Uncertainty in Water Rights Analysis: Overpromising vs. Over Curtailing

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Abstract

California water rights administrators allocate water following California's hybrid system consisting of riparian and appropriative water rights. In droughts water is curtailed to users based on water right type, right seniority and water availability. Error is unavoidable in water availability and water use estimates, leading to over promising or over curtailing individual water right users in retrospect. Buffer flows help balance these two errors in modeling to balance the expected number of curtailments, likelihood of false curtailments, and likelihood of false promises for a specific date and location. The number of expected curtailments and false promises increases with positive buffer flows, and decreases with negative buffer flows increasing false curtailments.

Introduction

Water rights analysis for droughts has unavoidable errors in hydrologic balances and water demands. Curtailment decisions must be made using imperfect forecasted available in flows and user diversion quantities. Actual flow availability and diversions can differ significantly from forecast hydrologic availability and use so there is always likelihood of over-promising and over curtailing use during droughts. The balance of a system to over-promise versus over-curtail water can be changed by adding or subtracting buffer flows in the water accounting system. Buffer flows become positive or negative safety factors for forecasted flows to water right-holders (Lord et al, 2017). Positive buffer flows artificially decrease the amount of water available for diversion, decreasing the likelihood higher seniority water rights will be deprived of water, but increasing the likelihood junior water rights will be curtailed. Policy considerations of water rights administrators determine proper buffer flow volumes. Even if buffer flows are not used, they illustrate the effects and management of uncertainty in water right curtailment analysis.

DWRAT's optimizations mathematically represent the logic of riparian and appropriative water law doctrines using two linear programs. First model run is for more senior riparian right holders and the second model run for appropriative right holders. The San Joaquin River basin in California's Central Valley is used as an example application.

This paper examines the effects of varying buffer flows for the San Joaquin River basin drought curtailments using the Drought Water Rights Allocation Tool (DWRAT). DWRAT mathematically determines water availability for individual users under drought conditions. It uses locations, water right seniorities, water availability, water use quantities and two linear programs to estimate legal curtailment requirements for all water right holders throughout a network of sub-basins.

California Water Law & Drought Curtailment

Water Rights

California has a mixed water rights system including riparian and appropriative water rights doctrines. Riparian rights are the most senior, highest priority rights, adapted from English common law. "Right-holders are entitled to the full natural flow of the water body, so long as downstream users are not "unreasonably affected" and the diverted water is used and not stored on the adjacent land parcel" (Lord, 2015). Unavoidable shortages are shared proportionally among all hydrologically connected riparian right holders.

Appropriative rights are almost always junior to riparian rights, and are ranked by seniority. The "first in time, first in right" rule represents a strict priority based on the application date of the water right. Appropriative rights are not tied to adjacent lands, and can change usage place, diversion point, or use purpose as long as it does not affect other water right holders subject to permit conditions. Appropriative right holders can lose their right if their water does not have a beneficial use (Attwater, et al, 1988). There are two classifications of these rights, pre-1914 rights, and post-1914 rights. Pre-1914 water rights have the highest appropriative rankings, were perfected before California passed the California Water Agency Act in 1913, and do not require a state permit. The Act created a state water rights agency to manage, distribute, and determine water right statutory procedures going forward. Post-1914 water rights are the only new water rights available today in California and require state water right permits. The State Water Resources Control Board (SWRCB) handles new water rights, water curtailments, and water rights legal disagreements.

Drought Curtailments

California's limited water supply, Mediterranean climate, and drought frequency increase chances and needs for water right curtailments. During California's most recent drought the SWRCB issued curtailments for the first time since 1977 (Lord, 2015).

State Water Resources Control Board curtailments for the San Joaquin River during the 2012-2016 drought were:

- May 27th and May 29th 2014 - junior water right holders in the Sacramento River and San Joaquin River watersheds
- April 23rd 2015- curtailment notices to junior water right holders in the San Joaquin River watershed
- April 30th 2015 - holders of 88 water rights in the Sacramento-San Joaquin Delta watershed
- June 12th, 2015 - curtailment notices to pre-1914 appropriative claims with priorities commencing in 1903 or later in the Sacramento-San Joaquin River & Delta watersheds

Drought Water Rights Allocation Tool (DWRAT)

DWRAT is a mathematical representation of user curtailments following California water law. The model first allocates to riparian users, who have the most senior water rights, and equally share shortages. The remaining water is allocated among appropriative right holders by seniority. "DWRAT has a spatially disaggregated approach to calculating water availability and shortages. This approach allows the model to account for local water availability by considering supply and demand at the HUC-12 scale" (Walker, 2017). The model accounts for spatial and hydrologic variation within the basin and individual sub-basins.

The model divides the San Joaquin River basin into 443 sub-basins and catchments using a hydrologic model developed from 12-degree Hydrologic Unit Code (HUC-12s) are identified by the U.S. Geologic Survey (USGS) (Walker, 2017). Current and historical gage data for the six valley rim locations are found from the California Data Exchange Center (CDEC). Gage data for Vernalis is from the California Nevada River Forecast Center. Vernalis is the most downstream gage in the basin, at the entrance to the Delta. Individual water right priorities and use volumes were acquired from the SWRCB.

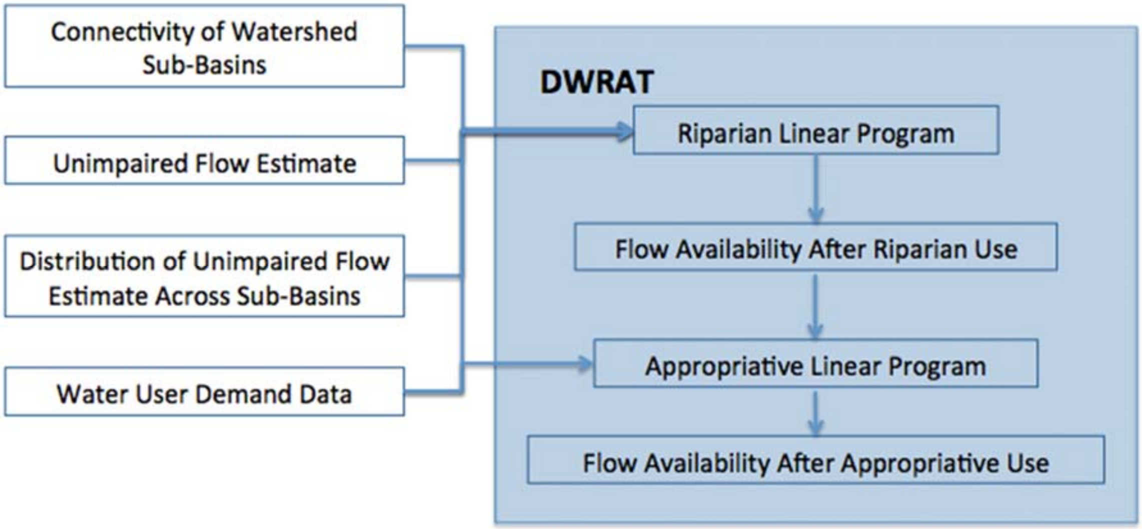

Figure 1. DWRAT model flowchart (Tweet, 2016)

DWRAT represents basin and sub-basin mass balances. Total water allocations A_i to users *i* cannot exceed the difference in sub-basin flow v_k, environmental flow requirement e_k, and buffer flow b_k for each sub-basin k.

Riparian mass balance:

$$\sum_{i\in k} A_i \leq v_k - e_k - b_k, \forall k \quad (1)$$

The mass balance of appropriative rights is represented by the same equation as riparian, but includes upstream riparian users.

Appropriative mass balance:

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

DWRAT Assumptions, Limitations and Errors

Researchers at UC Davis have developed DWRAT models for four California basins: the Eel River, Russian River, Sacramento River, and San Joaquin River (Lord, 2015; Whittington, 2016; Tweet, 2016; Walker, 2017, Lord et. al, 2017). These reports and papers provide DWRAT assumptions, limitations, and errors that are summarized below.

Major sources of error come from hydrologic, allocation, diversion quantity, and routing assumptions. (Tweet, 2016). DWRAT assumes all users within each sub-basin have physical access to the local water available. In reality, local sub-basin configurations restrict inflow to upstream users and can cause hydrologic errors (Lord et al, 2017). DWRAT considers surface water but ignores groundwater and surface water interactions. In droughts, groundwater is depleted, decreasing total water availability, perhaps leading to under-curtailments (Lord et al, 2017). Water rights allocation is determined assuming previous historic reported usage, which could significantly change in drought conditions. Assuming historical usage can cause allocation errors (Walker, 2017). DWRAT does not include reservoir releases as inflow, which can increase the volume of water available to appropriative right-holders, especially with non-consumptive hydropower releases. DWRAT models usually assume all water rights are consumptive, ignoring return flows and decreasing water availability, although various representations can be made (Tweet, 2016).

San Joaquin Basin and DWRAT Application

San Joaquin Basin

The San Joaquin River runs northwest and receives flows from the Merced River, Tuolumne River, Stanislaus River, Mokelumne River, and Cosumnes River tributaries. The basin is approximately 15,800 square miles, and mostly used for farming and agriculture production. Nut tree farms, almond orchards, various fruits, and many other crops dominate the basin. The east San Joaquin basin has more plum orchards, field crops and pasture (USGS, 2017).

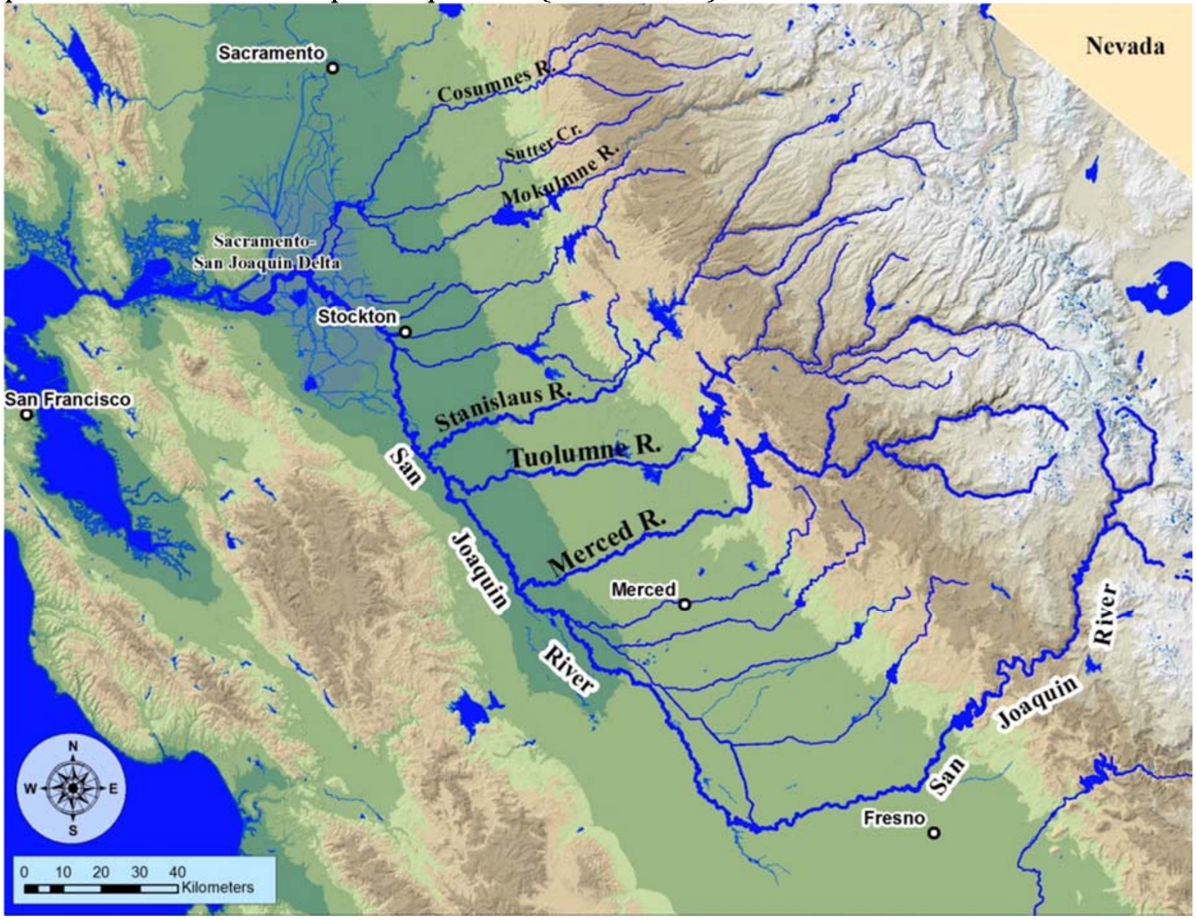

Figure 2. San Joaquin River Basin (Longfellow, 2014)

