Using the Updated CALVIN Model to develop Optimized Reservoir Operations for the Sacramento Valley

By

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Abstract

Recently, updates were made to the CALVIN (California Value Integrated Network) model, an economic-optimization model for California's water resources. These updates significantly improved Central Valley groundwater representation in the model and provided more reliable agricultural water demands and more accurate constraints on Delta outflow and pumping. To understand how these updates have altered the model results, a comparison was made between the base case results before and after the updates. In addition, the new base case results were compared with the results of a "no overdraft" scenario, where groundwater overdraft was prohibited at the end of the 72 year model run. These comparisons helped identify several improvements to the model results, including: the elimination of Central Valley calibration flows, more accurate groundwater overdraft, and more accurate agricultural scarcity.

The new CALVIN base case was then used to derive economically optimized operating rules for the major reservoirs of the Sacramento Valley, including Shasta, Trinity, Oroville, and Folsom. These rules were divided into two classes: 1) monthly release rules and 2) storage allocation rules to balance water storage between multiple reservoirs. The storage allocation rules show that operations between Shasta and Trinity are very sensitive to water availability, while those for Oroville and Folsom are more dependent on time of year. Finally, the optimized operations were compared with CalSim II operations for the same reservoirs.

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Chapter One: Introduction

California has some of the most difficult water resource challenges facing the developed world. Water is a scarce resource in California. Insufficient water to meet all demands incurs economic costs for suppliers and water users. Since people are often unwilling to pay the cost needed for additional water, water managers must efficiently allocate existing supplies. This task requires more than engineering alone. Optimization models such as the CALVIN (California Value Integrated Network) model can help maximize the economic values of agricultural and urban water operations (Draper et al. 2003). Currently CALVIN represents about 90% of California's urban and agricultural water demands and about two-thirds of all runoff in the state (Medellin-Azuara et al. 2008). Computer models can handle complex computations and monotonous calculations faster than any human and provide engineers with a place to develop and test ideas that might be expensive, dangerous, or time-consuming to test in real life. However, a computer model is more useful if it is updated with more accurate data; CALVIN is no exception. CALVIN has its origins in the late 1990s, but has been improved and expanded several times.

This study describes the latest major updates to the CALVIN model and uses the updated model to derive optimized reservoir operating rules for the Sacramento Valley. This chapter introduces the objectives of this research and the framework for explaining the results. Next, chapter 2 describes the latest updates made to the CALVIN model. These updates focused on improving the representation of groundwater in the Central Valley based on the C2VSIM model. The California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) is a historical model used to simulate groundwater flow in the Central Valley. Before these updates, groundwater supplies were overestimated in the Tulare and San Joaquin basins, requiring about 2 million acre-ft (maf) of groundwater to be removed from the system through calibration flows (Bartolomeo 2011). This extra water in the system reduced agricultural water scarcity in the southern Central Valley. In addition, updates were made to Central Valley agricultural water demands based on more recent SWAP (State Wide Agricultural Production) model runs (Howitt et al. 2012). Finally, constraints on Delta outflow and Delta pumping at Banks pumping plant were changed to reflect constraints seen in CalSim II.

Chapter 3 presents the results of running the CALVIN model after applying the updates described in chapter 2. To understand how these updates have affected the model results, the updated base case was compared to its pre-update counterpart. This comparison focuses on the economic and water supply aspects of California's water resource system in the Central Valley. In addition, the updated base case is compared with a new no overdraft scenario where overdraft in the Central Valley is prohibited over the 72 year modeling period. Groundwater overdraft is a controversial issue. Since surface water supplies are limited, many farmers in the Central Valley pump groundwater for their crops. During droughts dependence on groundwater becomes more severe and pumping outpaces recharge, leading to overdraft. As overdraft increases, pumping costs rise, along with several environmental consequences, such as subsidence and increased surface water infiltration from rivers to aquifer, diminishing streamflows. The objective of this comparison is to see how well California's water resources could be operated if long-term overdraft was prohibited. Harou and Lund (2008) presents the results from a similar CALVIN run limited to the Tulare basin, before applying the updates.

Finally, chapter 4 looks at optimizing reservoir operations in the Sacramento Valley based on the updated CALVIN model. Reservoirs are a vital part of our water resource system for flood control, water supply, hydropower, and other purposes; but, reservoirs do not operate themselves. Instead, operators monitor the system upstream and downstream and make decisions on when and how much water to release. Operators need to make these decisions with limited knowledge of water availability in the future. Proper reservoir operations are important for maximizing the benefit from limited water and storage resources. To aid their decisions, operators often develop simple operating rules based on their past experience and intuition, supplemented with information from historical records and simulations. Operating rules usually depend on the known state of the system, such as current or recent storage, season, and inflow. A well defined set of optimized operating rules could help California's water resource system perform better for the changing conditions and objectives of today's climate.

