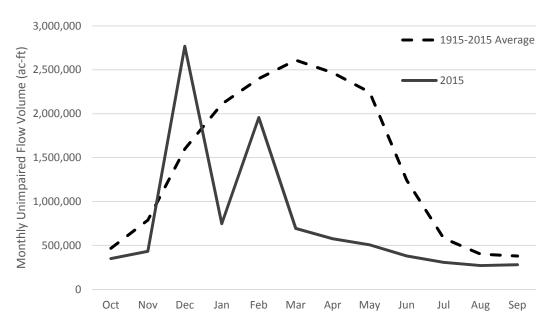

Figure 2-3: Comparing unimpaired monthly flow volumes in water year 2015 vs. 1915 – 2015 averages near the outlet of the Sacramento Basin at the 4-River Index location

User Water Demand Data

Below is a summary of water right demands in the Sacramento Basin based on the State Board's WRUDS database. Reported water use in previous years was used in the model, in lieu of nominal official water right quantities, to make the water balances more realistic and not over-curtail actual water uses.
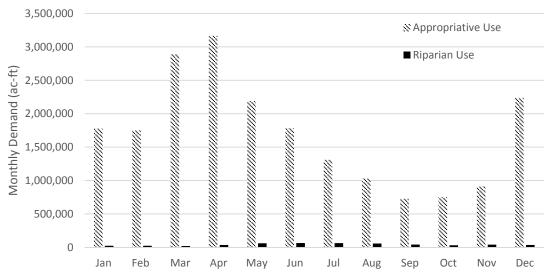
Figure 2-4: Monthly water demand of Sacramento Basin right holders averaged from 2010 - 2013

A summary of water rights in the Sacramento Basin by type appears in Table 2-1. Water rights with a reported annual demand of zero are removed for the calculations. While 30% of water rights are riparian, the total volume of normal water use held by riparian rights is only 2% of all water demand. Post-1914 rights account for most of the demand.

Table 2-1: Sacramento Basin water rights by type

Right Type	# of Right Holders	% of Total Right Holders	Annual Water Use (ac-ft)	% of Total Water Use
Riparian	1293	30%	493,386	2%
Pre-1914	348	8%	2,783,117	13%
Post-1914	2641	62%	17,733,862	84%
TOTAL	4282	100%	21,010,365	100%

Table 2-2 summarizes how Sacramento Basin water rights are diverted in terms of beneficial uses. Many water rights list several, eligible beneficial uses but not the quantities applied to each beneficial use. Since diverted water might serve several purposes, Table 2-2 allows double-counting of water and shows what percentage of total water demand is eligible for different beneficial uses.

Table 2-2: Sacramento Basin beneficial uses of water

Beneficial Use	# of Right Holders	% of Total Right Holders	Volume of Water Eligible (ac-ft)	% of Total Water Held
Irrigation/Stockwatering	3080	72%	16,375,196	78%
Municipal/Domestic	2413	56%	12,722,465	61%
Partial Power	107	2%	8,242,906	39%
Industrial	101	2%	11,356,944	54%
Other	1742	41%	12,326,910	59%

*Rights can serve multiple beneficial uses.

Optimization Software

The Sacramento DWRAT model uses an open-source optimization software package developed at the University of Auckland called SolverStudio, designed to handle large problems. The software is written in Excel VBA code and runs as an add-in to Excel but can handle much larger problems than the native Excel Solver (Mason, 2012). SolverStudio has no artificial limit on the number of decision variables and constraints like the native Solver. The native Excel Solver is limited to 200 decision variables and roughly 100 constraints. Table 2-3 shows the decision variable and constraint requirements for the Sacramento DWRAT model far exceed these thresholds. The appropriative and riparian linear programs apply four and eight constraints, respectively, to each water right.

Table 2-3: Decision variable and constraint specifications for DWRAT

Linear Program	# of Rights	# of Sub-basins	# of Decision Variables	# of Constraints
Riparian LP	1,293	768	768	6,144
Appropriative LP	2,989	768	2,989	11,956

Unlike the native Excel Solver, SolverStudio conducts the optimization calculations outside of Excel in a choice of 11 different solvers. Some solver packages are free, Python-based packages (e.g. PuLP and GLPK), while others are commercial (e.g. GAMS). For DWRAT, a Python-based package called PuLP is used. SolverStudio is an Excel add-in and acts as a mediator between the Excel spreadsheets and the PuLP solver. Identified data from Excel is pulled into PuLP, the optimization calculations are done by PuLP, and the results can be output back into the Excel spreadsheet. Since SolverStudio uses an outside solver, one must be able to write an optimization problem in the programming language required by that solver. The code itself is written in a macro window inside Excel, so the DWRAT user does not have to open another program to run SolverStudio.

Modeling Issues for Larger Basins

When modeling larger basins, some problems are likely to be more important than with smaller basins like the Eel or Russian. These problems include return flows, routing, more opportunities for hydrologic error, and larger numbers of decision variables and constraints.

Return flows from diversions can re-enter several miles downstream of the original diversion. Several miles might be the entire length of a smaller watershed, so return flows might re-enter the surface supply at or below the outlet of the basin, making none of the return available to users within the originating basin. Larger basins provide more space and opportunity for return flows to re-enter and accumulate to supply for users within the same basin. This makes return flows more likely to be important when modeling water availability in larger basins.

Routing (i.e., water travel time) is another issue when modeling larger basins. A drop of water at the top of a smaller watershed can travel to the outlet in the same day. If the same water is available to users both at the top and bottom of a basin within a day, accounting for routing before making daily allocation decisions for the basin's users is unnecessary. However, if it takes a week for water to travel from one end of the basin to the other, routing is more likely to be important for shorter time periods. At an average speed of 2 mph, it would take 14 days for water from the Pit River inlet (in the upper reaches of the Sacramento Watershed) to reach the outlet at Suisan Bay. This application of DWRAT circumvents the

routing problem by making allocation decisions for a representative day in a month. Within a week's time, any water that started out in Lake Shasta has made it past the city of Sacramento.

Larger basins also provide more opportunity for hydrologic error. DWRAT uses unimpaired flow estimates from state and federal agencies to establish available streamflow. Several variables that impair streamflow include general diversions, reservoir releases, seepage to or from groundwater, and contracted diversions of released water (separate from water right diversions). In a smaller system, fewer variables are likely to be important for estimating unimpaired flow. For example, the Russian River Basin has 1,800 water rights, one major tributary, and two major reservoirs. Both reservoirs are managed by the Sonoma County Water Agency (SCWA, 2016). The Sacramento basin has 4,200 water rights, thirteen major tributaries, eleven major reservoirs (Wikipedia, 2016), and no central agency managing them. With more variables and scattered data, it is significantly more difficult to unimpair streamflow in the Sacramento Basin. Greater difficulty often results in greater error.

The size of the Sacramento Basin brings computation issues as well. With nearly 3,000 appropriative users and over 750 sub-basins, the appropriative linear program must solve for nearly 3,000 decision variables and 12,000 constraints. A problem of this size requires robust optimization software and more computation time. While the computation times for the riparian and appropriative linear programs in the Sacramento DWRAT are 4.5 and 2.5 minutes, respectively, they are both under 30 seconds for the Russian River DWRAT.

Chapter 3 – Return Flow Methods and Example Results

Methods

A major consideration and addition for the Sacramento DWRAT model is consideration of return flows. Previous DWRAT models assumed all surface water uses were fully consumptive within the allocation time step. No allocated water re-entered the surface water supply through return flows. In the Russian and Eel Rivers, this is a more accurate assumption, but return flows to streams are larger in the Sacramento Valley and increase water available for many downstream right holders. To capture return flows, two methods were developed for the Sacramento model but can be applied to any DWRAT model.

The first method simply reduces applied use to consumptive use from which DWRAT makes allocation decisions. Water that percolates into aquifers is considered consumed by DWRAT because it does not return to the allocatable surface water supply. This simple approach assumes that all return flows return immediately to the point of diversion and that local flow availability is sufficient to support the gross water diversion.