There are 2823 registered water right holders in the San Joaquin River Basin. At its peak, the basin's daily water right demand is roughly 35,000 ac-ft. The chart and graph below summarize users in the basin and their monthly use.

Table 1.Numbers of San Joaquin water rights (Walker, 2017)

Water Right Type	Total	Total (%)	Active	Active (%)	Total Active (%)
Riparian	1001	35.5	101	10.1	10.5
Pre-1914 Appropriative	137	4.9	90	65.7	9.4
Post-1914 Appropriative	1685	59.7	770	45.7	80.1
Total Appropriative	1822	64.5	860	47.2	89.5
Users Total	2823	100.0	961	34.0	100.0

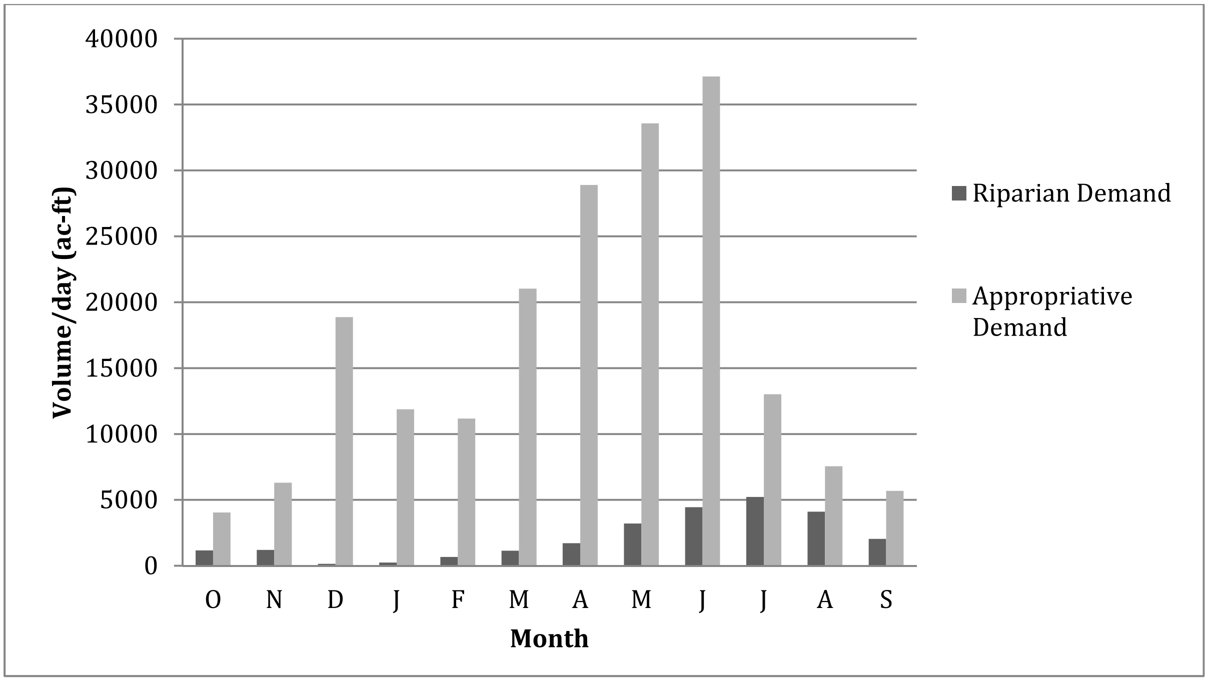

Figure 3. San Joaquin monthly total water use volume in a water year (Walker, 2017)

San Joaquin DWRAT

This paper uses the San Joaquin DWRAT model to examine insights from the analysis of buffer flows, false promises, and false curtailments in water right curtailment analysis. The San Joaquin DWRAT model is described and analyzed in "Drought Water Right Allocation Tool Applied to the San Joaquin River Basin" (Walker, 2017). Walker compares DWRAT curtailments to SWRCB curtailments for 2014, 2015, and 2015 with return flows. "DWRAT's design and methods allow for a more detailed accounting of the spatial variability in demand and supply within the basin. Compared to the Board's actions, DWRAT's approach allows some junior users in downstream locations with greater water availability to receive their allocation, while some senior users in basins with limited availability are shorted". Inclusion of return flows in the San Joaquin reduced some of DWRATs over-curtailment compared to SWRCB actions. The number of riparian users curtailed did not change with return flow, and the number of appropriative users decreased. The total volume shorted decreased.

Walker also did a forecast flow analysis comparing DWRAT curtailments with SWRCB curtailments using unimpaired forecast flows from CNRFC to emphasize inherent challenges in water availability forecasts. The report recommends buffer flows as a potential way to help improve water right curtailment forecast decisions (Walker, 2017).

False Promises and False Curtailments

False Curtailments

Positive buffer values artificially lessen the amount of water available for diversions, increasing the volume of curtailments and decreasing the likelihood of over-promising water where water promised to users in the analysis is actually unavailable. E(FC) is the expected volume of false curtailments where a water right is curtailed, but in actuality there was enough water for that right. In the equations below Q_{act} is all possible actual outflows, Q_{for} is a forecast outlet flow, and B is the buffer flow.

$$E(FC) = \int_0^{\infty} P(Q_{act}) FC(Q_{for,} Q_{act,} B) dQ_{act} \qquad (3)$$

where:

$$FC(Q_{for,} Q_{act,} B) = Maximum \begin{cases} C(Q_{for} - B) - C(Q_{act}) \\ 0 \end{cases} \qquad (4)$$

False curtailments, equation 4, are the difference between the predicted curtailments including buffer flow, and the ideal curtailments with the actual outlet flow in hindsight (Lord, 2015).

False Promises

Negative buffer values artificially increase the accounted amount of water available for diversion, decreasing the amount of curtailment but increasing the likelihood of over-promising water that is not there physically. E(FP) is expected false promises, Q_{act} is all possible actual outflows, Q_{for} is a forecast outlet flow, and B is the buffer flow.

$$E(FP) = \int_0^{\infty} P(Q_{act}) FP(Q_{for,} Q_{act,} B) dQ_{act} \qquad (5)$$

where:

$$FP(Q_{for,} Q_{act,} B) = Maximum \begin{cases} C(Q_{act}) - C(Q_{for} - B) \\ 0 \end{cases} \qquad (6)$$

False promises, equation 6, are the difference between the predicted curtailments of the actual flow and the predicted curtailments of the forecast flow including buffer flow, and the ideal curtailments with the actual outlet flow (Lord, 2015).

Buffer Flows

"Water rights curtailments for drought in California: Method and Eel River Application" (Lord, 2015) was the first DWRAT model made. This report introduces the idea of buffer flows, false promises, and false curtailments. Water use estimates and availability are not perfect. "Buffer flow, represented in the mass balances, can account for some error by modifying availability" (Lord, 2015). Uncertainty is inherent in water availability, leading to false promises and false curtailments of users. Buffer flow values modify the mass balance of water availabilities and can be used to adjust the balance of false promises and false curtailments. Buffer flows artificially increase or decrease the water availability within the basin. Varying buffer flows to represent uncertainty gives a range of curtailments for a specific date (Lord et al, 2017). "This capability allows much greater flexibility in predicting and accounting for uncertainty in DWRAT inputs" (Lord, 2015). How different buffer values impact water curtailment is very important for all users and monitoring and regulating institutions.

Usage and size of buffer flow will vary by policy administrator and their water right needs. Basin administrators must recognize the relative values of false promises versus false curtailments. In some cases false promises are more detrimental to users because they make planning decisions assuming they will have water they will not receive."In this situation a buffer flow that would decrease the probability of false promises would be optimal, but at the cost of increasing false curtailments" (Lord, 2015).

Lord recognizes the errors in water right reliability, and recommends implicit stochastic optimization to find curtailment thresholds and Monte Carlo analysis to create the probability of curtailment. Curtailment thresholds are an easy way to understand water curtailment and implementation: when inflows are below a certain volume, they cannot divert water. Understanding the probability of curtailment would help users better plan water diversions (Lord, 2015).

The San Joaquin Basin has 443 HUCs. DWRAT assumes all users within a HUC have access to flow at each HUC outlet. To simplify the process, one reference gage at Vernalis (VNSCO) is used for the entire basin and all HUCs. Unimpaired flow estimates for Vernalis are the sum of flow estimates for the Merced, Stanislaus, Tuolumne and Upper San Joaquin Rivers (Walker, 2017). HUC scaling factors reflect the modified flow point. This simplification is the greatest source of error within DWRAT water balances, and is discussed in a later section. In analyses here, the HUC-12 scaling factors are fixed, with all uncertainty assumed to be in basin outflow forecasts. In reality, these HUC-12 scaling factors have considerable uncertainty (Whittington, 2015).

San Joaquin False Promises and False Curtailments

This analysis compares individual user curtailments for an actual flow Q_a, a forecast flow Q_f, and various buffer flows, to calculate false promises and false curtailments. The forecast flow is the predicted flow, and the actual flow is the true flow that occurred in the basin. For illustration a forecast flow of 14,000 ac-ft/day was picked, the historical average daily unimpaired flow for Vernalis in July. Two actual unimpaired flows were used: 10,000 ac-ft/day and 18,000 ac-ft/day. Buffer flows ranging from -40% to 40% were examined. A false promise occurs when an individual user is not curtailed with the forecast flow, but should be curtailed with the actual flow. A false curtailment occurs when an individual user is curtailed with the forecast flow, but would not be curtailed with the actual flow.

Forecast Flow Exceeds Actual Flow

The more forecast flow exceeds the actual flow, the more false promises occur. To DWRAT, more water is available in the system, so users are over promised water that is not there. In this trial Q_a is 10,000 ac-ft/day and Q_f is 14,000 ac-ft/day. *Table 2* shows total false promises decrease as buffer flows increase. Negative buffer flows artificially increase the amount of water available causing more actual false promises. As buffer flows increase, less water is available so fewer false promises occur. False curtailment begins at 40% buffer flows as Q_a exceeds Q_f.