The obvious challenge is how to define the optimized operating rules. Any given reservoir will have a wide range of possible operations depending on how much and when the water should be released. One way to narrow this choice is to use results from a formal optimization model, such as CALVIN, and see how the reservoirs behaved. Optimization models usually do not have predefined reservoir operating rules, but operate with some specific performance objective, such as to minimize costs. Examining the model's results can reveal reservoir operation patterns and help identify desirable operating rules. Some common rules that can be inferred from optimization results are storage allocation rules, storage target rules, and release rules. Storage allocation rules are used to balance water storage among multiple reservoirs. These rules can help set storage targets, as well as identify parts of the system that have drawdown and refill priority. In contrast, release rules define how much water should be released from a specific reservoir for a specific month based on state variables for the system. Some example studies on developing optimized operating rules include Ferreira and Lund (1994), Lund and Kirby (1995), Murk (1996), and Lund (1996).

In addition to defining a set of optimized operating rules from CALVIN results, Chapter 4 also defines similar rules based on the simulation model CalSim II. CalSim II is a general purpose reservoir-river simulation model co-developed by the Department of Water Resources and the Bureau of Reclamation (Draper et al. 2004). The model was created in the late 1990s when DWR and USBR decided to combine their individual water resource models, DWRSIM and PROSIM respectively, because they were too complex and cumbersome. CalSim II focuses on the facilities and operations of the State Water Project and Central Valley Project, but operations of some other non-project facilities are included to varying degrees. The geographic coverage of CALSIM II includes the Sacramento and San Joaquin Rivers, the upper Trinity River, and the San Joaquin Valley with connections to Tulare Basin and Southern California areas served by the SWP. Where CALVIN defines the most economically beneficial operations for California's water resources, CalSim II describes how the system would behave under predefined operational priorities. For more detail on CalSim II see Munévar and Chung (1999), Close et al. (2003), Ferreira et al. (2005), and Parker (2006).

Chapter Two: CALVIN Model Update Summary

2.1. Introduction

The most recent set of updates for the CALVIN model improved representation of groundwater use and recharge in the Central Valley, the largest form of water storage in California. In CALVIN the Central Valley is divided into 21 CVPM (Central Valley Production Model) subregions, each with its own groundwater storage basin. The CVPM subregions are shown in Figure 2-1. Groundwater is a vital water source for many urban and agricultural areas throughout California, partly due to the limited and more variable supply of surface water and the geographical separation of surface water supplies and demand areas. Originally CALVIN's groundwater parameters, such as pumping capacities, groundwater inflows, and aquifer capacities, were developed from the Central Valley Ground Surface Water Model (CVGSM) 1997 No Action Alternative (NAA) run (USBR, 1997). Early in CALVIN's development this was the best available representation. Today CVGSM has been replaced by more detailed models such as C2VSIM and CVHM. To improve CALVIN, it was decided to compare the current groundwater parameters obtained from CVGSM with those used in C2VSIM and CVHM. For descriptions and comparisons of the CVHM and C2VSIM models see Zikalala (2012) and Chou (2012).

Updating a large scale computer model such as CALVIN is no simple task. Much effort was needed to understand the model representations and results for both CVHM and C2VSIM. Ultimately most updates were taken from the C2VSIM model. C2VSIM was chosen because its modeling period (1921 to 2009) was similar to CALVIN's (1921 to 1993) and because it used largely updated terms, similar to CVGSM (Chou, 2012). C2VSIM also divides the Central Valley into 21 subregions similar to the CVPM used in CALVIN. This chapter summarizes the updates from C2VSIM and other sources. Table 2-1 lists the groundwater parameters updated and Figure 2-2 shows a sample of the CALVIN schematic with the locations of updated parameters.

In CALVIN water demands are calculated for the entire modeling period based on a fixed level of development for the state's water resource infrastructure and a fixed pattern of land use. On the other hand, C2VSIM is a historical model with annually varying land use over its modeling period. To account for influences of current major water supply infrastructure, terms 1-3, 5-7 and 9-12 in Table 2-1 were calculated based on C2VSIM output from 1980 to 2009, rather than the entire modeling period (Zikalala, 2012). The external inflows to groundwater, term 4, were updated based on the C2VSIM inflow time series with slight adjustments to stream flow exchanges. Finally, the groundwater table depth and the pumping cost, term 8, were calculated from DWR well monitoring data for the year 2000. In addition to the ground water updates, the agricultural water demands for CALVIN were changed based on information from the updated Statewide Agricultural Production Model – SWAP (Howitt et al. 2012). Finally, the Delta outflow requirement constraint and the Banks pumping plant capacity were updated based partially on CALSIM II 2009 results (DWR, 2011). For documentation on the updating process as well as the actual numerical changes made to the model, see Zikalala (2012) and Chou (2012).