The second method calculates surface return flow volumes for water right holders and explicitly returns the water into the next sub-basin downstream. To explicitly return flows downstream requires another linear program to ensure the model maintains water right priorities. The linear program simplifies a more general method detailed by Israel and Lund (1999) and Ferreira (2007). Where surface return flows return immediately downstream of the user, they could become available to other users in the same sub-basin, but such reuse within a sub-basin is unavailable with this method. These methods are summarized in Fig. 3-1.
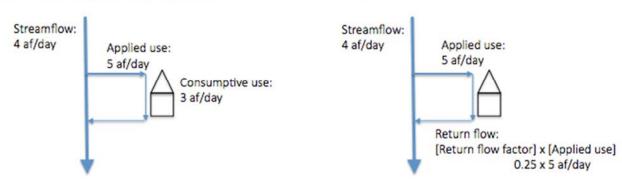

Figure 3-1: Summary of the two methods used to apply return flows to DWRAT

The Consumptive Use Diversions method tends to under-curtail water right holders and allows cases where users are not curtailed even when available streamflow is less than applied demand. Since this method reduces a user's demand to consumptive demand, DWRAT will not curtail a user unless the available streamflow is less than the user's consumptive demand. So if available streamflow exceeds a user's consumptive demand but is less than his applied demand, he will not be curtailed. One such instance is in Fig. 3-1.

In the Explicitly Return Flows Downstream method, all surface water return flows are applied to the next sub-basin downstream of the diversion. In reality, return flow from some users can be available to

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downstream users in the same sub-basin. So, this second method can over-curtail some users. Unfortunately, more precise accounting for the location of a user's return flow is not initially feasible for the Sacramento Basin's many users. The marginal improvement in result accuracy might not justify the large effort needed to acquire this additional accuracy.

The benefits and drawbacks to the several methods listed above are shown in Table 3-1.

Table 3-1: Benefits and drawbacks to return flow approaches

Method	Benefits	Drawbacks
Use Assumed Fully Consumptive	- Most simple	- Overcurtails
Reduced Consumptive Use Diversions	- Simple to implement - Creates upper bound	- Undercurtails
Explicitly Return Flows Downstream	- Adds level of accuracy - Creates lower bound	- Overcurtails - Complicated to implement
Precisely Represent Return Flows	- Accurately curtails	- Most complicated & data-intensive to implement - Time consuming

The Explicitly Return Flows Downstream method maintains user demand to be their applied demand and adds surface returns for use by water right holders in downstream sub-basins.

$$w_k = v_k - e_k - b_k + \sum_{i \in k} A_i r_i \tag{3-1}$$

where w_k is the available water in sub-basin k, v_k is the unimpaired flow available at the outlet of sub-basin k, e_k is any flow preserved for the environment in sub-basin k, b_k is the buffer flow provided as a factor of safety for estimations of user demands and available water for sub-basin k, K is the set of users upstream of sub-basin k, A_i is the allocation of water given to user i, and r_i is the surface return flow factor of user i.

When return flows are added back into the model, appropriative user priorities can no longer be maintained by the original, simple unit penalties used by DWRAT. Originally, DWRAT assigned unit penalties to appropriative water right holders using Eq. 2 below.

$$p_i = N + 1 - s_i \tag{3-2}$$

where p_i is the unit penalty of water right holder, i, N is the total number of appropriative water right holders in the watershed, and s_i is the seniority of water right holder, i. Using this method, the lowest-priority appropriative user has a unit penalty of 1 and the highest-priority user has a unit penalty of N. In a system with only fully consumptive demands and no return flows, a user's unit penalty must only be marginally larger than the user immediately junior to him for the optimization model to give him operational priority over all his junior users. However, the example below shows this is no longer true once return flows are involved.
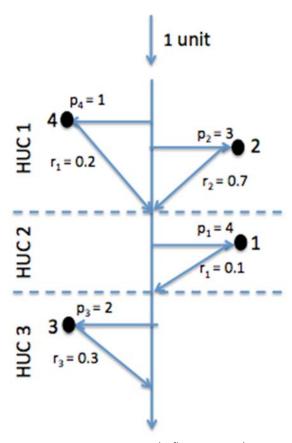
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Figure 3-2: Example flow network

In the example flow network portrayed in Fig. 3-2, four users are labeled 1 through 4, where 1 is the most senior and 4 is the most junior. One unit of water is available at the top of the network and each user's demand is for one unit. Each user, has an assigned unit penalty, p_i, and surface return flow factor, r_i. Unit penalties are assigned by applying Eq. 2. Using the above example, the total penalty incurred from four possible flow paths are considered.

The first path flows from user 4 → 1 → 3, skipping user 2. This path flows to user 4, skips user 2 and returns to user 1, then returns to user 3. The total penalty is calculated using the equation below:

$$total\ penalty = p_2 + p_1(1 - r_4) + p_3(1 - r_4 r_1) \hspace{2cm} (3\text{-}3)$$
$$total\ penalty = 1 + 4(1 - 0.2) + 2(1 - 0.2 * 0.1) = 6.06$$

All four flow paths and total penalties incurred are shown in Table 3-2 below along with the allocations for user 1 (the most senior user) provided from each flow path.

Table 3-2: Total penalties incurred by flow paths

Flow Path	Total Penalty	User 1 Allocations
4 → 1 → 3	6.06	0.3
2 → 1 → 3	4.06	0.7
2 → 3	5.60	0
1 → 3	5.80	1

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Given the above options, the optimal solution (least total penalty) is the second flow path, which provides user 2 with all 1 unit of his demand, user 1 with 0.7 units of demand, and user 3 with 0.07 units of demand. The next optimal solution is the third flow path, which provides zero water for user 1. The only flow path that follows appropriative doctrine and meets user 1's demands before all other junior users is the third flow path, which ranks third in optimality. Clearly, using Eq. 2 to assign unit penalties is insufficient to maintain user priorities in this example.

Individual unit penalties can be adjusted by-hand until user priorities are properly maintained. This method is reasonable for small flow networks like Fig. 3-2. But for networks with hundreds or even tens of users, such a "guess and check" method becomes quite laborious and prone to error. If return flows were to be added to DWRAT, a more efficient method of determining priority-based unit penalties is needed.

Determining proper unit penalties for networks with return flow
Israel and Lund (1999) developed a method to assign unit penalties for priority based operations in a Network Flow Programming (NFP) model with return flows. The method consists of eight rules to address different seniority and location relationships (e.g. senior user with downstream, junior users and senior user with upstream, junior users). Four of the rules apply only if storage users are part of the network. Since DWRAT is a single time-step model that does not view storage users as different from other users, these storage rules can be omitted from DWRAT applications. The four remaining rules are summarized below. Further explanation can be found in Israel and Lund (1999) and Ferreira (2007). The rules are numbered as in Israel and Lund (1999). Rule 1 relates to a scenario with no return flows, so Rule 1 is skipped and Rule 2 is discussed first.

Rule 2 – Senior user with downstream juniors
Rule 2 ensures that a user's unit penalty exceeds the sum of the unit penalties of all users that are both downstream of and junior to the user in question. The sum of unit penalties for downstream junior users that are also downstream of the senior user's return flow is decreased by the senior user's return flow fraction. The governing equation for Rule 2 is:

$$p_s \geq max_i \left\{ (1 - r_s) \sum_{j=1}^{N_i} (p_{dj}) + \sum_{j=1}^{M_i} p_{uj} \right\} + \varepsilon \qquad (3\text{-}4)$$

where p_s is the unit penalty of a (relative) senior user, r_s is the surface return flow factor for the senior user (ranges from 0 to 1), p_{dj} is a the unit penalty of a junior user who is downstream of the senior user's return flow location, p_{uj} is the unit penalty of a junior user who is downstream of the senior user, but upstream of his return flow location, ε is a marginal value, N_i is the number of junior users downstream of the senior return flow, and M_i is the number of downstream junior users upstream of the senior's return flow location. This rule is evaluated for every possible flow path, i, from the senior user to a sink and the maximum value is taken.

There are often many possible flow paths from a senior user to the sink in the Sacramento DWRAT model, so when applying Rule 2, it is assumed all uses downstream of a senior user, s, are non-consumptive. This leads to a single possible flow path. Priorities are properly maintained, but unit penalties are often larger than necessary.