Table 2. Total false promises, false curtailments, and correct curtailments when $Q_f>Q_a$, San Joaquin basin, July Q_f = 14,000 af/d, Q_a = 10,000 af/d

Buffer	Total FC:	Total FP:	Correct Curtailments
-40%	0	102	2721
-30%	0	98	2725
-20%	0	97	2726
-10%	0	97	2726
0%	0	97	2726
10%	0	27	2796
20%	0	23	2800
30%	0	0	2823
40%	8	0	2815

Actual Flow Exceeds Forecast Flow

When actual flow exceeds the forecast flow, more false curtailments occur. Less water is available in the system, so DWRAT curtails more users. In this trial Q_a is 18,000 ac-ft/day and Q_f is 14,000 ac-ft/day. Table 9 shows with greater buffer flows, total false promises decrease, and false curtailments increase. When buffer flows increase, less water is available, causing less false promises but more false curtailments. More water is available than forecast, allowing fewer users receive water shortages. Between -20% and 0% buffer flows, there are no identified false promises or false curtailments. Within this range there is enough water in the system for the same users to be curtailed with Q_f and Q_a; however, the volume of water curtailed for each user with Q_f and Q_a can vary.

Table 3. Total false promises, curtailments and correct curtailments when $Q_a > Q_f$ assuming San Joaquin basin in July where Q_f = 14,000 af/d, Q_a = 10,000 af/d

Buffer	Total FC:	Total FP:	Correct Curtailments
-40%	0	5	2818
-30%	0	1	2822
-20%	0	0	2823
-10%	0	0	2823
0%	0	0	2823
10%	70	0	2753
20%	74	0	2749
30%	97	0	2726
40%	105	0	2718

*Figure **4*** shows false promises and false curtailments of both scenarios with varied buffer flows. When actual flow is smaller than forecast flow, there are more false promises. Negative buffer flows magnify this result because they artificially increase water availability. When actual flow exceeds forecast flow, there are more false curtailments. Positive buffer flows magnify this result because they artificially decrease water availability.

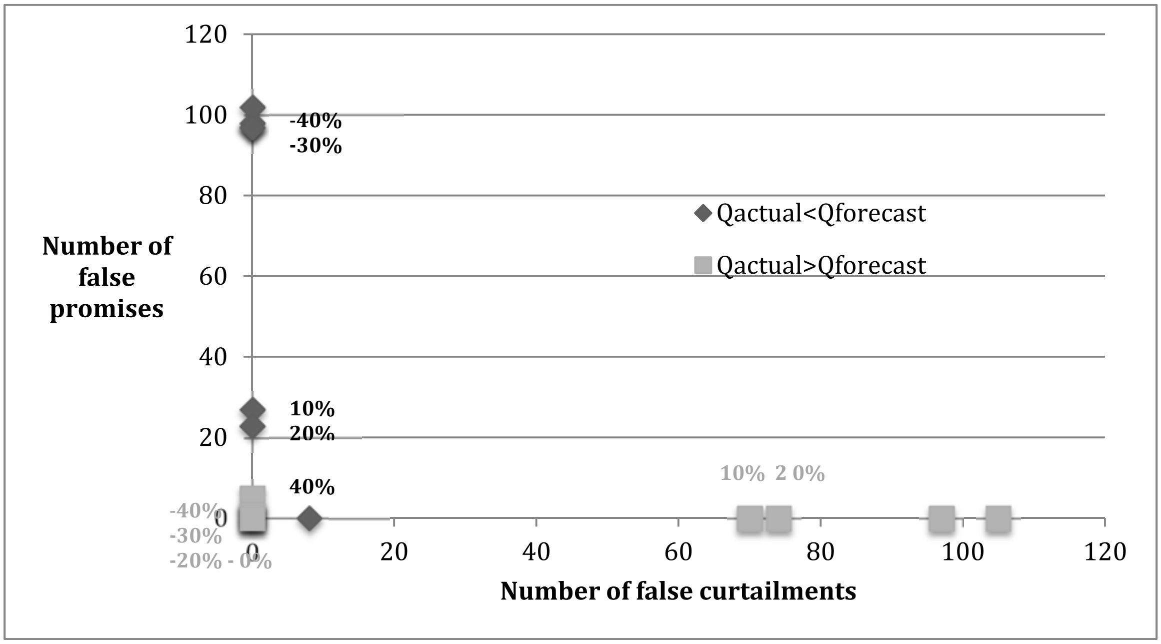

Figure 4. False Promises and False Curtailments with varied buffer flows comparing Q_a and Q_f assuming San Joaquin basin in July where Q_f = 14,000 af/d, Q_a = 10,000 af/d

Deterministic Analysis of Buffer Flows

This analysis compares individual user curtailments for various buffer flows. The three flow volumes chosen are the 1%, 10%, and 20% July flows. They were chosen to represent severe and moderate drought conditions, and are shown in *Table **4***.

Table 4. Deterministic analysis of flow volumes for July historical unimpaired flows

Flow Percent (%)	1	10	20
Flow Volume (ac-ft/day)	1700	3900	5500

DWRAT was run for nine buffer flows: -40%, -30%, -20%, -10%, 0%, 10%, 20%, 30% 40%. Positive buffer flows decrease water availability and increase curtailments. Larger positive buffer flows create a safety factor for senior right holders, but additional curtailments for more junior right holders (Lord et al., 2017).

Total Expected Curtailments

Negative buffer flows artificially increase water availability, therefore decreasing the likelihood of curtailment. Positive buffer flows decrease water availability, and so increase curtailments. These trends are mirrored in for flow volumes 3900 (ac-ft/day) and 5500 (ac-ft/day). Expected curtailments increase along the table as the buffer flow value increases, and decrease down the table as inflow volume increases. Overall there are many less riparian expected curtailments than appropriative curtailments, because of their highest priority. Stagnant expected curtailments with increasing buffer flows are common for riparian users. As riparian users are curtailed, the number of curtailed users tends to change slowly, but the amount of water shorted from them increases with drier conditions.

Table 5 shows the expected riparian and appropriative curtailments for *Table **4*** flows. An anomaly is seen at 1700 (ac-ft/day) flow volume for riparian users when buffer flows are -30% and 10%. At those buffer flows riparian expected curtailments are 0. There is so little water in the basin that DWRAT cannot find a feasible result. These inaccuracies can be seen in all graphs and tables using 1,700 ac-ft/day results.

Table 5. Deterministic riparian and appropriative total expected curtailments for varied buffer flows, assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

	Riparian Expected Curtailments			Appropriative Expected Curtailments		
Buffer Flow (%)	1700 ac-ft/day	3900 ac-ft/day	5500 ac-ft/day	1700 ac-ft/day	3900 ac-ft/day	5500 ac-ft/day
-40	120	43	4	309	187	141
-30	0	43	4	376	193	151
-20	134	43	41	329	254	176
-10	140	43	43	337	264	180
0	140	43	43	347	277	187
10	0	43	43	376	281	194
20	140	43	43	350	288	264
30	150	114	43	360	300	279
40	297	120	43	375	309	285

Figures 5 and 6 show the expected total curtailments for riparian and appropriative users for different buffer flows. Expected curtailments increase as the buffer flows increase. Appropriative rights are most affected by buffer flows because they have lower priority. Curtailment jumps indicate large increases or decreases in expected curtailments between two buffer flows. Curtailment jumps are circled in black. Water basin managers can use knowledge of curtailment jumps to avoid buffer flows where the number of users curtailed dramatically increases. Conversely, buffer jumps can be used to increase curtailment volumes without increasing the number of users affected.

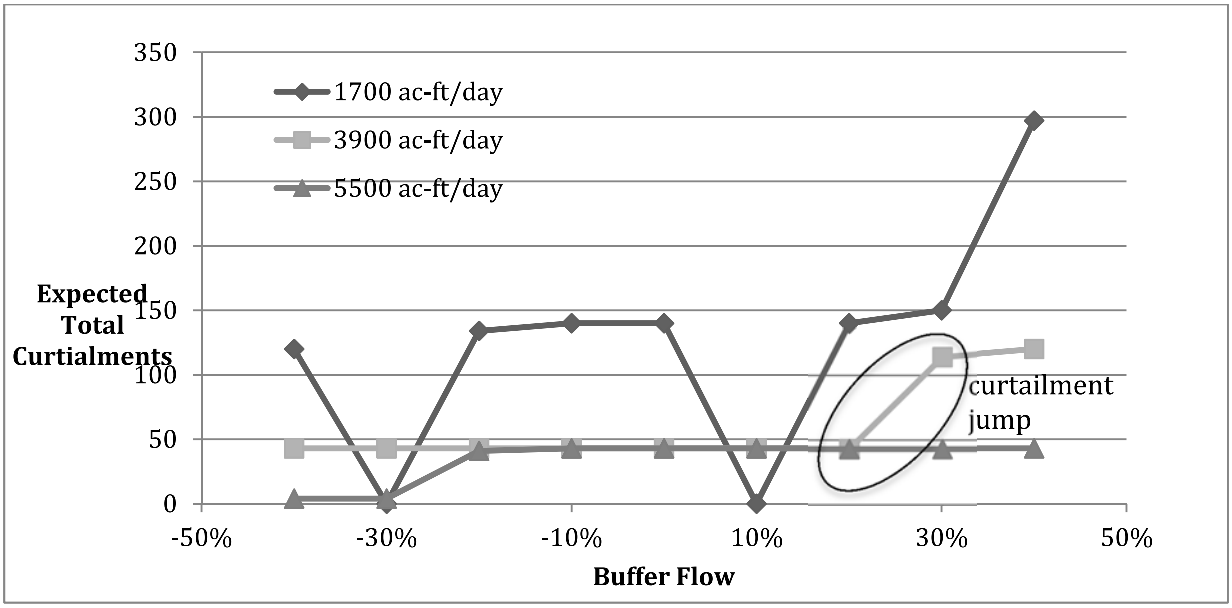

Figure 5. Deterministic riparian expected total curtailments with varied buffer flows assuming Q_a *= 10,500 ac-ft/day and* Q_f *= 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July*