Figure 2-1: Central Valley Groundwater Basins in CALVIN and Corresponding CVPM Subregions (from Zikalala, 2012)

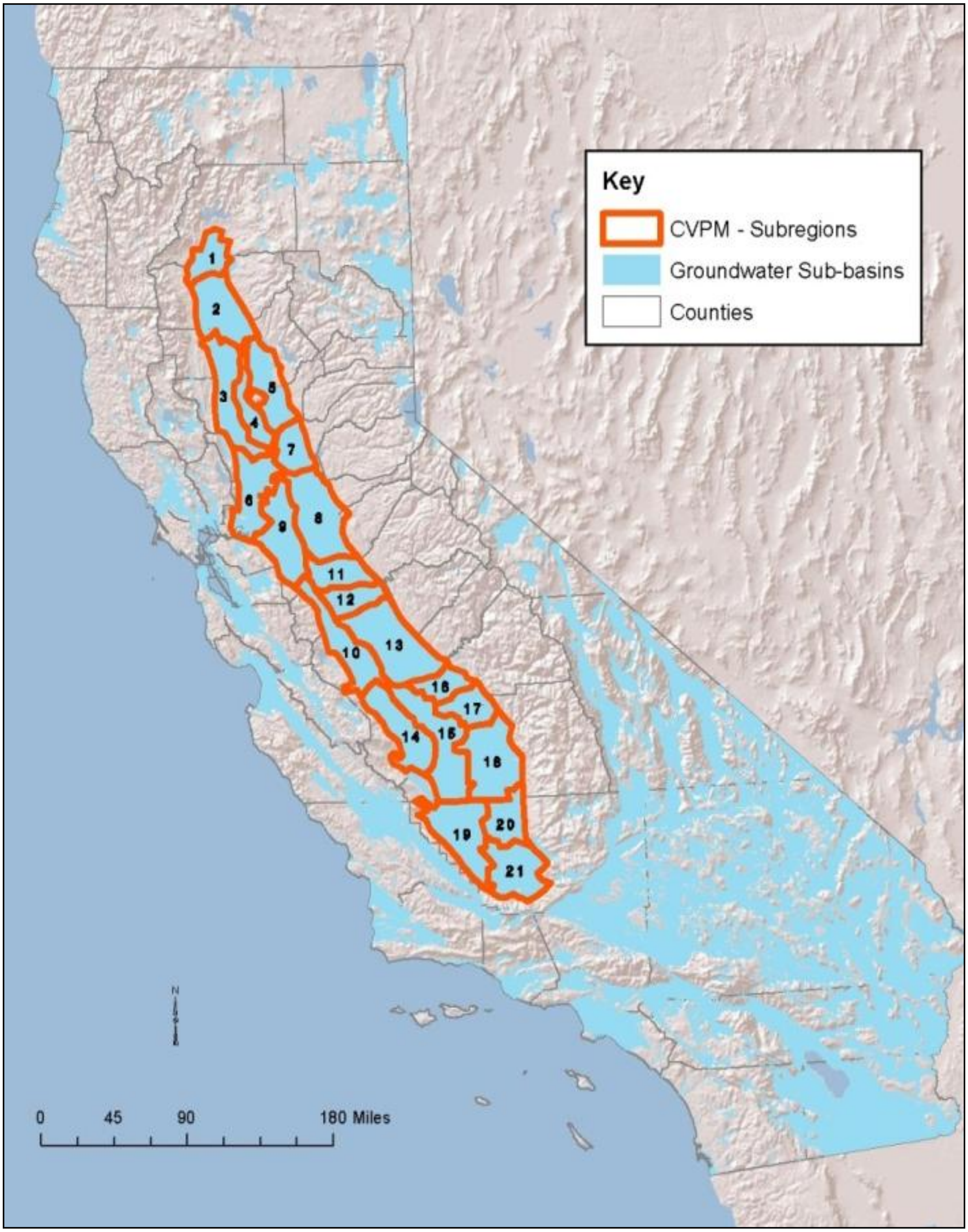
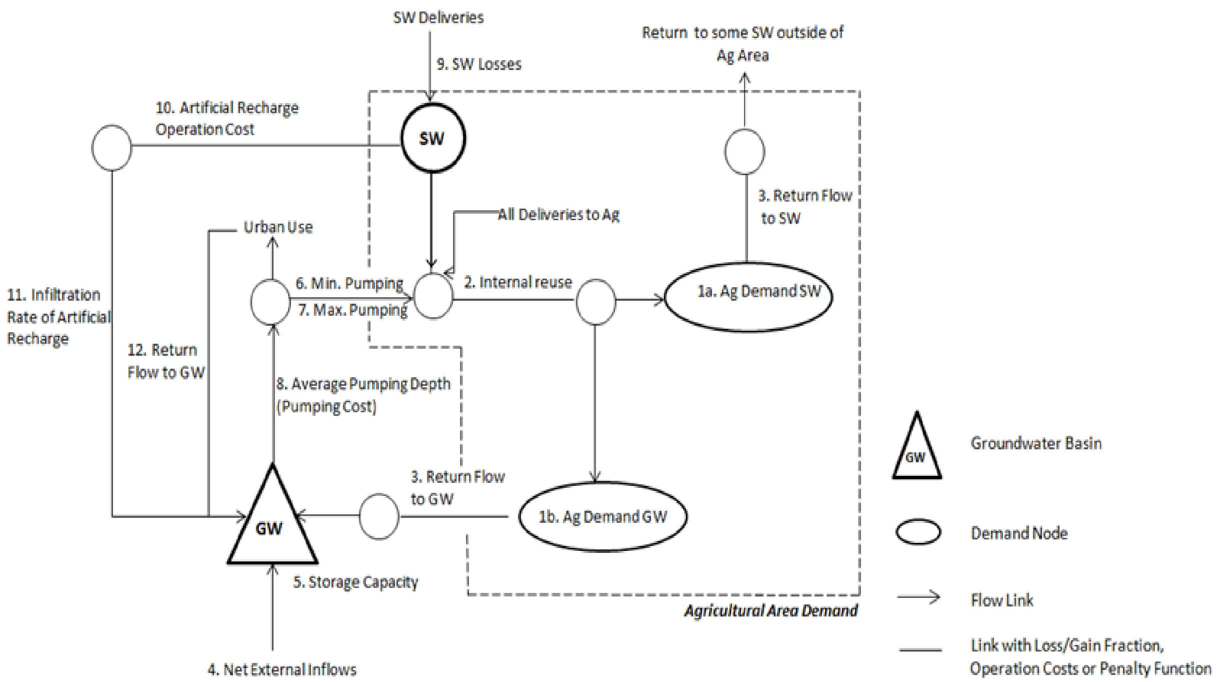