Rule 3 – Senior user with upstream juniors

The third rule ensures that a user's unit penalty is larger than any upstream, junior user's unit penalty scaled by the junior user's return flow factor.

$$p_s \geq max_i \left\{ \frac{p_j}{1-r_j} \right\} + \varepsilon \, , \forall \, j \in U \tag{3-5}$$

where p_j is the unit penalty of a junior user, j, r_j is the surface return flow factor of user, j, and U is the set of junior users upstream of the senior user. This rule also is evaluated for every possible flow path, i, and the maximum value is taken.

Rule 4 – Ordinal/Ranking rule

With Rule 2 above, a user with a very large surface return flow fraction can be assigned a unit penalty smaller than users junior to him. For this reason, a ranking rule is imposed to ensure a user's unit penalty is at least marginally larger than the user immediately junior.

$$p_s \geq p_{s-1} + \varepsilon \tag{3-6}$$

Rule 5 – Baseline rule

The final rule simply sets the unit penalty of the most junior user to a pre-determined baseline value.

$$p_N \geq base \tag{3-7}$$

Objective

$$Min \, Z = p_N - p_1 \tag{3-8}$$

The objective of the unit-penalty-setting linear program is to minimize the range of unit penalties. Many solutions can follow Rules 2 – 5, but with large problems, the unit values can reach values large enough to inhibit the solver from finding a solution. So, the model minimizes the range of consistent unit penalties.

Applying the above, four rules along with the objective, the following results are achieved. The *base* and ε values are both set at 1.

Table 3-3: User's unit penalties

User	Downstream Constraint	Upstream Constraint	Unit Penalty
1	$p_1 \geq (1-0.1)(p_3) + \varepsilon$	$p_1 \geq max \left\{ \begin{array}{c} \frac{p_4}{(1-0.2)} + \varepsilon \\ \frac{p_2}{(1-0.7)} + \varepsilon \end{array} \right\}$	11.83
2	$p_2 \geq (1-0.1)(p_3) + \varepsilon$	$p_2 \geq (1-0.2)(p_4) + \varepsilon$	3.25
3	N/A	$p_3 \geq (1-0.2)(p_4) + \varepsilon$	2.25
4	N/A	N/A	1

Results with Example Model

Before applying the Consumptive Use Diversions and Explicitly Return Flows Downstream methods of adding return flows to the Sacramento DWRAT model, they are applied to a DWRAT model for an example basin. The simple example is the one used by Benjamin Lord (2014) and appears in Figure 3-3. The basin has eight sub-basins (labeled A-H) and 11 users labeled by their seniority with 1 being the most senior. Each sub-basin receives seven units of local inflow at the top of the sub-basin so all seven units are accessible to every user in the sub-basin. User applied demand is summarized in Table 3-4.
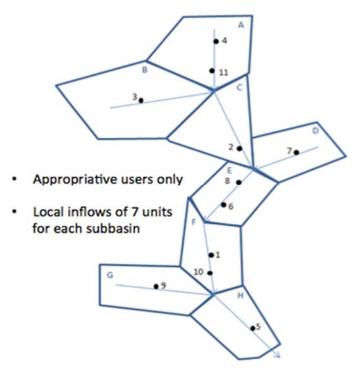

Figure 3-3: Example Basin

Table 3-4: Applied demand

User	1	2	3	4	5	6	7	8	9	10	11
Applied Demand	7.0	4.0	8.0	8.0	8.0	4.0	3.0	9.0	9.0	7.0	10.0

To test the effects of adding return flows via the two major methods described in earlier in Chapter 3, each method was applied to the example model and run 10 times, with return flow values increased from 0.1 to 1 in increments of 0.1. To simplify analysis, every user had the same surface return flow fraction for each run (i.e. for one run, all 11 users were given a return flow fraction of 0.4). The effect of method and return flow factor on the percent of met demand is shown in Fig. 3-4.
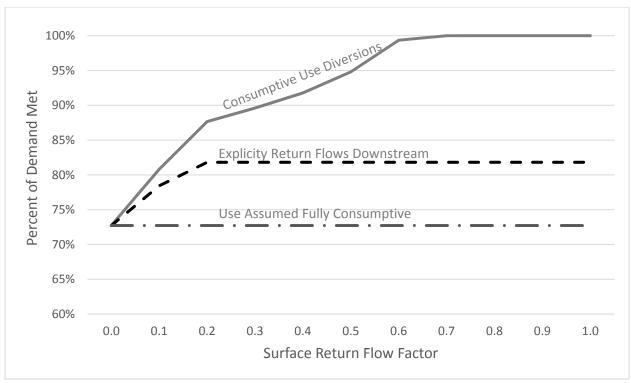
Figure 3-4: Comparing met demand across return flow methods

When the example model is run without return flows added, 73% of demand is met. Both methods of adding return flows increase met demand as users' return flow factors increase, but reducing users' applied demand to consumptive demand always meets more demand than explicitly returning flows back into the system. The results from the two methods follow closely when return flow fractions are small. With return flow rates of 0.1 and 0.2, the percentage of met demand varies by 2.4% and 5.8%, respectively. In reality, most users' surface return flow fractions are less than 0.2, but larger return flow fractions are considered for a fuller analysis.   High surface flow return factors occur in practice mostly for run-of-river hydropower plants and thermal cooling of power plants.

As return flow rates increase beyond 0.2, no additional demand is met through the Explicitly Return Flows Downstream method, but the Consumptive Use Diversions method continues to unrealistically meet more and more demand until 100% of demand is met at return flow factors of 0.7 and greater. The "percent of demand met" for the Consumptive Use Diversions method is the percent of *consumptive* demand met, not *applied* demand. This enables the model to provide 100% of demand with larger return flow factors. As shown in Fig. 3-1, method 1 is prone to under-curtail users and allows for modeled demand to be met when it is not physically possible.

The results from explicitly returning flows downstream do not vary for return flow factors beyond 0.2 because at that point, the seven units of inflow available at the rims are entirely used. No matter how large the return flow fractions are, more water cannot be made available in the rim sub-basins (A, B, D, and G), and since demand in three of the upper rim sub-basins exceed local inflows, there will always be shortages. The upper rim sub-basins have the greatest differences between the two methods. For a larger basin, the difference in results would likely be less because the ratio of upper rim sub-basins to interior sub-basins would tend to be smaller.

By using both methods of adding return flows to assess a decision of over-curtailment and under-curtailment, a good middle-ground decision could be made. As noted above, most users' surface return flow fractions are less than 0.2, which is the region where the two methods perform most closely, so a middle-ground decision will not be so far off from either method's decision. Other sources of error, such as hydrologic and demand quantity estimates, are likely to be more important.

Determining Sacramento Users' Surface Return Flow Factors
Surface return flow factors vary by type, place, and time of use. A field of tomatoes watered by flood irrigation in winter along the bank of a river will return much more of its applied water than an almond orchard watered by drip irrigation in summer, 50 miles from the nearest stream. At present, this level of detail is not considered, partly because such data is unavailable, for determining an individual right holder's surface return flow factor in DWRAT.

For this work, surface return flow factors were calculated based on 19 possible beneficial use categories diverted water could be applied toward. In the 2010-2013 use data reported to SWRCB, right holders identified what beneficial uses their water could be used for, including irrigation, stock watering, domestic, power, recreation, mining, and snow-making. There are 19 unique uses in the Sacramento Basin. In this analysis, each type of use is assigned a surface return flow factor ranging from 0 to 1. As mentioned earlier, most factors are less than 0.2.

Many right holders claim multiple beneficial uses. For example, a water utility that diverts water to storage behind a dam for hydropower generation could claim boating recreation as another beneficial use to their diverted water. When a user claims multiple beneficial uses, the average return flow factor is calculated. Well-documented standards exist for calculating return flows for various irrigation practices, but not for most of the 19 uses listed by Sacramento users. Even for irrigation practices, return flow is most frequently discussed in terms of total return flow—returned to both surface and groundwater—rather than strictly surface returns. Due to the disparity of data, surface return flow values were derived through personal judgment influenced by available data (Gosain et al., 2005). To be cautious, most types of use are assigned factors of 0.125. Several large diversions, particularly for the state and federal water projects, divert storage and release water to supply Delta export pumping, which becomes a fully consumptive use with respect to the Sacramento River basin.

A broad approach is used to calculate return factors in this analysis, but with more detailed return flow data, DWRAT's estimates of water availability and curtailment decisions will improve.