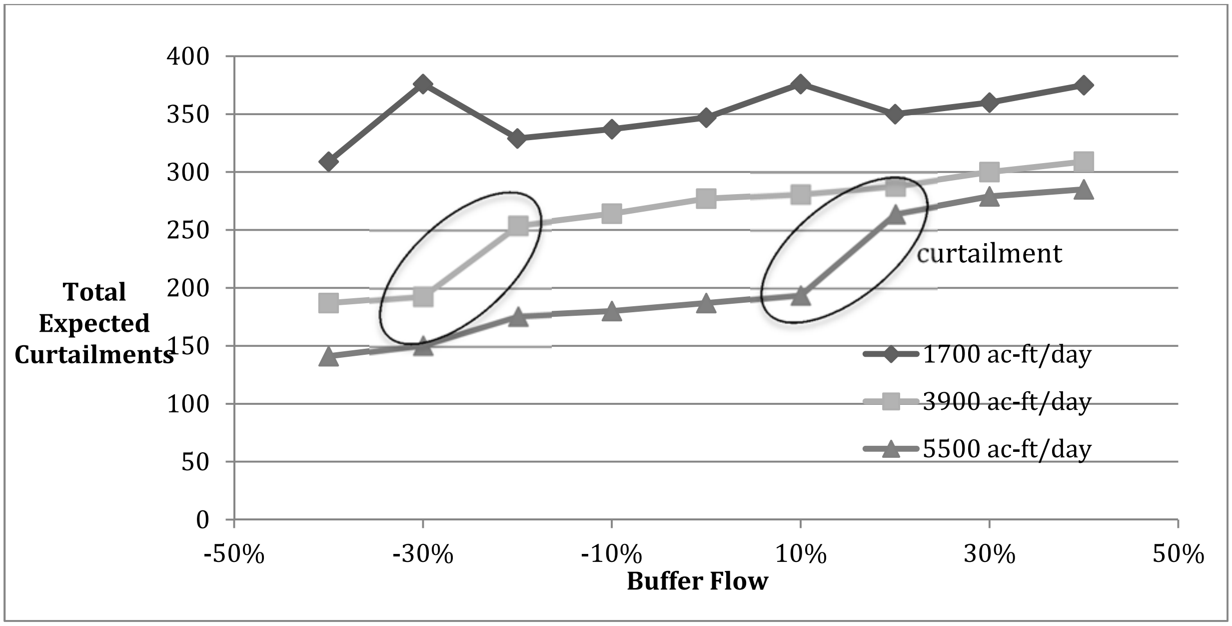

Figure 6. Deterministic appropriative total expected curtailments with varied buffer flows assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

Expected False Promises and Curtailments

False promises and false curtailments arise from discrepancies between forecasted water availability and actual/true water availability. Buffer flows artificially increase and decrease inflows, and increase or decrease differences between forecasted inflows and actual inflows. When the forecast flow is smaller than the actual flow, the expected number of false curtailments increases. To DWRAT, less water is available in the system so more users are curtailed. In this trial Q_a is 10,500 ac-ft/day and Qf is 1,700 ac-ft/day, 3,900 ac-ft/day and 5,550 ac-ft/day respectively. Table 6 and 7 show the expected false promises and curtailments from each flow volume. Because all Q_f values are significantly smaller than the Q_a, and this is a deterministic example, only expected false curtailments occur. Flow volume of 1,700 ac-ft/day has the most false curtailments for riparian and appropriative users. It provides the smallest inflow and the largest number of curtailments. The same odd behavior seen for total expected curtailments for -30% and 10% buffer flow reoccurs for expected false promises and curtailments.

Table 6. Deterministic riparian false promises and curtailments with varied buffer flows, assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

	Q_f = 1700 ac-ft/day		Q_f = 3900 ac-ft/day		Q_f = 5500 ac-ft/day	
Buffer Flow	FP	FC	FP	FC	FP	FC
-40%	0	116	0	39	0	0
-30%	4	0	0	39	0	0
-20%	0	130	0	39	0	37
-10%	0	136	0	39	0	39
0%	0	136	0	39	0	39
10%	4	0	0	39	0	39
20%	0	136	0	39	0	39
30%	0	146	0	110	0	39
40%	0	293	0	116	0	39

Table 7. Deterministic appropriative false promises and curtailments with varied buffer flows, assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

	1700 ac-ft/day		3900 ac-ft/day		5500 ac-ft/day	
Buffer Flow	FP	FC	FP	FC	FP	FC
-40%	0	199	0	77	0	31
-30%	0	266	0	83	0	41
-20%	0	219	0	144	0	66
-10%	0	227	0	154	0	70
0%	0	237	0	167	0	77
10%	0	237	0	171	0	84
20%	0	266	0	178	0	154
30%	0	240	0	190	0	169
40%	0	265	0	199	0	175

Figures 7 and 8 show expected false curtailments of appropriative and riparian users with varied buffer flows. These graphs are almost identical to the total expected curtailment graphs. When only false curtailments occur, total curtailments equal false curtailments. -30% and 10% buffer flows have the same error seen in total curtailment, where DWRAT provides infeasible results showing zero expected false curtailments.

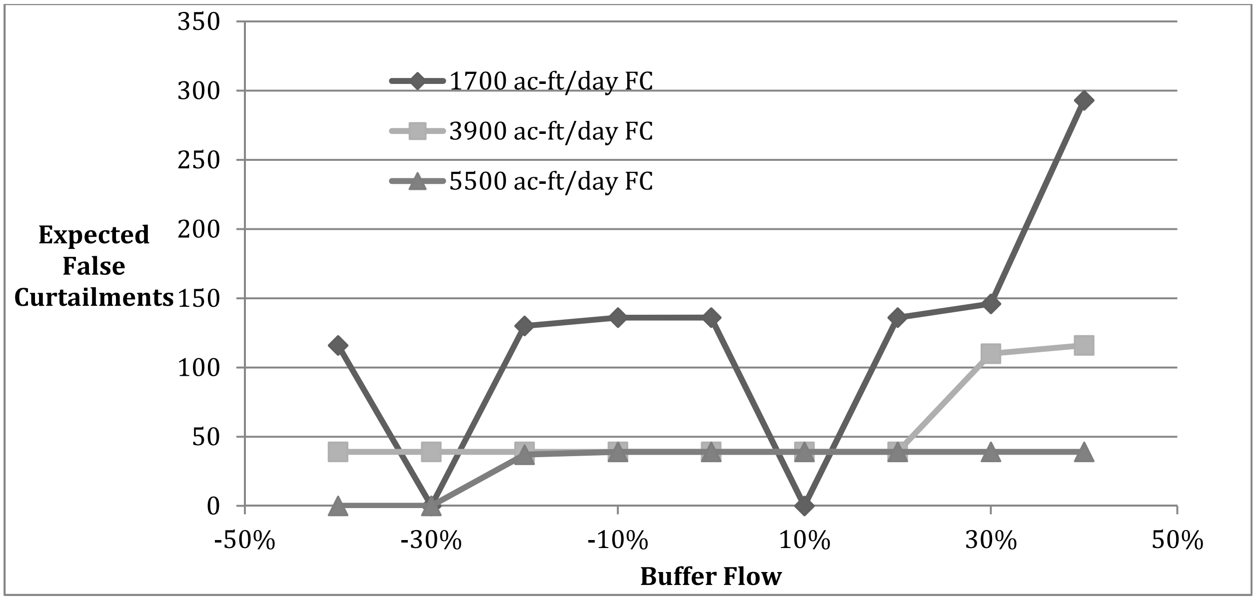

Figure 7. Deterministic riparian expected false curtailments with varied buffer flows assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

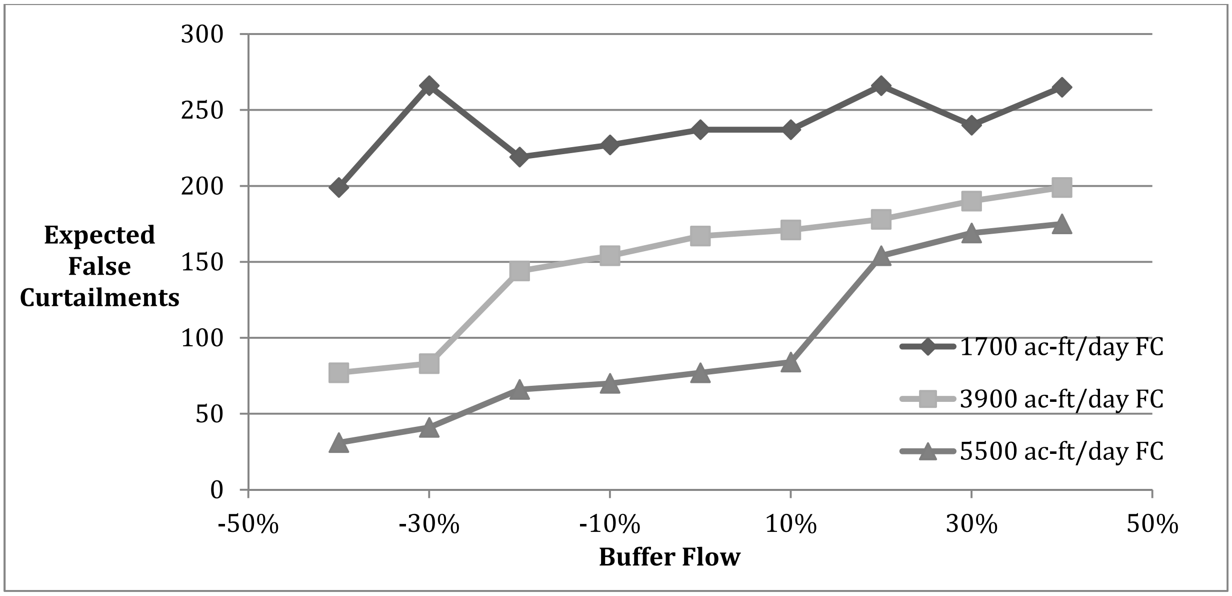

Figure 8. Deterministic appropriative expected false curtailments with varied buffer flows assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

Volumes Shorted for Various Buffer Flows

Table 8 and figures 9 and 10 show the volume of water shorted for each buffer flow for riparian and appropriative rights. All volumes are in acre-feet per day. The total volume of riparian water allocated in 5,230 ac-ft/day. The total volume of appropriative water allocated is 13,010 ac-ft/day.

Table 8. Deterministic riparian and appropriative volumes shorted for various buffer flows assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

	Riparian User Volume Shorted			Appropriative User Volume Shorted		
Buffer Flows (%)	1700 ac-ft/day	3900 ac-ft/day	5500 ac-ft/day	1700 ac-ft/day	3900 ac-ft/day	5500 ac-ft/day
-40	2880	1310	630	12200	10030	8460
-30	0	1500	660	13010	10230	8980
-20	3120	1680	750	12400	10490	9440
-10	3240	1870	1020	12500	10800	9730
0	3370	2060	1290	12610	11100	10010
10	0	2250	1550	13010	11400	10300
20	3610	2440	1820	12820	11700	10710
30	3730	2640	2090	12920	12000	11130
40	3870	2910	2350	13010	12230	11560

Figure 8 and 9 show the volume of water curtailed for a range of buffer flows. Large shortages occur for all three flow volumes for riparian and appropriative users. These volumes represent low flows in times of drought when there is very little inflow. Appropriative users have larger shortage volumes. They are junior to riparian users, and have larger diversion allocations because they can store and transport water.