Table 2-1: Updated Groundwater Parameters (Item numbers correspond to numbers in Figure 2-1) (from Zikalala, 2012)

Item	Groundwater Components for CALVIN	Data type
1	Agriculture return flow split (GW & SW)*	Fraction (a+b=1)
2	Internal reuse	Amplitude (>1)
3	Agricultural areas return flow of total applied water	Amplitude (<1)
4	Net External Flows sum of:	Monthly time series
4a	Inter-basin Inflows	
4b	Stream exchanges	
4c	Lake exchanges	
4d	Conveyance seepage	
4e	Deep Percolation of Precipitation	
4f	Boundary Inflow	
4g	Subsidence	
4h	Tile Drain Outflow	
5	GW Basin Storage Capacity (Initial, Maximum, Ending)	Number (Volume)
6	Lower-bound pumping for Ag. (minimum)	Number value
7	Upper-bound pumping for Ag. (maximum)	Number value
8	Average Pumping Depth Representative Depth to GW (Pumping Cost)	Cost (2008 dollars)
9	Surface Water Losses including Evaporation & Diversion losses to GW	Fraction (<1)
10	Artificial Recharge Operation cost	Cost (2008 dollars)
11	Infiltration Fraction of Artificial Recharge	Fraction (<1)
12	Urban Return Flow to GW	Fraction (<1)

Notes: ** Ag Demand GW represents the non-consumptive use portion of irrigation water that deep percolates to groundwater, and Ag Demand SW represents the portion that returns to surface water systems as tailwater.*

Figure 2-2: Updated CALVIN Groundwater Schematic (from Zikalala, 2012)



2.2. Summary of CALVIN Groundwater Updates

2.2.1. Agricultural Return Flow Split between Surface Water and Groundwater (Term 1)

Applied water is the water volume delivered to agricultural demand areas for irrigation. Of this water some portion evapotranspires to the atmosphere, while the rest remains on the surface, joining nearby streams or lakes and infiltrating into groundwater. The agricultural return flow split defines how much of the return flow from applied water will become groundwater and how much will return as surface water. From C2VSIM the return flow from applied water is already estimated, including how much infiltration occurs. However, additional infiltration occurs from precipitation and C2VSIM lumps these two volumes together as infiltration water. Since the evapotranspiration is already known, we can perform a water balance on the root zone to calculate how much water percolates into the groundwater. After separating this deep percolation into portions from applied water and precipitation, we now have the total applied water that entered the groundwater. Finally we can calculate the fraction of non-consumed applied water that entered groundwater and surface water. These fractions were calculated from the C2VSIM results for each month between 1980 and 2009 and then the final splits were taken as the average of weighted annual average amplitudes. The pre and post-update agricultural return flow splits for each sub-region of the Central Valley are given in Table 2-2.

Table 2-2: Central Valley Applied Water Return Flow Fractions to Surface and Groundwater (from Zikalala, 2012)

	Ag Return Flow Split to Surface Water (1A)		Ag Return Flow Split to Groundwater (1B)	
CVPM	Old CALVIN	Updated CALVIN	Old CALVIN	Updated CALVIN
1	0.56	0.72	0.44	0.28
2	0.23	0	0.77	1
3	0.22	0.4	0.78	0.6
4	0.82	0.01	0.18	0.99
5	0.26	0.28	0.74	0.72
6	0	0.02	1	0.98
7	0.45	0	0.55	1
8	0.79	0.07	0.21	0.93
9	0.3	0	0.7	1
10	0.74	0.06	0.26	0.94
11	0	0.06	1	0.94
12	0.62	0.06	0.38	0.94
13	0.66	0.03	0.34	0.97
14	0	0	1	1
15	0.6	0	0.4	1
16	0.69	0.16	0.31	0.84
17	0.39	0	0.61	1
18	0	0	1	1
19	0	0	1	1
20	0.01	0.18	0.99	0.82
21	0	0	1	1