Chapter 4 – Results with Sacramento DWRAT for 2015 drought

The Sacramento DWRAT model was tested on water year 2015 (October 1, 2015 – September 30, 2015) and the results are shown below. Both demand and supply data are in monthly time-steps, so DWRAT acquired results for a single representative day each month. The Sacramento DWRAT model hydrology has yet to undergo extensive calibration, so these results should be seen as preliminary. It should be mentioned again that the hydrologic input for this model analysis is historical, not forecasted. Ideally, DWRAT can be used in combination with forecasts of unimpaired streamflows to help the SWRCB prepare for necessary, future curtailments. However, these data were unavailable for the Sacramento Basin at the time of research, so historical hydrologic data is used. There is less error in historical data than forecasted so this analysis overstates the accuracy of DWRAT decisions made for future conditions.

Results Without Return Flows

Figure 4-1 shows the percentage of active water diverters that would be curtailed by DWRAT throughout water year 2015 when return flows are not included. Users are considered active if their reported demand exceeded zero for the month. Users are considered curtailed if they DWRAT allocates less than 100% of their demand. Results are compared to estimated unimpaired flow at the outlet.
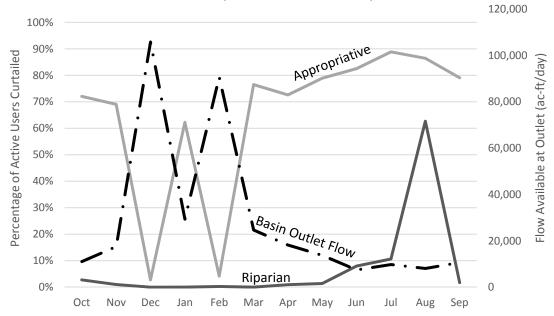

Figure 4-1: Percentage of Sacramento Basin water right holders curtailed each month using DWRAT for water year 2015. Unimpaired flow at the outlet is shown by the dashed line.

Over this very dry year, 3% to 89% of appropriative users are curtailed in any month. When basin outlet flows are high, fewer rights are curtailed by DWRAT and vice versa. Riparians are only noticeably curtailed in October, June, July, and August by 3%, 8%, 11%, and 63% respectively. Because riparians are equal in priority and share shortage, most of their curtailments are only partial, while appropriative users are most often completely curtailed. Riparian curtailments tended to occur in drier, more isolated upstream tributaries.

The spike in riparian curtailments in August results from an undiagnosed glitch in the DWRAT model. Many riparian users curtailed by DWRAT in August are completely curtailed despite available water in

their sub-basin. Riparians should never be completely curtailed unless zero water is available to them. Otherwise, any available water should be shared among riparian users with access. These odd curtailments also occur in June and July to a lesser extent. In June, July, and August, the numbers of affected sub-basins are 14, 13, and 213, respectively.

The reason DWRAT completely curtails some riparian users with available water is uncertain at this time, but these odd curtailments appear to be directly linked to water availability. When streamflows are artificially increased in the Sacramento DWRAT model, the occurrence of these odd curtailments decreases. As flows decrease, certain sub-watersheds are affected before others, and within affected sub-watersheds, upstream sub-basins are affected before downstream ones. Further investigation is being conducted to resolve the issue.

Results With Return Flows

When return flows are added through the Consumptive Use Diversions method, the following results are obtained. These results under-estimate ideal curtailments.
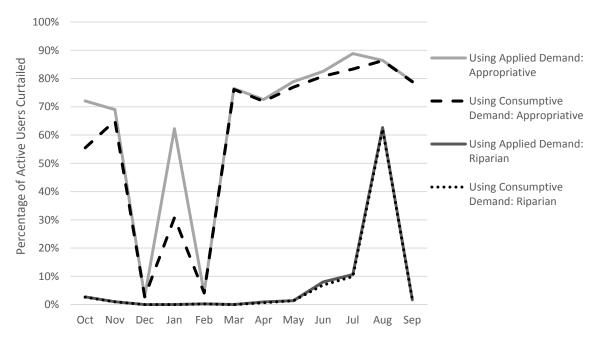

Figure 4-2: Comparison of DWRAT results for water year 2015 with and without return flows included. Return flows are included using the Consumptive Use Diversions method.

The results with and without return flows follow closely for most months. Noticeable reductions in percentage of curtailed appropriative users occur in October, November, January, and July by 17%, 4%, 31%, and 5% respectively. The Consumptive Use Diversions method will undercurtail users, so Fig. 4-2 shows the largest possible reduction in curtailed users from the addition of return flows (given users' return flow factors are accurate). There is no noticeable difference in the percentage of riparian water rights curtailed. Since upstream appropriative rights are entirely curtailed before riparian users are curtailed, upstream return flows from appropriative users should have no effect on riparian curtailment, which occurs only in very dry conditions.

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Figure 4-3 compares the percentage of normal use curtailed by volume for each month, where 100% indicates zero water allocated and 0% indicates full demand allocated. Values for the results using consumptive demand are derived from dividing consumptive demand – not applied demand – by DWRAT allocations. While the trend is similar to that in Fig. 4-2 above, a few things stand out. Unless mentioned otherwise, the values used in the remainder of this chapter refer to results from the Consumptive Use Diversions Method. While only 3% and 1% of riparian users are curtailed in October and November, respectively, a significantly larger 15% and 28% of normal riparian use is curtailed in these months.
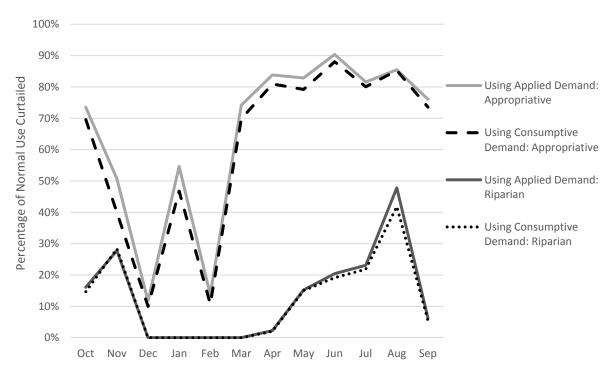

Figure 4-3: Comparison of percentage of normal use curtailed by volume by DWRAT in water year 2015 with and without return flows included. Return flows are included using the Consumptive Use Diversions method.

A more consistent decrease in curtailment occurs from implementing return flows in terms of the percentage of normal use volume curtailed in Figure 4-3 versus the percentage of users curtailed in Figure 4-2. In 11 out of 12 months, implementing return flows causes a decrease exceeding 2% in normal appropriative use curtailed. A 2% or greater decrease in curtailed appropriative users only occurs in six months.

A different relationship exists for riparian curtailment. The percentage of curtailed riparians in Figure 4-2 most often does not exceed the percentage of curtailed normal riparian use in Figure 4-3, with exceptions in February and August when the percentage of curtailed users is 0.25% and 20% greater than the percentage of curtailed normal use, respectively (August results for riparians, however, are suspect due to the many odd curtailments discussed previously). In the remaining months, the percentage of curtailed users is 8% less than the percentage of curtailed normal use, on average. This is counter to expectations given the nature of riparian rights. Riparians must share shortage, so even a slight water shortage in a sub-basin would cause the DWRAT model to disperse the shortage across every riparian user in the sub-basin. This results in 100% of riparian users in that sub-basin curtailed even if there is only a 1% shortage

in water volume. This being the case, the percentage of riparian users curtailed is expected to exceed the percentage of riparian normal use curtailed. However, the Sacramento Basin has hundreds of sub-basins and a single dry basin with a large riparian demand can skew the results and cause the percentage of curtailed riparian normal use to exceed the percentage of riparian users curtailed.

October and November were two months with the highest differences between the percentage of riparian users curtailed and the percentage of curtailed riparian use, a 12% and 27% difference, respectively. In October, 802 riparian users were active and 21 were curtailed, but the curtailed users came from only four of the 768 sub-basins in the Sacramento Watershed. One curtailed user was in the Little Chico Creek sub-basin with a large demand amounting to 13% of all riparian demand in October. Little Chico Creek has no sub-basins upstream and was extremely dry in October, so DWRAT only allocated 4% of this user's demand. Because of the user's large demand, his shortage was 88% of all riparian curtailed use in October.