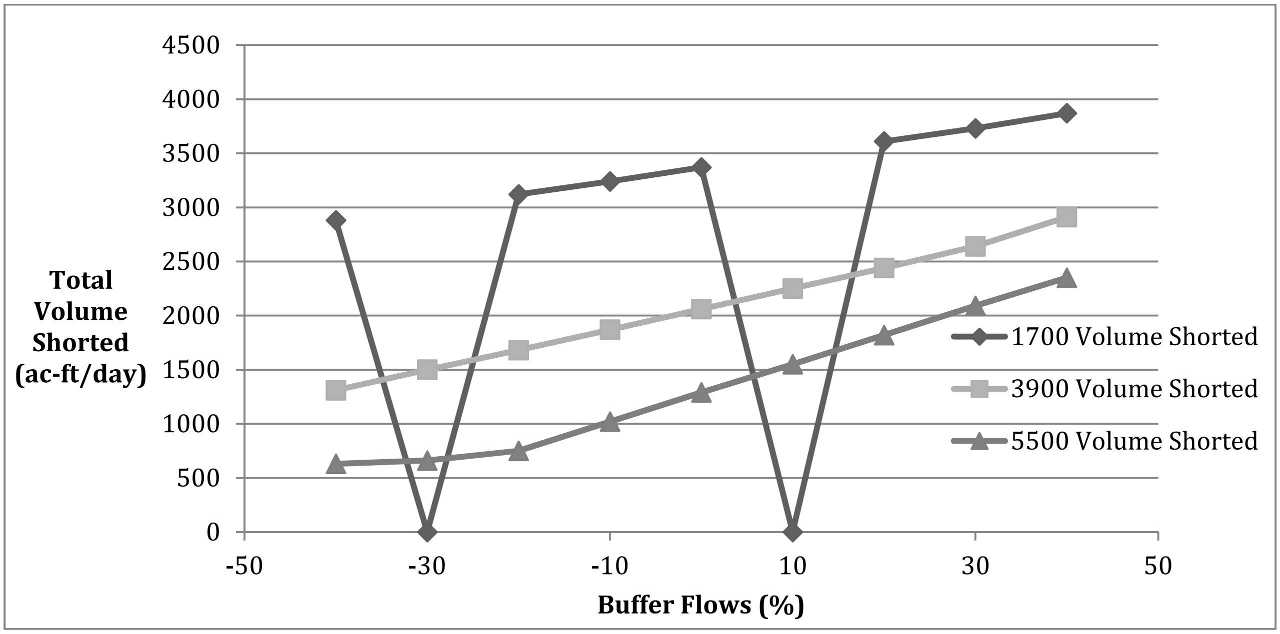

Figure 9. Deterministic total volume shorted for riparian users for various buffer flows, assuming Q_a = 10,500 ac-ft/day and Q_f = 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July

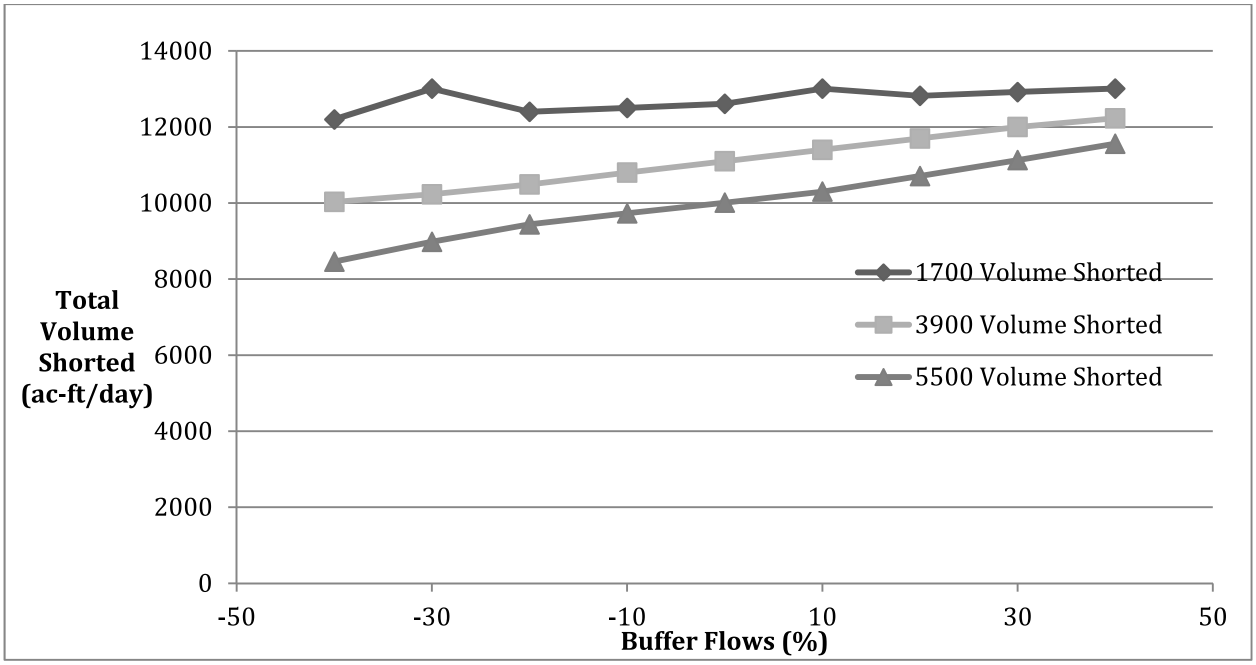

Figure 10. Deterministic total volume shorted for appropriative users for various buffer flows, assuming Q_a *= 10,500 ac-ft/day and* Q_f *= 1700, 3900, and 5500 ac-ft/day respectively, in the San Joaquin basin in July*

Probabilistic Analysis of Buffer Flows

Buffer Flows with a Probability Distribution of Outflows

This analysis compares individual user curtailments using a probability distribution of total unimpaired basin outflow centered on July mean flow with the historical variance and various buffer flows to determine expected curtailments, false promises, and false curtailments. Q_f is 10,500 ac-ft/day, the 50% flow occurrence probability, and Q_a is the entire flow probability distribution. It uses averaged July water availability from 103 historical monthly-unimpaired flows on record. The monthly data was aggregated from daily time steps. The data fit a lognormal distribution best (Walker, 2017). A lognormal distribution of possible actual unimpaired Vernalis gage flows were created.

Table 9. July historical mean flow statistics from Vernalis gage in ac-ft/day

Mean	14400
Standard deviation	13200
Mean ln(x)	9.27
Standard deviation ln(x)	0.78

The graph below shows the lognormal probability distribution (PDF) and cumulative distribution (CDF) of the July daily flows. Using these functions and the probability distributions, DWRAT was run for nine buffer flows: -40%, -30%, -20%, -10%, 0%, 10%, 20%, 30% 40%.

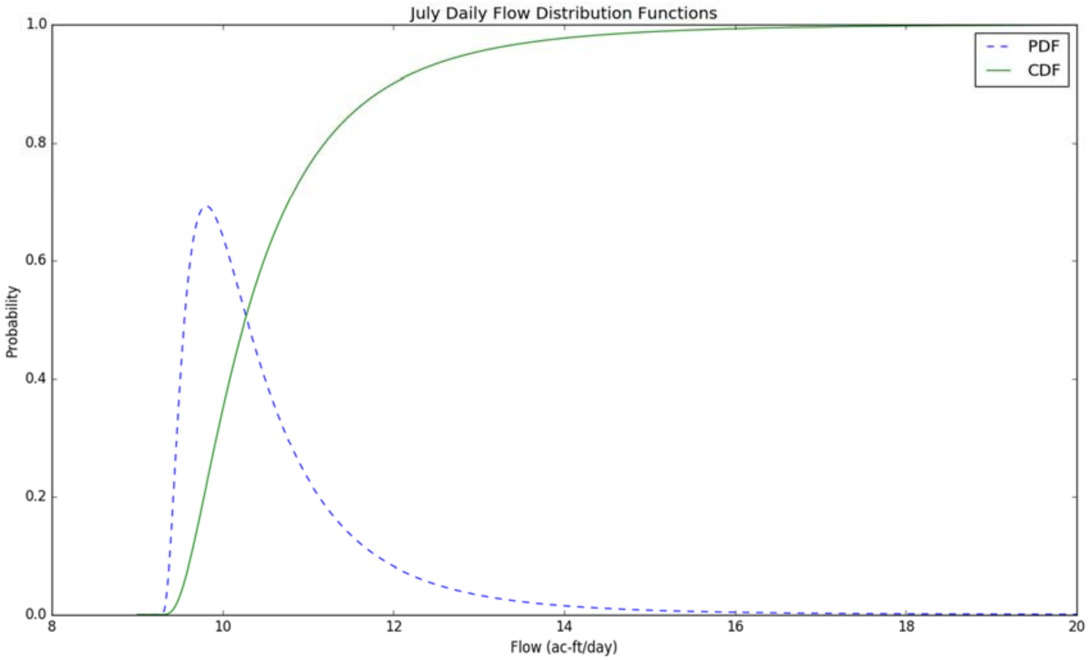

Figure 11. July historical unimpaired flow probability and cumulative distribution functions in TAF/day assuming San Joaquin basin in July

Eleven flow volumes were chosen with occurrence probabilities of 0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.99. These cover a wide range of flows and bin every 10%. The mean, standard deviation, and flow occurrence probabilities can be seen in Tables 9 and 10.

Table 10. Historical unimpaired outflow probability volumes for July at Vernalis in San Joaquin basin

Exceedance Probability	Flow Volumes (ac-ft/day)
0.01	1700
0.1	3900
0.2	5500
0.3	7000
0.4	8700
0.5	10600
0.6	12900
0.7	15900
0.8	20400
0.9	28800
0.99	65300

Expected curtailments for each buffer flow were found mathematically using Equation 7. Each buffer flow curtailment is multiplied by the probability of curtailment and summed over the entire distribution.

Table 11, Table 12, Figure 4, and Figure 12 show the riparian and appropriative buffer flow curtailments for each exceedance probability.

<u>Total Curtailments with a Basin Outflow Probability Distribution</u>

Expected number of curtailments for each buffer flow is the sum of each curtailment C_B, multiplied by its probability of curtailment $P(Q_{act})$.

$$\sum P(Q_{act})(C_B) = E(C) \qquad (7)$$

The below tables and figures show curtailments for buffer flows ranging from -40% to 40%.

Table 11 shows the expected number of riparian curtailments for a range of buffer flows and flow volumes, represented by exceedance probability. As the buffer flow increases, the number of curtailments increases. As exceedance probability increases, the number of curtailments decreases. This is most pronounced for the positive range of buffer flows (10%, 20%, 30%, 40%), and smallest exceedance probabilities (1%, 10%, 20%). The maximum number of curtailments is 297 when 40% buffer flow and 1% exceedance probability.

Table 11. Probabilistic riparian expected total curtailments with varied buffer flows assuming San Joaquin basin in July

	Exceedance Probability (%)										
Buffer Flows (%)	1	10	20	30	40	50	60	70	80	90	99
-40	120	43	4	4	4	4	4	0	0	0	0
-30	0	43	4	4	4	4	4	0	0	0	0
-20	134	43	41	4	4	4	4	0	0	0	0
-10	140	43	43	4	4	4	4	4	0	0	0
0	140	43	43	4	4	4	4	4	0	0	0
10	0	43	43	43	4	4	4	4	0	0	0
20	140	43	43	43	4	4	4	4	4	0	0
30	150	114	43	43	43	4	4	4	4	0	0
40	297	120	43	43	43	43	4	4	4	4	0

Table 12 shows the expected number of appropriative curtailments for a range of buffer flows and flow volumes, represented by exceedance probability. The maximum number of curtailments is 375, when buffer flow is 40% and exceedance probability is 1%. The number of curtailments is significantly higher for appropriative users than riparian users. This occurs because there are 821 more appropriative users than riparian users, and appropriative rights are generally much larger. Riparian water can only be used on land adjacent to the river, appropriative water does not have this restriction.