2.2.2. Amplitude for Internal Reuse (Term 2)

Agricultural reuse water is the portion of applied water that flows from one farm to another, effectively reusing the water. In CALVIN this is represented by multiplying the delivered water by the reuse amplitude. A reuse amplitude equal to 1 represents the first application of the applied water; an additional small fraction added to that 1 represents the amount of reused water within the water demand area. For example, if a demand area receives 100 TAF of water and has an internal reuse amplitude of 1.1, 10% of the applied water is reused and the demand area receives the benefits of 110 TAF. In C2VSIM the amount of reused water is already estimated. The reuse amplitude is found by summing the reused and applied water and then dividing by the applied water. This amplitude was calculated from the C2VSIM results for each month of the irrigation season (April to October) between 1980 and 2009 and then averaged for the final values. The pre and post-update reuse amplitudes for each sub-region of the Central Valley are given in Table 2-3.

Table 2-3: Central Valley Amplitude for Internal Agricultural Re-use (from Zikalala, 2012)

	Reuse Amplitude	
CVPM	Old CALVIN	Updated CALVIN
1	1	1
2	1	1
3	1.05	1.183
4	1.13	1.001
5	1.06	1.1
6	1.32	1.001
7	1.08	1.056
8	1.1	1.009
9	1.1	1.012
10	1.05	1.009
11	1.04	1.052
12	1.1	1.037
13	1.1	1.001
14	1	1.013
15	1.05	1
16	1.1	1.082
17	1.1	1
18	1	1
19	1	1
20	1.07	1.003
21	1	1.012

2.2.3. Amplitude for Agricultural Return Flow of Total Applied Water (Term 3)

In section 2.1 above we calculated how the applied water not consumed by the crops was divided between groundwater and surface water. For term 3 we want to estimate what fraction of the total applied water will become return flow. In C2VSIM the return flow and the total applied water are known so taking the ratio of the two will produce the fraction. This fraction was calculated from the C2VSIM results for each month between 1980 and 2009 and the final values were taken as the average of the weighted annual average amplitudes. The pre and post-update return flow fractions for each sub-region of the Central Valley are given in Table 2-4. However, some of the fractions were changed during calibration to better represent system scarcities (Zikalala, 2012)

Table 2-4: Central Valley Amplitude for Agricultural Return Flow of Applied Water (from Zikalala, 2012)

	Return Flow Fraction from Ag	
CVPM	**Old CALVIN**	**Updated CALVIN**
1	0.32	0.47
2	0.26	0.26
3	0.28	0.2
4	0.21	0.14
5	0.283	0.21
6	0.08	0.1
7	0.3	0.25
8	0.23	0.12
9	0.21	0.1
10	0.33	0.2
11	0.272	0.22
12	0.18	0.18
13	0.18	0.13
14	0.22	0.18
15	0.21	0.12
16	0.18	0.28
17	0.17	0.13
18	0.25	0.18
19	0.21	0.03
20	0.17	0.1
21	0.25	0.1

2.2.4. Net External Inflows to Groundwater (Term 4)

Groundwater flow depends on the hydraulic head in and around aquifers. In CALVIN many of these flows are grouped together as a single time series of the net external inflow to each groundwater aquifer area. Vertical flows connecting the aquifer to surface water include deep percolation from precipitation and interactions with streams and lakes. Horizontal flows include inter-basin flows between the modeled aquifers, as well as boundary flows from outside the model. In addition, the net external inflow contains tile drain outflows for subregions 10 and 14, which control the groundwater table by transferring water to diversions on the surface. Finally, water gains and losses due to subsidence and expansion of buried clay layers in each aquifer are included in the term. Other flows that affect groundwater storage that are not part of the net external inflow time series are deep percolation from applied water, urban return flow to groundwater, diversion losses to groundwater, artificial recharge, and groundwater pumping.

In C2VSIM the terms that compose net external inflow are represented dynamically based on historical land use and infrastructure development. In 1951 new surface water delivery infrastructure, such as the Delta Mendota Canal, allowed for greater access to surface water supplies in the Central Valley and less dependence on groundwater. Consequently, after 1951 C2VSIM shows significant changes in the net external inflow to groundwater. The base case CALVIN, on the other hand, operates with fixed land use and infrastructure at 2005 levels and does not model these changes. Therefore, using the C2VSIM time series directly in CALVIN could cause water balance problems. Since it would be difficult to run C2VSIM with the same conditions as CALVIN, updating the net external inflow in CALVIN relied on the C2VSIM time series after 1951. The pre and post-update annual average net external groundwater inflows for each sub-region in the Central Valley along with the regional totals are given in Table 2-5.