In November, 495 riparian users were active and only five were curtailed in three sub-basins. All three sub-basins had three or fewer sub-basins upstream. The two users with the largest percentages of curtailed normal use had a combined daily average demand that accounted for 33% of all normal riparian use in November. Both of their sub-basins were upstream and very dry, so DWRAT only allocated them 13% and 15% of their respective normal use. The shortage of these two users accounted for 98% of the November riparian use curtailed. Despite 99% of riparian users receiving their full demand in November, the large demands of a few users in dry, upstream sub-basins resulted in 30% of all riparian normal use curtailed.

The daily total applied and consumptive demands for appropriative and riparian users in the Sacramento Basin is in Figure 4-4. Riparian water rights account for very small amounts of water use compared to appropriative rights.
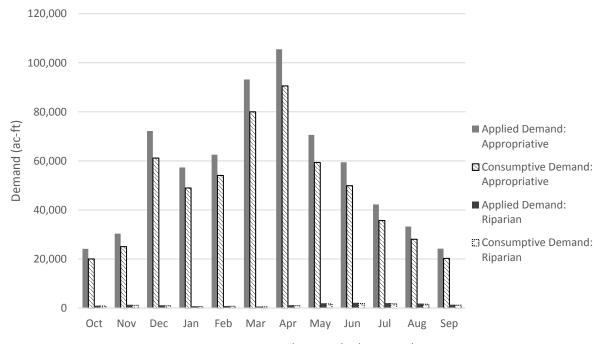

Figure 4-4: Consumptive Demand vs. Applied Demand in water 2015

DWRAT and State Board Curtailments Compared

In October of water year 2015, all post-1914 appropriative rights were curtailed from a State Board order that went into effect in May of 2014. By mid-November, post-1914 rights were released from curtailment until the following May, when the State Board again ordered all post-1914 appropriative users to curtail water use. In June of 2015, the Board increased curtailments to include appropriative users with a 1903 priority date or later. In September, the Board released pre-1914 users on the mainstem of the Sacramento and Feather Rivers, but not those on the American river (SWRCB, 2016a). The State Board's curtailment decisions are compared to DWRAT decisions in Figures 4-5 and 4-6.
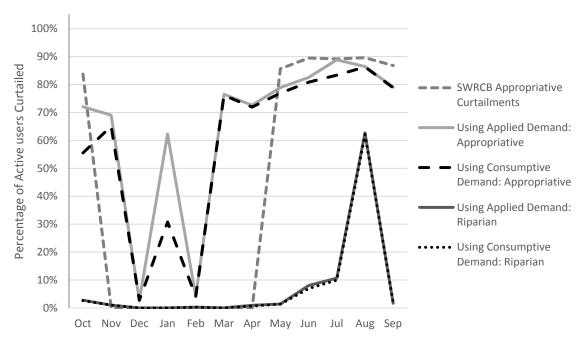

Figure 4-5: Comparison of percentage of users curtailed by State Board compared to DWRAT in water year 2015

In months when the State Board curtailed water rights, the percentage of appropriative users curtailed by the DWRAT model using applied demand was 0.3% to 12% less than the Board's decisions, with an average difference of 6%. The largest difference is in October.

A major difference is that the Board never curtailed riparian water rights in water year 2015 while DWRAT curtails up to 3% of riparians in October (higher percentages are curtailed in June, July, and August, but the results are suspect as discussed previously). Also, the Board did not curtail any water rights from November through April while DWRAT curtails 3% to 76% of appropriative users during that time.
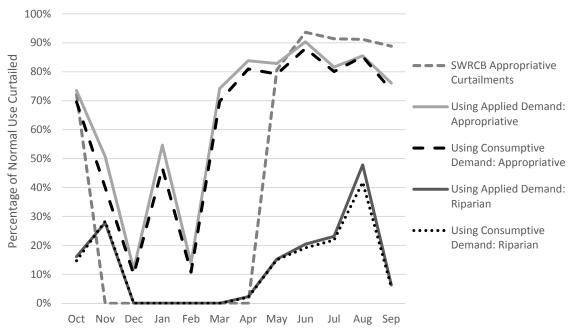
Figure 4-6: Comparison of percentage of normal use curtailed by volume resulting from State Board curtailment decisions compared to DWRAT decisions in water year 2015

Figure 4-6 compares the percentage of normal use by volume curtailed by the SWRCB and DWRAT. A similar difference exists in Figure 4-6 as when comparing the percentage of users curtailed by SWRCB and DWRAT in Figure 4-5. In October and May the percentage of appropriative normal use curtailed by the Board is 1% and 2% lower than the DWRAT model's results using applied use diversions. From June to September, however, the curtailments suggested by DWRAT curtail 3% to 13% less normal use than the Board. On average, the percentage of normal use curtailed by DWRAT is 5% than curtailed by the Board.

The differences between SWRCB and DWRAT curtailments are generally quite close considering DWRAT uses historical calculated flows at reference locations and model-based flow scaling at sub-basins, while the SWRCB used forecast flows with more aggregated basins.

Figures 4-7 and 4-8 show how user priority affects DWRAT's curtailment decisions in May and July, respectively. There are 1,023 active riparian users and 2,162 active appropriative users in May, making 3,185 total. Every user is assigned a unique priority from 1 through 3,185 with 1 being the highest priority. Because riparian users are the most senior as a class and equal in priority amongst each other, they are assigned priorities 1 through 1,023 based on percentage of normal use curtailed. Appropriative users are assigned priorities 1,024 through 3,185 based on their year of first use or file date. The same process is done for July, in which there are 1,137 active riparian users and 2,007 active appropriative users.

Results are calculated using consumptive use diversions. Figures 4-7 and 4-8 plot the percentage of normal use curtailed by DWRAT –100% being allocated zero water, 0% being allocated a user's full consumptive demand. Several appropriative and many curtailed riparian users are only partially curtailed and appear in the middle regions of the figures. As expected due to their shortage-sharing nature, a much higher proportion of riparian users are partially curtailed compared to appropriative users. Of the appropriatives curtailed in May and July, only 1% are partially curtailed. Of the riparians curtailed in May

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and July, 100% and 40%, respectively, are partially curtailed. As long as there is some streamflow available, riparians should never be completely curtailed because they share shortage among each other. In July, however, the American River Basin is modeled with zero streamflow, so 60% of curtailed riparians are completely curtailed by DWRAT. July is also one of the three months when some odd riparian curtailments occurred in DWRAT as discussed in the beginning of chapter 4. Table 4-1 summarizes the percentages of active users not curtailed, partially curtailed, and completely curtailed by DWRAT in May and July.

Table 4-1: Percentage of users not, partially, and completely curtailed by DWRAT in May and July

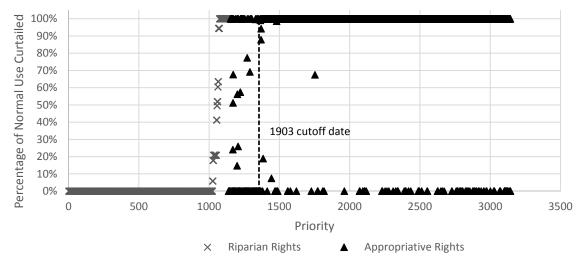|	Zero Curtailment	Partial Curtailment	Total Curtailment
Riparian - May	99%	1%	0%
Riparian - July	90%	4%	6%
Appropriative - May	23%	1%	76%
Appropriative - July	17%	1%	82%

Figure 4-7: Percentage of individual normal use curtailed in July compared to water right priority. A dashed line shows the 1903 cutoff date used by the SWRCB in July 2015. Results from DWRAT calculations using consumptive use diversions.
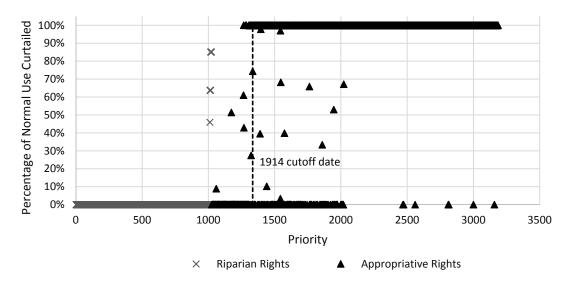
Figure 4-8: Percentage of individual normal use curtailed in May compared to water right priority. A dashed line shows the 1914 cutoff date used by the SWRCB in May 2015. Results from DWRAT calculations using consumptive use diversions.