Table 12. Probabilistic appropriative expected total curtailments with varied buffer flows assuming San Joaquin basin in July

	Exceedance Probability (%)										
Buffer Flows (%)	1	10	20	30	40	50	60	70	80	90	99
-40	309	187	141	133	106	36	36	0	0	0	0
-30	376	193	151	133	110	36	36	32	0	0	0
-20	329	254	176	141	123	106	36	35	0	0	0
-10	337	264	180	141	133	110	36	36	0	0	0
0	347	277	187	153	141	110	96	36	35	0	0
10	376	281	194	180	141	133	110	36	35	0	0
20	350	288	264	187	153	141	123	106	36	0	0
30	360	300	279	215	180	143	133	110	36	35	0
40	375	309	285	265	187	179	141	133	106	36	0

For all riparian and appropriative curtailments, curtailment trends are the same: water curtailments increase as buffer flows increase and exceedance probability decreases. This occurs because smaller exceedance probabilities represent smaller volumes of available water, and larger buffer flows decrease the water available in the system.

Table 11 and *Table 12*. There are fewer curtailments for riparian water rights because it is the most senior type of water right and shortage is shared. The total number of curtailments is more gradual for appropriative rights than riparian rights. Figure 9 highlights curtailment jumps between buffer flows for riparian rights. The most visible drop in curtailments occurs between 40% buffer flow and 30% buffer flow and exceedance probability 1% and 20%. Buffer flows and exceedance probabilities have a much larger effect on appropriative rights, which created the repetitive down-step pattern in Figure 10. These graphs are driven more by the structure of water right holders and the size of the water right rather than the buffer flow percent.

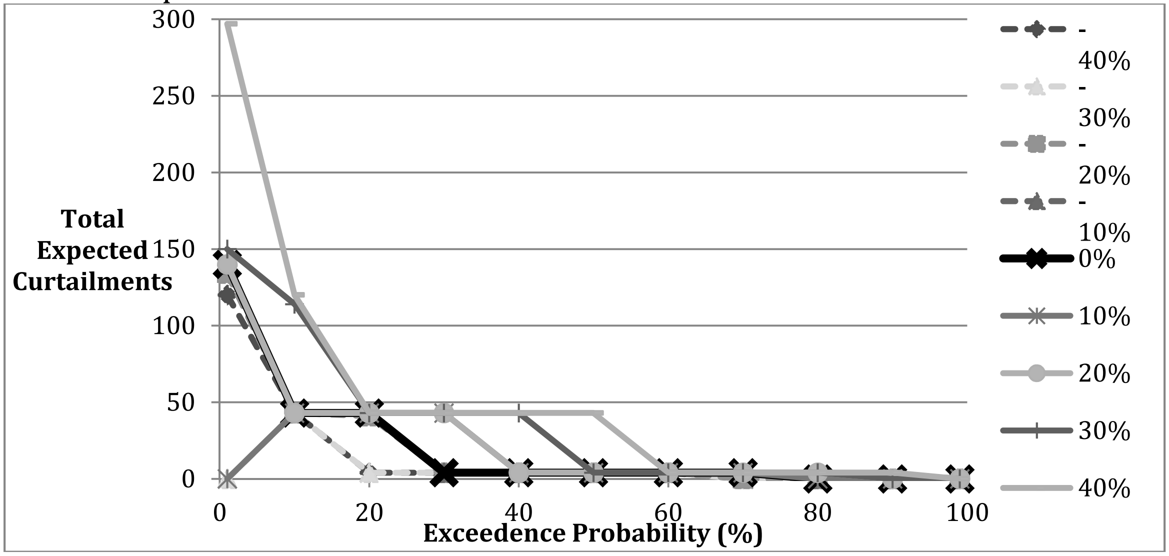

Figure 12. Probabilistic riparian total expected curtailments for varied buffer flows assuming San Joaquin basin in July where Q_f = 10,500 af/d and Q_a = unimpaired outflow probability volumes

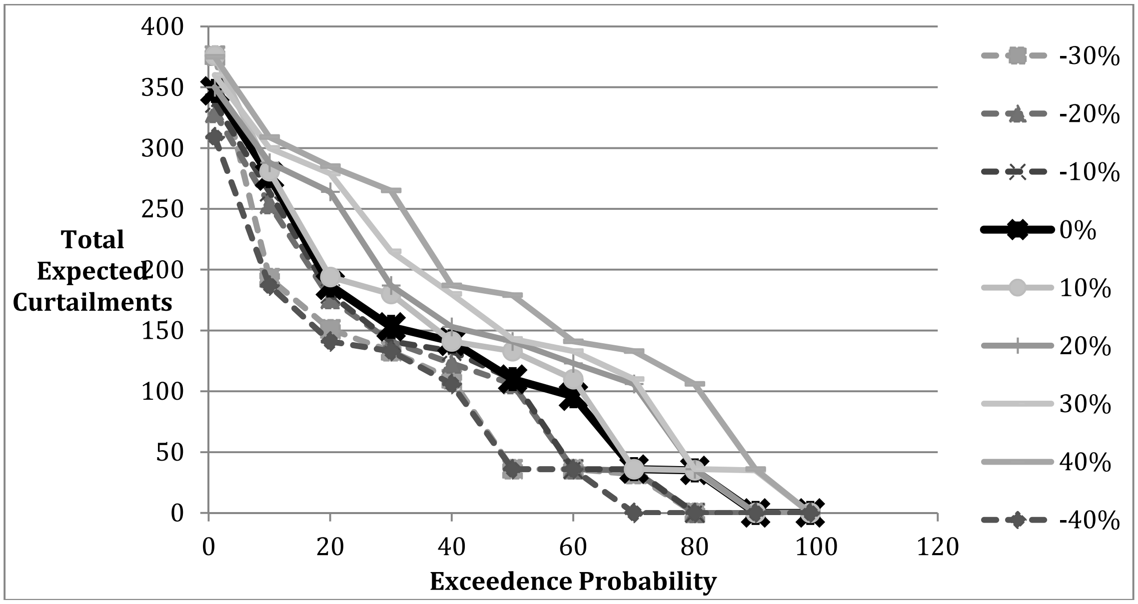

Figure 13. Probabilistic appropriative total expected curtailments with varied buffer flows assuming San Joaquin basin in July where Q_f = 10,500 af/d and Q_a = unimpaired outflow probability volumes

False Promise and Curtailments Tradeoffs

False promises happen when the forecast flow Q_f exceeds the actual flow Q_a. False curtailments happen when the actual flow exceeds the forecast flow. For this analysis the actual flow is the probability distribution for the mean July flow from the Vernalis gage, and the forecast flow is the 50% exceedance probability of 10,500 ac-ft/day, plus or minus the error. Negative buffer flows increase the accounted water available, making false promises more likely. Positive buffer flows decrease the accounted water available in the system, making false curtailments more likely. *Table 13* shows the number of false promises and false curtailments for riparian users. The number of false promises decreases as the number of false promises increase. Only one false promise occurs in the system while the number of false curtailments increases. Riparian users are less likely to be over promised and over curtailed because they are the most senior water rights. *Figure 14* and *Figure 15* show the expected false promises and false curtailments for each buffer flow.

Table 13. Probabilistic riparian number of expected false promises, curtailments, and correct curtailments with varied buffer flows assuming San Joaquin basin in July where Q_f = 10,500 af/d and Q_a = unimpaired outflow probability volumes

Buffer Flow	FP	FC	Total Falsities	Correct Curtailments
-40%	1	5	6	915
-30%	1	4	5	916
-20%	1	9	10	911
-10%	1	9	10	911
0%	1	9	10	911
10%	1	12	13	908
20%	0	13	13	907
30%	0	24	24	896
40%	0	30	30	891

Figure 14 shows the total falsities for false promises and false curtailments with various buffer flows for riparian water users. There is only a slight drop in false promises but a steep increase in false curtailments with positive buffer flows. Curtailment jumps are biggest at 20%, 30%, and 40% buffer flows. Water managers can use this information to make curtailment rules that minimize the number of false curtailments and promises. Figure 13 shows the change of false promises and curtailments with each buffer flow.

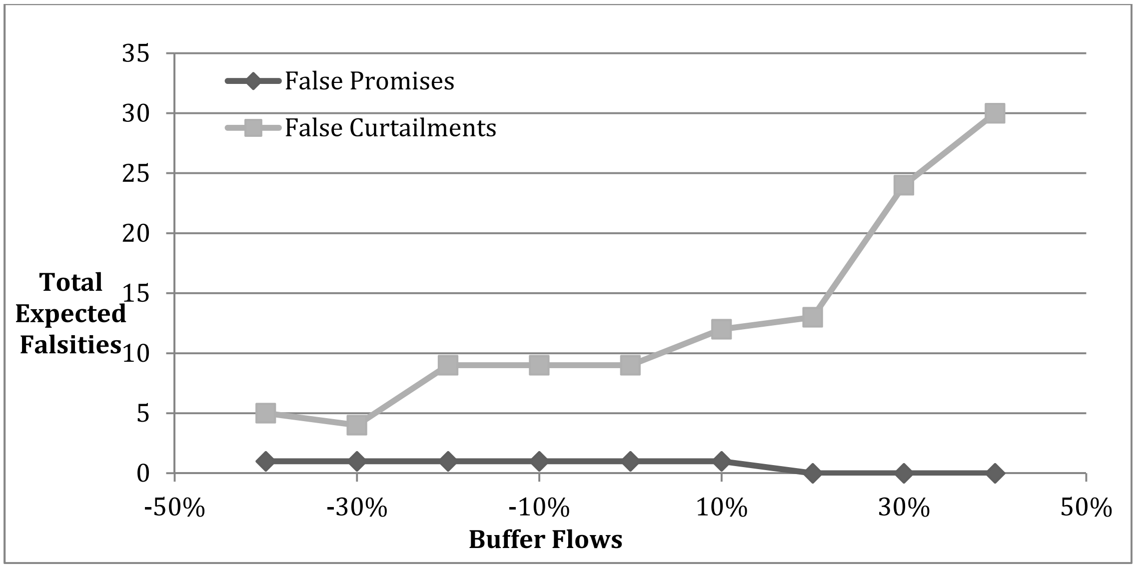

Figure 14. Probabilistic riparian number of total falsities with expected false promises and curtailments assuming San Joaquin basin in July

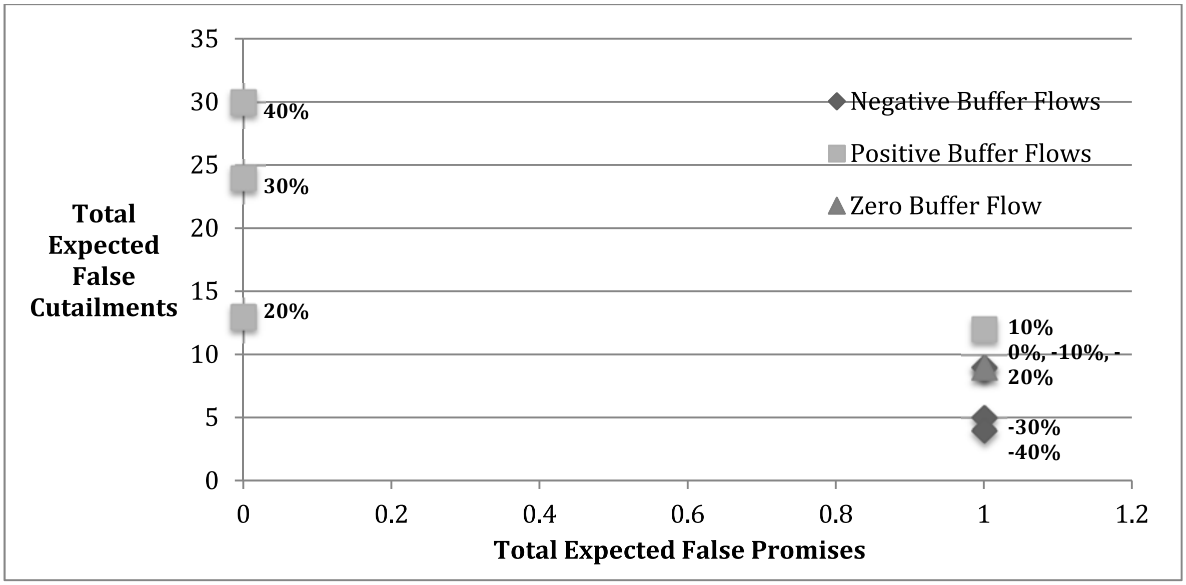

Figure 15. Probabilistic riparian number of total expected false promises and curtailments in the San Joaquin basin in July

Table 14 shows the number of false promises and false curtailments for appropriative users. The number of false promises decreases as the number of false promises increase for larger buffer flows. There are tens more false promises and curtailments for appropriative users than riparian uses.