The pre-1951 inflows were adjusted based on the difference in annual average inflows before and after 1951. Adjusting the inflows is required to account for the higher level of development in CALVIN before 1951. However, the inter-basin flows, diversion losses, and deep percolation of precipitation terms were not changed. Inter-basin flows depend on many different process and variables besides the development level. Therefore, it would be difficult to determine how much the post 1951 developmental conditions influenced the inter-basin flows without running C2VSIM with CALVIN conditions. Similarly, it would be difficult to determine how much of the change in deep percolation of precipitation from before 1951 to after 1951 was caused by land use changes or changes in hydrology. Diversion losses were not adjusted because the annual average difference before and after 1951 was usually small. Finally, stream flow exchange was only updated for streams where the annual average difference in pre and post-1951 flow exceeded 50 TAF/yr.

Table 2-5: Annual Average Net External Inflows in the Central Valley (from Zikalala, 2012)

	Net External Inflows to Groundwater (TAF/Yr)	
CVPM	Old CALVIN	Updated CALVIN
1	2	28
2	403	231
3	12	-10
4	263	-70
5	145	87
6	366	224
7	278	165
8	747	395
9	13	133
10	299	69
11	-157	29
12	157	48
13	872	360
14	200	274
15	1167	679
16	278	50
17	359	93
18	485	238
19	167	420
20	219	98
21	390	318
Totals		
Sacramento	2229	1184
San Joaquin	1171	506
Tulare	3266	2171
Central Valley	6665	3861

2.2.5. Groundwater Basin Storage Capacity (Term 5)

In CALVIN three storage values are needed to represent aquifer storage: the maximum capacity, initial storage, and ending storage. The maximum capacity is defined as the maximum historical storage seen between 1980 and 2009 and was simple to update by looking at the C2VSIM output for that period. Initial aquifer storage is the storage in the aquifer when a model run begins. Since base case CALVIN operates using a 2005 level of development the initial storage was taken as the C2VSIM ending storage for 2005. Finally, the ending storage is the storage that CALVIN is constrained to meet by the end of the modeling period. This was determined by calculating the annual average historical overdraft for 1980 to 2009 seen in

C2VSIM and multiplying it by the number of modeling years in CALVIN, which is 72. This limits allowable groundwater overdraft for the entire run. The ending storage was taken as the initial storage in the aquifer minus the allowable overdraft. The pre and post-update maximum, initial, and ending groundwater storage values for each sub-region of the Central Valley are given in Table 2-6.

Table 2-6: Central Valley Groundwater Capacity & Overdraft Constraint in CALVIN (from Zikalala, 2012)

	Maximum Storage		Initial Storage		Ending Storage	
	(TAF)					
CVPM	Old	Updated	Old	Updated	Old	Updated
1	5,448	38,510	1,902	38,447	1,774	39,437
2	24,162	136,757	11,843	136,494	11,242	137,376
3	22,127	133,958	13,345	132,687	13,545	131,748
4	15,362	61,622	10,350	60,728	10,581	60,508
5	24,399	92,020	15,552	91,113	14,561	90,457
6	22,864	175,719	17,948	174,968	16,077	175,275
7	12,270	58,484	10,025	56,539	12,168	51,210
8	32,842	193,433	22,366	190,665	16,276	182,829
9	23,395	139,752	17,744	139,472	20,474	139,834
10	29,250	91,920	22,213	90,210	23,477	87,055
11	15,543	59,302	10,948	58,838	8,747	58,246
12	13,919	43,510	10,380	42,602	9,414	40,865
13	47,484	142,508	31,143	138,216	31,169	128,560
14	65,235	181,001	51,075	178,840	45,763	172,009
15	90,978	313,759	70,494	309,643	70,415	306,666
16	11,650	64,915	6,359	64,696	0	64,438
17	13,492	98,836	7,311	97,214	7,005	93,653
18	59,544	322,480	40,775	321,375	33,947	332,438
19	68,266	147,060	43,085	141,750	43,087	128,223
20	40,814	141,457	22,630	137,073	23,403	125,136
21	80,772	351,327	51,595	341,142	47,588	313,239
Total						
Sacramento	182,869	1,030,255	121,075	1,021,114	116,698	1,008,673
San Joaquin	106,196	337,241	74,684	329,867	72,808	314,726
Tulare	430,751	1,620,834	293,324	1,591,732	271,208	1,535,803
Central Valley	719,816	2,988,329	489,083	2,942,713	460,714	2,859,201

2.2.6. Minimum and Maximum Pumping Rates (Term 6 and 7)

Groundwater pumping is a major water source for Central Valley agriculture. However, because of mechanical limitations on well depths and pumping equipment there are upper bounds on maximum monthly pumping rates. In the updated CALVIN model the maximum agricultural pumping capacity was chosen to be the maximum pumping volume seen between 1980 and 2009 in C2VSIM. In addition to the maximum constraint, some agricultural areas may have minimum pumping requirements because they lack infrastructure to receive surface water. In the updated CALVIN model, the minimum agricultural pumping capacity was chosen to be the minimum pumping volume seen between 1980 and 2009 in C2VSIM. Unfortunately, C2VSIM does not identify specific areas in California that only have access to groundwater so all of the updated minimum pumping constraints were 0 TAF/month (Zikalala 2012). The pre and post-update maximum and minimum agricultural pumping rates for each sub-region of the Central Valley are given in Table 2-7.