In May of 2015, the State Board curtailed all appropriative rights with a 1914 priority date or later, which amounted to 86% of active appropriative users and 81% of normal appropriative use by volume. In July, the Board increased curtailments to include appropriative rights with a 1903 priority date or later, which amounted to 89% of active appropriative users and 91% of normal appropriative use. In the same months, DWRAT curtailed 77% of active appropriative users and 79% of normal use in May and 83% of active appropriative users and 80% of normal use in July. The dashed lines in Figure 4-7 and 4-8 represent the 1914 and 1903 cutoffs. No riparian users were curtailed by the Board.

Some users junior to the 1914 and 1903 cutoff dates are not curtailed by DWRAT. In total, 218 appropriative users curtailed by the Board are not curtailed by DWRAT in May (170 in July), and 33 appropriative users curtailed by DWRAT were not curtailed by the Board (53 in July). This accounts for 10% and 2% of active appropriative users, respectively, in May, and 8% and 3% of active appropriative users in July.

Some of the most junior users in the Sacramento Basin were allocated 100% of their consumptive demand by DWRAT. At the same time, some of the more senior users in the Sacramento Basin were allocated none of their consumptive demand by DWRAT. This is because some sub-basins were modeled with more than enough water to satisfy the demands of every right within the sub-basin and others were modeled as extremely dry. For example, the July unimpaired flow at the American River at Folsom reference gage was estimated to be zero, so the whole region scaled by that gage was modeled with no water and none of the appropriative or riparian users in that region received any allocation from DWRAT in July. DWRAT allocates water based on local water availability and hydrologic connectivity to more senior users. Figures 4-7 and 4-8 show that for a large basin with much hydrologic variability, a single priority cutoff date should ideally not be applied to the entire basin.

Of the 218 appropriative users curtailed by the Board but not by DWRAT in May, 97% are in the southern half of the Sacramento Watershed. The 33 appropriative users curtailed by DWRAT but not the Board are

primarily in the northern half of the Sacramento Watershed. Of the 170 appropriative users curtailed by the Board but not by DWRAT in July, 88% are in the western half of the most-southern region of the Sacramento Watershed. Streamflow for this area is scaled by the 4-River reference gage, which is located at the outlet and has the largest unimpaired flows in the Sacramento Basin. Currently, the large outflows at the 4-River gage are scaled to the western half of the most-southern region because it is the nearest available unimpaired gage. Were a reference gage located on the western side of the mainstem Sacramento River, this region would likely be modeled drier and cause DWRAT to curtail more users.

For May, the rates of these curtailments are spread evenly across upstream and downstream sub-basins according to the proportion of active users in upstream and downstream basins. Table 4-2 summarizes the locations all active appropriative users in May and the locations of users curtailed by the Board and not by DWRAT and users curtailed by DWRAT and not by the Board. User location is characterized by the number of sub-basins upstream – a value derived from the connectivity matrix mentioned in Chapter 1. Most HUC-12 sub-basins in the Sacramento Watershed do not have sub-basins upstream and the most downstream sub-basin has 750 upstream sub-basins. Relative locations of users are divided into five categories.

Table 4-2: Active and curtailed appropriative users by location category in May

# of Sub-basins upstream	Zero	1-5	2-20	21-100	101-750
# of users curtailed by DWRAT	753	369	232	173	140
% of users curtailed by DWRAT	78%	72%	75%	87%	82%
# of users curtailed by the Board	837	412	270	181	152
% of users curtailed by the Board	86%	81%	87%	91%	89%
# of active users	**971**	**510**	**310**	**200**	**171**
% of active users	**45%**	**24%**	**14%**	**9%**	**8%**
# of users curtailed by the Board but not by DWRAT	99	51	43	9	16
% of users curtailed by the Board but not by DWRAT	45%	23%	20%	4%	7%
# of users curtailed by DWRAT but not by the Board	15	8	5	1	4
% of users curtailed by DWRAT but not by the Board	45%	24%	15%	3%	12%

The percentages of appropriative users curtailed by the Board and not DWRAT and by DWRAT and not the Board in May are in proportion to the percentage of all active appropriative users in the location category. For example, 24% of all active appropriative users in May have 1-5 sub-basins upstream. Proportionally, 24% of the users curtailed by the Board but not by DWRAT also have 1-5 sub-basins upstream. The proportions are not exact for every location category, but they are all very close.

SWRCB never curtailed riparian rights in water year 2015, but DWRAT curtailed 13 and 113 riparian users in May and July, respectively. In May, the 13 curtailed riparians are allocated 45% to 85% of their normal demand by DWRAT and are in three different sub-basins, all of which have no sub-basins upstream. In July, slightly over half are located in the American River Basin and 100% of their normal use is curtailed because, as mentioned above, the unimpaired flow at the American River at Folsom reference gage is

zero in July. The remaining curtailed riparian users were curtailed 6% to 100% of their normal use and are located predominately in the most upstream sub-basins, with only one or zero sub-basins upstream.

Figures 4-9 and 4-10 show how relative location affects the rate of curtailment by DWRAT for riparian and appropriative users in May and July. The location categories and their corresponding number of active riparian and appropriative users are summarized in Tables 4-3 and 4-4, respectively.

For riparian users, curtailment is strongly correlated to the number of sub-basins upstream. This is because upstream sub-basins likely have less streamflow than downstream sub-basins. In May, the only curtailment of riparian users occurred in sub-basins with zero upstream sub-basins. In July, nearly 12% of riparians with zero upstream sub-basins are curtailed by DWRAT. Only 4% of users with 1 to 5 sub-basins upstream are curtailed, and no users with 101 to 750 sub-basins upstream are curtailed.
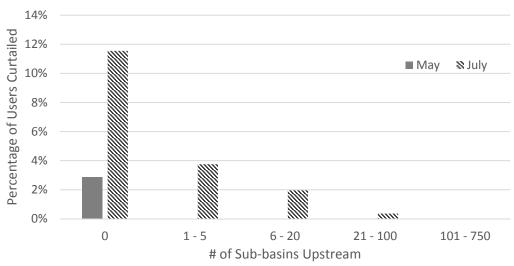

Figure 4-9: Percentage of active riparian users curtailed by the Sacramento DWRAT model in May and July compared to relative location

Table 4-3: Active riparian users per location category in May and July

# of Sub-basins Upstream	0	1 − 5	6 − 20	21 − 100	101 - 750
% of Sub-basins	54%	36%	10%	6%	4%
# of Active Riparian Users in May	451	238	163	114	57
% of Active Riparian Users in May	44%	23%	16%	11%	6%
# of Active Riparian Users in July	537	798	968	543	339
% of Active Riparian Users in July	17%	25%	30%	17%	11%

The relative location of appropriative users does not impact whether they are curtailed by DWRAT to the same degree as riparians. In Figure 4-10, between [72 – 87%] and 81 - 89% of appropriative users are curtailed in May and July, respectively, depending on how many sub-basins are upstream and there is little to no correlation between relative location and curtailment. This is likely because appropriative curtailment decisions heavily depend on user priority, unlike decisions for riparian users who all have equal priority and must share shortage. For example, a junior appropriative user in the outlet sub-basin with large unimpaired flows will be curtailed by DWRAT if the water supply is already allocated to senior users upstream or is required by a large senior user in the same sub-basin.
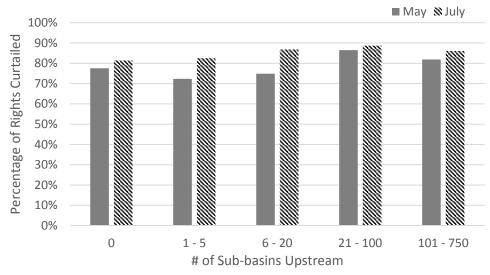

Figure 4-10: Percentage of active appropriative users curtailed by the Sacramento DWRAT model in May and July compared to relative location.