Table 14. Probabilistic appropriative number of expected false promises, curtailments, and correct curtailments with varied buffer flows in the San Joaquin basin in July

Buffer Flow	FP	FC	Total Falsities	Correct Curtailments
-40%	49	15	64	1612
-30%	46	17	63	1613
-20%	38	28	66	1610
-10%	38	30	68	1608
0%	28	34	62	1614
10%	27	41	68	1609
20%	20	52	72	1604
30%	16	62	78	1599
40%	9	76	85	1592

Figure 14 shows the total falsities for false promises and false curtailments with various buffer flows for riparian water users. There is steady decrease in false promises and increase in false curtailments as buffer flow percent increases. Between various buffer flows, appropriative curtailment jumps are larger than riparian curtailment jumps. This is likely happening because appropriative users are curtailed in strict seniority. Figure 15 shows the change of false promises and curtailments with each buffer flow. This graph is similar to Figure 8 and Figure 13 but includes basin outflow the flow probability distribution for appropriative rights.

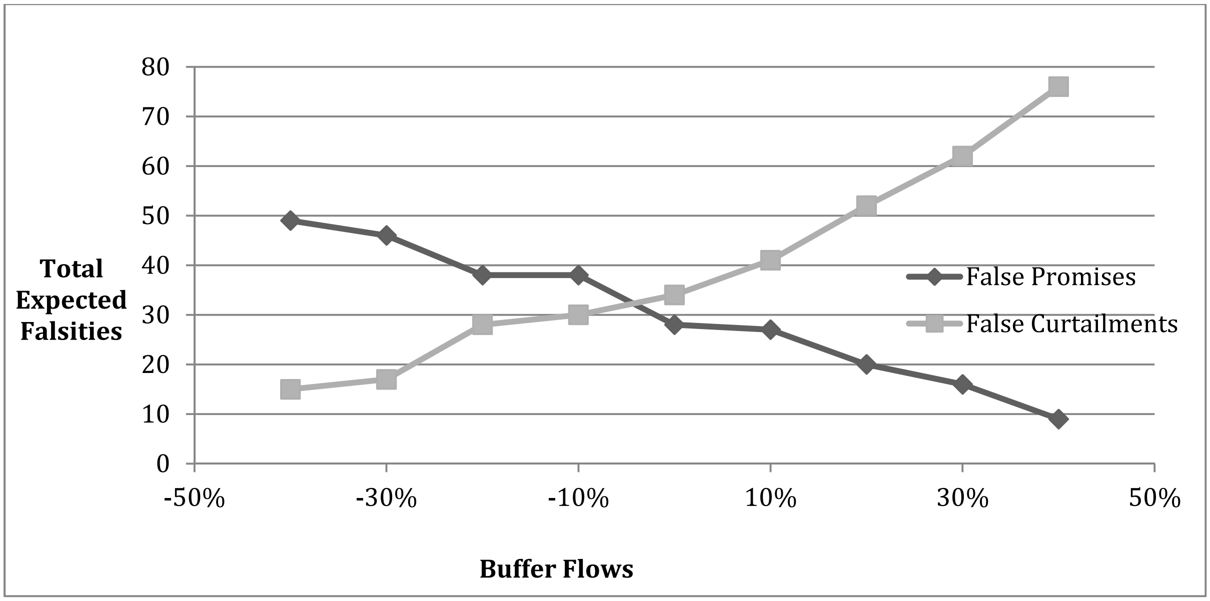

Figure 16. Probabilistic appropriative number of total expected falsities with expected false promises and curtailments in the San Joaquin basin in July

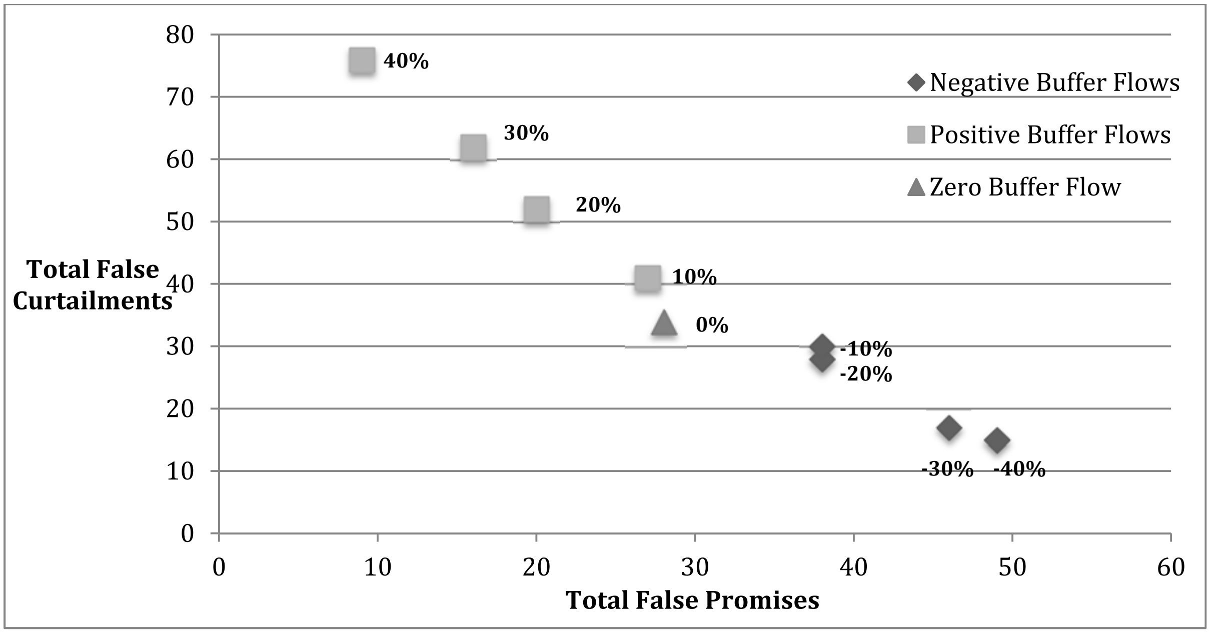

Figure 17. Probabilistic appropriative number of total expected false promises and curtailments in San Joaquin basin in July

Curtailments are based on two main factors, priority and watershed basin location. Higher priority users in downstream basins near or on the main-stem of the San Joaquin River are least likely to be shorted. Downstream water users are less likely to be curtailed; water availability increases further downstream as tributaries add inflow and are less likely to be impacted by local shortages (Lord, 2016). Along the mainstem curtailment is more likely to be determined by priority. Large water rights and users upstream are more likely to be curtailed than small due to water shortages in upper sub-basins (Whittington, 2016). Results supporting these conclusions were also found by Walker (2017) when Implicit Stochastic Optimization (ISO) was applied to DWRAT in July. ISO was used to determine the probability of shortage for water holders in July and develop curtailment rules. Expected false promises and curtailments act similarly to expected curtailments. Both occur more frequently in upper reaches further from the San Joaquin River main stem. These locations have less available inflow and greater likely forecast errors. The most false promises occurred in the Middle San Joaquin, Upper San Joaquin, Upper Stanislaus, and Upper Tuolumne HUCs respectively. The most false promises occurred in the Middle San Joaquin, Upper Mokelumne, Upper Cosumnes, and Upper Stanislaus HUCs respectively. The “Upper” HUCs are the most remote basins for each tributary river, where the least amount of inflow is available to users. In theses places small riparian shortages occur. With large positive buffer flows false curtailments increase dramatically, especially among lower priority users. Most curtailed users are post-1914 appropriative rights, are located on San Joaquin River tributaries. As positive buffer flows increase curtailments increase most in upper basins off the mainstem of the San Joaquin basin. Negative buffer flows decrease curtailments throughout the entire basin, most dramatically among

junior post-1914 rights. It might be desirable to have larger buffer flows in upper basins, diminishing further down the basin as tributaries accumulate.
Policy objectives of water rights administrators will determine the use and value of buffer flows. If minimizing total falsities in the system is the goal, zero buffer flow is optimal (Lord et al, 2017). These tradeoffs can be seen in Figure 17. Zero buffer flow has the fewest total falsities. Positive buffer flows increase false curtailments while decreasing false promises. The cost of false promises and false curtailments vary by user. False promises could be more damaging because a user is receiving less water than planned. Any type of unseen curtailment and shortage will negatively affect users.

Table 15 represents a different way to understand how buffer flow affects curtailments. It shows the expected value percent of correct non-curtailments, correct curtailments, false promises, and false curtailments. Using 20% buffer flow the expected percent of false promises is .71%, and the expected percent of false curtailments is 2.3%. The expected percent agreement for non-curtailment is 91%, and agreement for curtailment is 89% for Q_f of 10,500 ac-ft and Q_a the entire flow probability distribution with 20% buffer flow.

Table 15. Curtailment actions compared to correct curtailments for 20% Buffer flow using probabilistic total expected curtailments in San Joaquin basin in July

		Correct Curtailments	
		Not Curtailed (%)	Curtailed (%)
Curtailment Action	Not Curtailed (%)	91%	11%
	Curtailed (%)	9%	89%

Volumes Shorted For Various Buffer Flows

The tables and graphs below represent the volume of water shorted, and percentage of water shorted for each buffer flow for riparian and appropriative rights. All volumes are in acre-feet per day. Table 15 shows the total volume of riparian water shorted, and the total percent of riparian volume shorted. The total volume of riparian water allocated is 5,230 ac-ft/day. The maximum volume curtailed is 1,140 ac-ft/day, 22% of total riparian volume. The table below shows the total volume of appropriative water shorted, and the total percent of appropriative volume shorted. The total volume of appropriative water allocated is 13,010 ac-ft/day. The maximum volume curtailed is 7,660 ac-ft/day, 60% of total appropriative volume.