Table 2-7: Central Valley Subregion Monthly Groundwater Pumping Limits for Agricultural Demand Areas (from Zikalala, 2012)

	Maximum AG Pumping (TAF/Month)		Minimum AG Pumping (TAF/Month)	
CVPM	Old CALVIN	Updated CALVIN	Old CALVIN	Updated CALVIN
1	21	7	0	0
2	153	93	0	0
3	171	176	0	0
4	110	109	0	0
5	226	240	0	0
6	148	86	0	0
7	96	121	0	0
8	208	186	0	0
9	74	44	0	0
10	198	185	0	0
11	52	65	0	0
12	81	87	0	0
13	291	226	0	0
14	333	221	0	0
15	408	335	0	0
16	61	62	0	0
17	152	153	0	0
18	349	238	0	0
19	171	214	0	0
20	108	125	0	0
21	228	266	0	0
Total				
Sacramento	1207	1061	0	0
San Joaquin	622	563	0	0
Tulare	1810	1614	0	0
Central Valley	3639	3238	0	0

2.2.7. The Depth to Groundwater and the Pumping Cost (Term 8)

In CALVIN the groundwater pumping cost includes operating and maintenance costs for wells, including energy consumption. To estimate the pumping costs for CALVIN begin with the pumping lift, which is the distance from the groundwater surface to the ground surface or the distance over which the groundwater must be pumped. The pumping lifts were calculated based on actual DWR well depth measurements in the year 2000 for each Central Valley subregion. We include an estimated well drawdown to this pumping lift. The pumping unit cost must be adjusted to 2020 conditions as detailed in Appendix J and G. In CALVIN it is assumed that to lift 1 AF of groundwater 1 ft it costs $0.20 for the year 2000. By multiplying the 2020 adjusted pumping head by $0.20 we get the updated pumping cost in year 2000 dollars. However, for CALVIN costs are represented in 2008 dollars, so the 2000 cost must be multiplied by 1.296 to convert it to a 2008 cost. The pre and post-update pumping cost in 2008 dollars for each sub-region of the Central Valley are given in Table 2-8.

Table 2-8: Estimated Agricultural Pumping Costs (from Zikalala, 2012)

	GW Pumping Cost, 2008$ ($/AF)	
CVPM	Old CALVIN	Updated CALVIN
1	44.40	23.59
2	41.74	15.82
3	35.22	11.93
4	23.68	9.33
5	27.82	11.93
6	26.94	11.93
7	42.62	23.07
8	42.33	31.89
9	30.19	11.93
10	23.09	9.07
11	30.49	19.45
12	34.93	24.89
13	44.40	25.93
14	113.07	69.22
15	68.97	30.08
16	44.10	19.7
17	46.77	16.07
18	66.90	27.48
19	101.82	44.85
20	99.46	84
21	103.01	59.37

2.2.8. Surface Water Losses - Evaporation and Percolation to GW (Term 9)

California's surface water delivery infrastructure, such as aqueducts and canals, have some water losses. Surface water losses are divided into non recoverable, due to evaporation, and recoverable losses, due to percolation to groundwater. In CALVIN these two losses are lumped together and the total loss is represented by multiplying the diversion flow by an amplitude that is less than or equal to one. The recoverable portion of the losses is added separately to the net external inflow to groundwater described in section 2.4. In C2VSIM these losses are represented independently and, because of some differences in model construction, they may appear over several links, where in CALVIN they are combined into a single link. To update CALVIN many of these separate loss factors were summed together to match the CALVIN representation; for a full list of the C2VSIM loss factors used to update CALVIN see Appendix B of Zikalala (2012). The pre and post-update surface water loss amplitudes for diversions in each sub-region of the Central Valley are in Table 2-9. During calibration, some loss amplitudes were too small and were increased as shown in parentheses in column three.

Table 2-9: Surface Water Diversion Losses in the Old and Updated CALVIN Models (from Zikalala, 2012)

Central Valley Subregion	Old CALVIN Total Loss Amplitude	Updated CALVIN Loss Amplitude	CALVIN Links where losses occur
1	0.97	0.96	HSU1SR3_C3
	1	0.88 (1)	T41_Ext: Redding & T41_Int: Redding
	0.97	0.95	HSU1D5_C3
	0.97	0.52	HSU1D74_C3
2	0.93	0.47 (0.88)	HSU2D77_C6
	0.93	0.64 (0.88)	HSU2C1_C6
	0.93	0.95	HSU2C11_C6
	0.93	0.88	HSU2C9_C6
3	0.95	0.9	HSU3C11_C302
	0.95	0.85	HSU3C13_C302
	0.95	0.88	HSU3D66_C303
	0.95	0.76 (0.88)	HSU3C305_C303
4	0.97	0.88	HSU4D30_C14
5	0.96	0.88	HSU5C35_C26
	0.96	0.52 (0.88)	HSU5C77_C26
	1	0.82 (1)	T61_Ext: Yuba and T61_Int: Yuba
	0.96	0.76 (0.88)	HSU5C80_C26
6	0.96	0.88	HSU5C83_C26
	0.93	0.76	HSU6C314_C17
	1	0.84	T14_ERes: Napa-Solano, T14_Ind: Napa-Solano and T14_IRes: Napa-Solano
	0.93	0.88	HSU6C16_C17
	0.93	0.59	HSU6C21_C17