Table 4-4: Active appropriative users per location category in May and July

# of Sub-basins Upstream	0	$1-5$	$6-20$	$21-100$	101 - 750
% of Sub-basins	54%	36%	10%	6%	4%
# of Active Appropriative Users in May	971	510	310	200	171
% of Active Appropriative Users in May	45%	24%	14%	9%	8%
# of Active Appropriative Users in July	940	469	265	168	165
% of Active Appropriative Users in July	47%	23%	13%	8%	8%

Error Analysis of Flow Scaling Ratios

Several types of error could affect the DWRAT model's results, including 1) estimates of unimpaired flow at the reference locations, 2) flow scaling ratio errors (Whittington, 2016), 3) water use estimation from reports, and 4) surface water return flow factors. This thesis briefly analyzes the potential error in the flow scaling ratios. More detailed error analysis is conducted with the snmaller Russian River DWRAT model (Whittington, 2016).

To estimate available unimpaired streamflow, DWRAT uses data from a statistical unimpaired flow model developed by the U.S. Geologic Survey. This model estimates historical unimpaired monthly average flows for every HUC-12 sub-basin in the Sacramento Basin from 1950 to 2010. From these flow estimates, ratios or other functions relating flow between any two sub-basins can be developed. Water year 2015 was one of the driest years on record, so unimpaired flow estimates from the severe 1976-77 drought are used to calculate the flow scaling ratios used in the Sacramento DWRAT. Flow ratios are calculated between the six sub-basins containing the unimpaired flow reference gages and the sub-basins in their respective regions (see Fig 2-2). These ratios from 1977 are then used to disaggregate the 2015 unimpaired flow estimates to the rest of the Sacramento Watershed. However, no two years are the same and there might be a historical year – or combination of years – that better represents water year 2015 hydrologically.

To analyze the potential error created by using 1977 flow scaling ratios, flow ratios are calculated for the 20 driest years between 1950 and 2010. Figure 4-11 shows how scaling ratios varied from year to year for the month of July in six sub-basins throughout the Sacramento Basin. One sub-basin was selected from each of the six regions of the Sacramento Basin shown in Fig. 2-2. Years are listed from most to least dry.
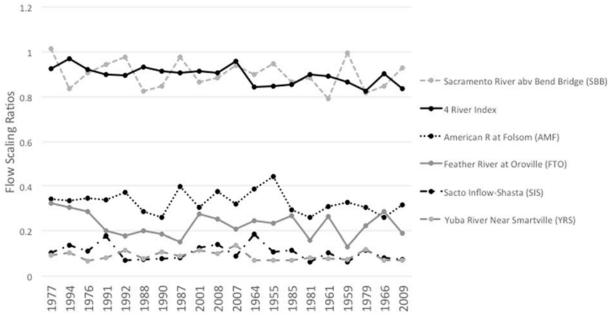

Figure 4-11: July flow scaling ratios for six sub-basins during the 20 driest years. Years listed from most to least dry.

Even among dry years, Figure 4-11 shows that scaling ratios vary significantly from year to year. Flow ratios in some years are more than double those in other years for sub-basins with smaller flow ratios. Sub-basins with larger flow ratios do not vary as much, relatively. Peaks and valleys of several of the

curves in Figure 4-11 follow similar patterns for a few years, but most of the figure shows inconsistency between the curves. Very little can be gleaned from this figure other than the tendency for sub-basins with smaller flow scaling ratios to vary more. However, when the flow ratios for sub-basins within the same region are analyzed, a more interesting picture appears.

Figure 4-11 graphs flow scaling ratios for the 20 driest years in the months of October, January, April, and July for four sub-basins in the American River Basin (using the American R. at Folsom, AMF reference gage). Years are listed from most to least dry. The curves in the October graph are labeled by the average annual streamflow at the outlet of the selected sub-basin during dry years.
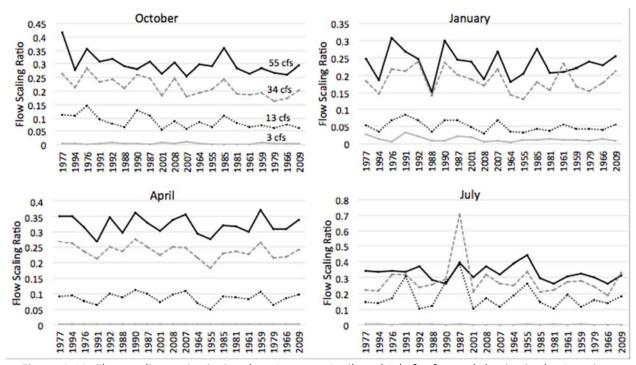

Figure 4-12: Flow scaling ratios in October, January, April, and July for four sub-basins in the American River Basin during the 20 driest years. Years listed from most to least dry.

Figure 4-12 shows that when comparing sub-basins in the same region, the peaks and valleys of the flow ratio curves mimic each other. With two exceptions, there is very little cross over of the curves in Figure 4-12 compared to Figure 4-11. This indicates the disaggregation model is consistent within a region, but not from region to region. The peaks and valleys of the flow ratio curves of sub-basins in the 5 other regions mimic each other as well.

While Figure 4-12 shows a consistent pattern, the scaling ratio for a sub-basin can still vary significantly in the same month depending on the dry-year chosen. For example, the flow ratio in January, 1988 for the sub-basin with an average streamflow of 55 cfs is nearly double the flow ratio in January, 1990. Because ratios can vary significantly, care should be taken to select the dry year that most resembles the present year. It may be advantageous to select different dry years for different regions, or even different dry years for different months. Alternatively, using averages across dry years rather than a single dry year for flow scaling ratio calculations could reduce error. Work is also being done to improve the U.S. Geologic Survey's statistical model, which estimates the 1950 - 2010 unimpaired flows (Magnusson-Skeels, 2016).

To assess which dry year most resembles the present year, an estimate of unimpaired flow could be made at additional locations within each of the six regions in the Sacramento Basin. The flow ratios between unimpaired flow at the outlet (where it is already estimated) and the new locations could be calculated and used to indicate the particular dry year pattern. Adding several new locations of unimpaired flow within a region could help better identify the type of dry year, but even one new location would likely make a large improvement. Since the flow ratio curves tend to mimic each other (as shown in Fig. 4-12), knowing the ratio at one location should give a good indication of streamflow in other sub-basins in the region.

Figure 4-13 shows the normalized monthly standard deviation of flow ratios in dry years for four sub-basins in the region of the American River Basin. The same four sub-basins are analyzed as in Figure 4-12. Monthly standard deviations are normalized by dividing by the monthly average scaling flow ratio. Sub-basins with more streamflow tend to have lower normalized standard deviation values. This is likely because sub-basins with larger streamflows are also closer to the regional outlet where the reference gage is located and have larger watersheds and base flows. Flow ratios will be most accurate closest to a reference gage.
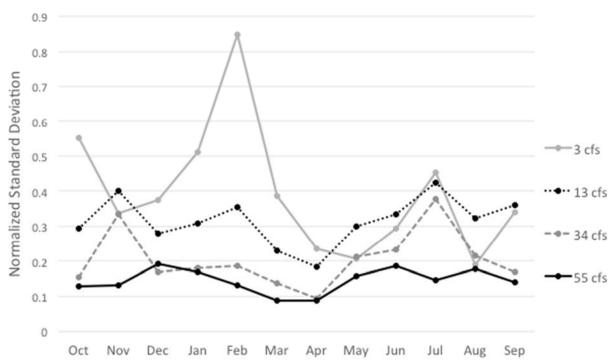

Figure 4-13: Monthly normalized standard deviation of scaling flow ratios for dry years for four sub-basins in the American River Basin. Sub-basins are labeled by their average streamflow in dry years.

The relationship between scaling flow ratio variability and sub-basin location is further examined with Figure 4-14. Twenty-four sub-basins (four from each of the six regions) are divided into five categories of relative location and their normalized standard deviations of flow scaling ratios are averaged over all dry years. Location is characterized by the number of sub-basins upstream, as in Figure 4-9. Sub-basins farther downstream generally have less variability in flow scaling ratios. The correlation between number of sub-basins upstream and average normalized standard deviation of sub-basin scaling ratios is not as strong as with the percentage of riparian users curtailed in Figure 4-9, but it is still strong. The average normalized standard deviation of scaling ratios is larger for sub-basins with five or fewer sub-basins

upstream than for sub-basins with six or more sub-basins upstream. For sub-basins with 101 to 750 sub-basins upstream, it is nearly half that of sub-basins with no upstream sub-basins.
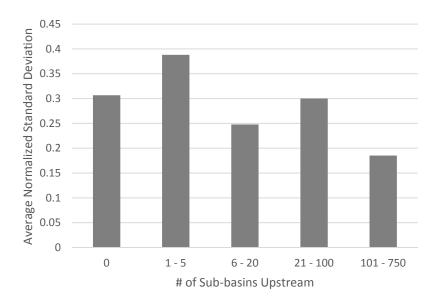

Figure 4-14: Normalized standard deviation of scaling flow ratios averaged over dry years and 24 sub-basins in the Sacramento Watershed compared to relative location of sub-basins. Relative location is categorized by the number of sub-basins upstream.