Table 16. Probabilistic riparian and appropriative volume shorted for varied buffer flows in the San Joaquin basin in July

	Riparian Volume Shorted		Appropriative Volume Shorted	
Buffer Flow	Volume (ac-ft/day)	% Shorted	Volume (ac-ft/day)	% Shorted
-40%	330	6	3420	26
-30%	350	7	3760	29
-20%	430	8	4170	32
-10%	500	10	4600	35
0%	580	11	5070	39
10%	650	12	5640	43
20%	800	15	6220	48
30%	950	18	6880	53
40%	1140	22	7660	59

Figures 18 and 19 show the volume of water and percent of water curtailed for a range of buffer flows. Riparian users lose a much smaller percentage of water with various buffer flows compared to appropriative users. Shortages disproportionately affect appropriative users because of the larger volumes of water and secondary priority compared to riparian users. These volumes quantify water loss in times of drought. Water rights administrators and water rights holders can now understand the amount of water they might be shorted depending on the total inflow volume.

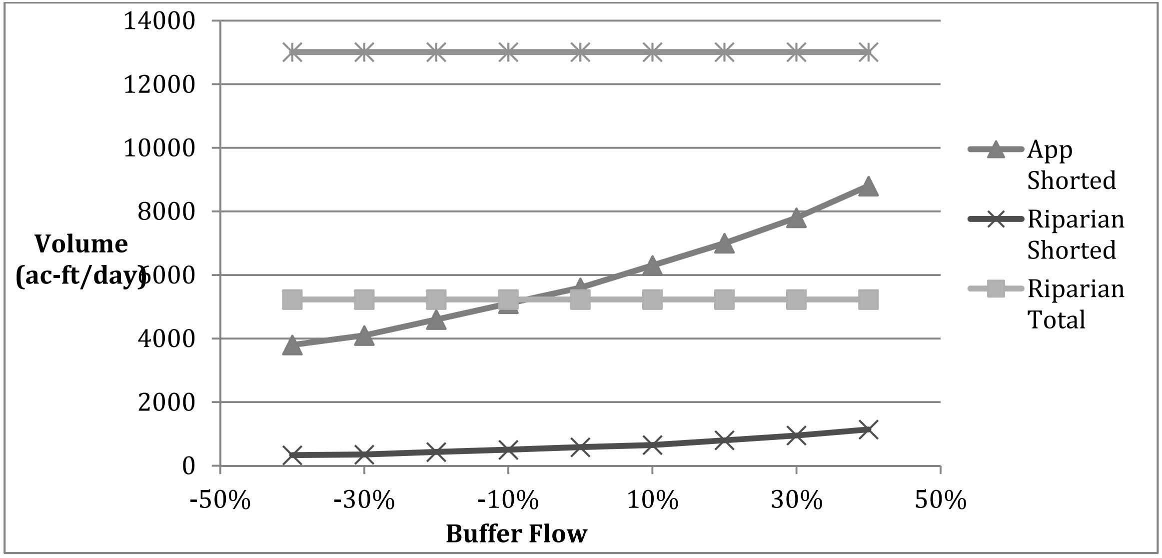

Figure 18. Probabilistic volume shorted for riparian and appropriative water rights holders for various buffer flows in the San Joaquin basin in July

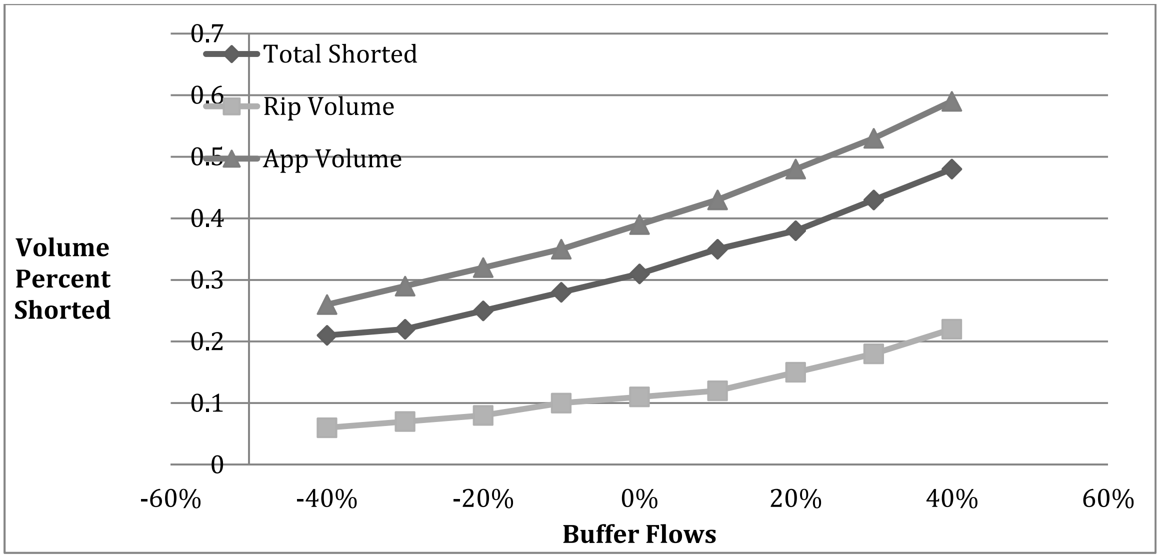

Figure 19. Volume percent shorted for riparian and appropriative water rights holders for various buffer flows in the San Joaquin basin in July

Buffer Flow Uncertainties and Limitations

This paper simplifies the San Joaquin DWRAT model and examines buffer flows using unimpaired flow estimates from the basin outlet gage, Vernalis. Using one gage helped simplify modeling and ensured uniformity. This simplification is the greatest source of error and uncertainty. Decreasing the number of gages used means that flow for every HUC-12 in the basin is estimated from a gage at the bottom outlet of the watershed. The entire 15,800 square mile area and six tributary rivers have their hydrologic information determined from one gage.

All DWRAT models use scaling factors to disaggregate flows for each HUC from reference stream gages. The San Joaquin DWRAT model uses seven gages for unimpaired flow estimates (Walker, 2017). Scaling ratios are determined from unimpaired gage flows and estimate available unimpaired flow in the basin. Walker (2017) discusses the error in scaling ratios in the San Joaquin DWRAT model. Monthly flow ratios representing the 20th percent of driest years were calculated to create more realistic and accurate flow estimates. Overall, July had the least variation and coefficient of variation among dry years, but substantial variation occurs spatially within the watershed. “Even among dry years there can be significant variation in the monthly scaling ratios, especially in HUCs with higher flows lower in the watershed (e.g. Lower San Joaquin and Merced). Likewise, HUCs further up in the watershed, not on the mainstem river (e.g. Stanislaus and Upper San Joaquin), have lower scaling ratios that are more consistent among years” (Walker, 2017).

Overall hydrologic error in water availability probably increases when reservoirs, groundwater interactions, and other diversions are considered. These are not represented in current DWRAT models and can affect the accuracy of unimpaired flow estimates.

Policy Implications

Buffer flows have the capability to reduce water demand uncertainty during drought. Water rights administrators should determine proper buffer flow usage by examining the damage associated with false promises versus false curtailments. If false promises are more harmful, a positive buffer flow should be used. Using a positive buffer flow will decrease the likelihood of false promises but increase the likelihood of false curtailments, especially to junior users in remote reaches.

Walker (2017) and Lord (2016) suggest appropriative users "call" in their water diversions in advance (Escriva-Bou, et. al, 2016) to improve inflow estimates and basin curtailments in droughts. This system would benefit both water users and water managers. Water right holders would be informed about their allocation, granting them the ability to plan water use while water managers would have a transparent and reliable system to curtail water.

Conclusions

California droughts force users to curtail their use of water rights. DWRAT is useful to identify water rights curtailments in a networked basin following riparian and appropriation water law doctrines. Nevertheless, its use and interpretation depend on water rights administrators' discretion. Forecasted and modeled estimates of water availability and demand are imperfect. Buffer flows grant water rights administrators flexibility in water curtailment assessment for various conditions. Water curtailments increase as buffer flows increase, and decease as buffer flows decrease. Buffer flows affect appropriative users more than riparian users because their rights are more junior. Expected curtailments quanitify the number of curtailed users based on water availability and identify optimal buffer flows for a specified number of curtailments. Water basin managers can use knowledge of curtailment jumps and drops to make more effective water allocations decisions.

False promises and false curtailments arise when there is disparity between predicted water available and actual water available. As buffer flows increase, less false promises and more false curtailments occur. As buffer flows decrease, less false curtailments and more false promises occur. Buffer flows affect the probababilty of total falsities, total false promises, total false curtailments, and total expected curtailments of a basin. To achieve minimal total falsities, administators should use a buffer flow percentage of zero. In many situations it is optimal to minimize false water promises to users, but this likely increases false curtailments for junior water rights holders. (Lord et al., 2017). Water administrators select various buffer flows to optimize policy demands and users needs.

Bibliography

Attwater, W., Markle, J. (1988). Overview of California Water Rights and Water *Quality Law. Pacific Law Journal*. Volume 19.

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

Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, J., Moyle, Peter., Thompson, B. (2011). Managing California's Water from Conflict to Reconciliation. Public Policy Institute of California. San Francisco, CA.

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

Jankowski, J. (2017) Drought Water Rights Allocation Tool Guide (Draft). *University of California Davis*, *Center for Watershed Sciences.*

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

Lord, B. (2015). "Water rights curtailments for drought in California: Method and Eel River Application," Master's Thesis, Department of Civil and Environmental Engineering, University of California, Davis.

Lord, B., Magnuson-Skeels, B., Tweet, A., Whittington, C., Adams, L., Thayer, R., Lund, J. (April 2017). Drought water right curtailment analysis for California's Eel River. *Journal of Water Resources Planning and Management*. ASCE.

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

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

State Water Resources Control Board (2015a). "2015 Tuolumne R. To San Joaquin R. Supply/Demand Analysis". State Water Board Drought Year Water Actions. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/analysis/docs/sjprorated.pdf

State Water Resources Control Board (2015b). "Order WR 2015-0002-DWR" Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/2015sacsjinfoorder.pdf

State Water Resources Control Board (2016a). "Notices of Water Availability (Curtailment and Emergency Regulations)". State Water Board Drought Year Water Actions. Retrieved from http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/water_availability.shtml

State Water Resources Control Board (2016b). "In the Matter of Administrative Civil Liability Complaint Against Byron-Bethany Irrigation District and In the Matter of Draft Cease and Desist Order Against The West Side Irrigation District ". Order WR 2016-0015.

State Water Resources Control Board (2016c). "Draft Revised Substitute Environmental Document in Support of Potential Changes to the Water Quality Control Plan for the Bay-Delta: San Joaquin River Flows and Southern Delta Water Quality".
Tweet, A. (2016). Water Right Curtailment Analysis for California's Sacramento River: Effects of Return Flows (Master's thesis.) University of California, Davis - Center for Watershed Sciences.

Whittington, C. (2016). "Russian River Drought Water Right Allocation Tool (DWRAT)," Master's Thesis, Department of Civil and Environmental Engineering, University of California, Davis.

Walker, W. (2017). "Drought Water Right Allocation Tool Applied to the San Joaquin River Basin," Master's Thesis, Department of Civil and Environmental Engineering, University of California, Davis.