Table 4-5 summarizes the relative locations of the 24 sub-basins used for Figure 4-14. Distribution of sub-basins is relatively even between categories.

Table 4-5: Number of sub-basins per location category

# of Sub-basins Upstream	0	$1-5$	$6-20$	$21-100$	101 - 750
# of Sub-basins	6	5	5	2	6

Discussion

When looking at the percentage of users and normal use curtailed, the curtailments administered by the Board in water year 2015 are similar to DWRAT's suggestions. However, when the specific curtailed users are examined, differences appear. The Board based curtailment decisions on the outlet flow of the Sacramento Basin, and in May, curtailed every water right in the basin with a priority date of 1914 or later. Figure 4-7 shows that a single curtailment date for the entire Sacramento Basin is a coarse resolution. DWRAT allocated 100% of demand to many appropriative users in May with a priority date later than 1914. Even some of the most junior users in the basin received their full demand from DWRAT. By incorporating spatial variability, DWRAT can recognize senior users in dry, upstream sub-basins and junior users in wetter, downstream sub-basins and allocate water accordingly.

DWRAT's decisions should not yet be entirely trusted on a single-user level. The hydrologic data used by DWRAT should be better calibrated and tested. Even then, some error is unavoidable. However, while DWRAT may not yet know which specific sub-basins are dry or wet, there are certainly dryer and wetter

sub-basins, and this analysis shows the importance of considering spatial variability when making curtailment decisions.

Return flows can have a small affect on overall curtailment for most months, but for several months, the impact is significant. For the right holder at the border of curtailment, the impact is always significant. May results are more impacted by return flows, where the percentage of normal appropriative use curtailed decreased by 3.6%. While a small percentage, it amounts to 2,569 acre-feet per day of applied demand and could have considerable economic value. The effect on modeled water availability from return flows will vary with the return flow factors assigned to different users or types of use. Including surface water return flows requires additional parameter estimation, however.

The historical year used to calculate flow scaling ratios for the DWRAT model significantly affects modeled water availability. Hydrology in a drought year will not always be similar to the 1976-77 drought. By basing flow ratios on a historical drought that best resembles a current drought, the water availability data input to the DWRAT model will improve and so will curtailment decisions. The historical drought year used could vary from region to region and month to month. Adding additional locations where present-day unimpaired flow is estimated will improve the ability to select a similar drought year. Even without adding unimpaired flow locations, using average flow scaling ratios from the driest years could counteract the error from choosing an historical drought with poor resemblance to a current drought. Error analysis can be based in part on the distribution of historical dry year scaling ratios.

Chapter 5 – Further Research and Conclusions

This thesis presents preliminary results and ideas for the DWRAT model of the Sacramento Valley. There are many ways to improve the accuracy in how DWRAT models both diversions and hydrology.

Further Research

For hydropower users, there are several ways DWRAT could better represent their diversions (and releases). Some water diverted by a hydropower right is actually left in stream and does not affect streamflows; this is called a direct diversion. Other times, a hydropower user diverts water to storage for later use, categorized as a diversion to storage. Currently, DWRAT removes direct diversions from a hydropower's demand because it is non-consumptive, but diversions to storage are considered fully consumptive. However, diversions to storage are still non-consumptive in a sense because the water is later released into the stream and becomes available to downstream users at a later time. The only consumption of water is through evaporation of water in the storage reservoir. So while fully consumptive during storage, water diverted to storage becomes available to downstream appropriative users at a later – and often dryer – time. Most single-purpose hydropower storage diversions are in upper watersheds, and do effectively shift water availability from the wet winter and spring to the summer when hydropower releases are greatest.

Ideally, data on the quantity and timing of diversions to storage and reservoir release data for hydropower users would be included in DWRAT. Diversions to storage could be modeled as fully consumptive at the time of diversion, but later added to the water supply according reservoir release schedules.

The question of who has legal access to reservoir releases is another complication with hydropower water rights. Riparian right holders are entitled to the natural flow of the river. Reservoirs alter the natural flow of a river, so some argue that riparians have no right to reservoir releases if it makes the river's flow greater than it naturally would be at that time of year. In this case, for DWRAT, reservoir releases would be added to water available for the appropriative right curtailment model, but not be included in the initial riparian curtailment model.

Furthermore, removing direct diversions from the demand of hydropower users can pose a problem. This is acceptable if streamflow always exceeds the direct diversion demand, but in a severe drought streamflow can drop below the direct diversion demand of some large hydropower users. When this happens, upstream users with lower priority than the hydropower user should be curtailed to avail water for the hydropower user to make direct diversions. Since DWRAT does not currently consider direct diversions as a demand, it will never make such a curtailment decision.

Curtailment decisions from DWRAT can be further improved with more frequently updated user demand data. Water right holders might divert water in a different month than in the past. Normally, this would not pose a problem, but in a drought it can significantly alter modeled demand from true demand for water and lead to suboptimal curtailment decisions. A direct remedy would be to require larger water right holders to "call" the use of their right in advance, so water right administrators can better set curtailments. This is common practice in western states that annually curtail water rights (Escriva-Bou, et al., 2016). The State Board took steps in this direction with the Information Order sent to senior right holders at the start of the 2015 (SWRCB, 2015a).

As stated earlier, the values of surface return flow factors applied to users will have a large impact on the effect of return flows on modeled water availability. Currently, a user's return flow factor is based on broad categories of beneficial use including irrigation, municipal, and mining. Much improvement can be made on this front. For example, rather than applying the same return flow factor to every irrigator, return factors could be based on variables like crop type, irrigation method, and topography. Irrigation return flow factors pose the greatest room for improvement (especially since irrigation accounts for the majority of water use in the Sacramento Basin), but factors for municipalities can be better specified too. Depending on a city's outdoor water use (mostly consumptive) and wastewater treatment methods, their surface return flow could vary considerably. Diversions for out-of-basin use, such as many CVP and SWP diversions, also are fully consumptive for the Sacramento Valley.

Another application for DWRAT is in water transfers. The California Water Code states water transfers are not allowed to "injure any legal user of the water" (California Water Code, § 1725), which includes both senior and junior users downstream. This requirement makes the approval process take several months or even years for long-term transfers. The effects of proposed transfers could be quickly analyzed by DWRAT to hasten the approval process.

Conclusions

This thesis shows it is possible to make a model to allocate water to individual right holders for multiple water right doctrines in a basin as large as the Sacramento. Also, return flows can be included in an allocation model of this size with simplicity by reducing users' applied demand to consumptive demand.

Surface return flows are part of the natural system and impact water availability. While the DWRAT model is (and always will be) imperfect in modeling the exact location and volume of surface returns, this analysis demonstrates their potential impact. Even with conservative surface return flow factors, modeled return flows reduced the percentage of normal use curtailed by 2-11% for most of water year 2015.

While modeling return flows by explicitly returning flows downstream adds a level of accuracy, reducing applied use to consumptive use is easier to implement and produces similar results when surface return flow factors are below 0.2. Considering return flow factors for most types of water use are below 0.2, using consumptive use diversions offers a valuable alternative.

The State Board's curtailment decisions are affirmed in both the number and volume of water rights curtailed, although DWRAT suggested some differences in the specific rights curtailed. Accounting for spatial variability is crucial when making curtailment decisions. The reliability of water for a user who diverts from a seasonal creek is not the same as a user diverting at the mouth of the Sacramento River, and they should be treated accordingly.

Due to the error analysis and calibration needed for hydrologic and diversion data, several years should be spent refining the Sacramento DWRAT model before its full utilization in curtailment decisions. But in the interim, it could be a useful advisory tool and framework for combining estimates of water availability and user demands for estimation of water right curtailments.

Acknowledgments

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