7	0.93	0.88	HSU7D42_C34
	0.93	0.64 (0.88)	HSU7C33_C34
	0.93	0.88	HSU7C67_C34 (Include diversions from Butte Creek & Little Chico)
8	1	0.76 (1)	T4_Ext: Sacramento and T4_Int: Sacramento
	1	0.94 (1)	T43_Ext: CVPM8 and T43_Int:CVPM8
	0.92	0.76 (0.88)	HSU8C173_C36
	0.92	0.88	HSU8C37_C36
	0.92	0.76 (0.88)	HSU8D98_C36
9	1	0.88 (0.93)	HSU9D507_C68
	1	0.93	HSU9D521_C68 and HSU9D515_C68
10	0.9	0.82	HSU10C10_C84
	0.9	0.93	HSU10C30_C84
	0.9	0.82	HSU10D731_C84
	0.9	0.88	HSUD803_C84 (IN CALVIN as CA Aqueduct, Harvey Bank Pumping Station, should confirm this)
	0.9	0.93	HSU10C85_C84
11	0.8	0.64 (0.82)	HSU11D16_C172
	1	0.7 (1)	T45_Ext:CVPM11 and T45_Int:CVPM11
	0.88	0.82	HSU11D672_C172
	0.88	0.82	HSU11D662_C172
	0.88	0.82	HSU11D664_C172
	0.88	0.82	HSU11D689_C172
12	0.9	0.82	HSU12D664_C45
	1	0.76 (1)	T66_Ext:CVPM12 & T66_Int:CVPM12
	0.9	0.82	HSU12D662_C45
	0.9	0.82	HSU12D645_C45
	0.9	0.82	HSU12D649_C45
	0.9	0.82	HSU12D699_C45
13	0.9	0.94	HSU13D606_C46
	0.9	0.82	HSU13D649_C46
	0.9	0.82	HSU13D645_C46
	0.9	0.75 (0.88)	HSU13C72_C46
	0.9	0.82	HSU13D634_C46
	0.9	0.82	HSU13D624_C46
	0.9	0.82	HSU13D694_C46
	0.9	0.75 (0.88)	HSU13D731_C46
14	0.9	0.82	HSU14D608_C91
	0.9	0.93	HSU14C92_C91
	1	0.94	D750_Ext:CVPM14

15	0.84	0.8	HSU15C52_C90
	0.84	0.82	HSU15D608_C90
	0.84	0.93	HSU15C75_C90 (CALVIN as CA Aqueduct, name for State is CA Aqueduct and Fed operation refers to San Luis Canal)
	0.84	0.93	HSU15C49_C90
16	0.8	0.82	HSU16D606_C50
	0.8	0.85	HSU16C53_C50
	0.8	0.93	HSU16C49_C50
	1	0.88 (1)	T24_Ext: City of Fresno and T24_Int: City of Fresno
17	0.9	0.8	HSU17C53_C55
	0.9	0.93	HSU17C76_C55
18	0.9	0.83	HSU18C56_C60
	0.9	0.83	HSU18C58_C60
	0.9	0.93	HSU18C688_C60
	1	0.94 (1)	C688_T51 (New supply for 2100 from FKC to CVPM18)
19	0.9	0.92	HSU19C73_C100
	0.9	0.93	HSU19D847_C100 and HSU19D850_C100
	0.9	0.93	HSU19C62_C100
	0.9	0.93	HSU19C74_C100
20	0.9	0.84	HSU20C65_C63
	0.9	0.93	HSU20C64_C63
	0.9	0.93	HSU20C74_C63
	1	0.88	T53_Int:CVPM20 and T53_Ext:CVPM20
21	0.8	0.9	HSU21C65_C66
	0.8	0.93	HSU21C689_C66
	0.8	0.93	HSU21C74_C66
	1	0.94 (1)	T28_Int:Bakersfield and T28_Ext:Bakersfield

2.2.9. Artificial Recharge - Operating Costs and Infiltration Factor (Terms 10 and 11)

Artificial Recharge is water that is purposefully added to aquifers to increase groundwater storage. Facilities for Artificial Recharge are present in subregions 13 and 15 through 21 of the Central Valley. Old CALVIN did not represent artificial recharge in these regions, so these capabilities were added with the updates. The infiltration factor for artificial recharge was chosen to be 95 %, the same as in C2VSIM, with a 5 % non-recoverable loss. The operating cost for all artificial recharge facilities was calculated as $6.5/AF, including the cost of facility operations and the opportunity cost for the land. The new artificial recharge capabilities represented in CALVIN are summarized in Table 2-10.

Table 2-10: Description of Artificial Recharge in CALVIN (from Zikalala, 2012)

CALVIN Groundwater Basin	CALVIN Link	Diversions for Spreading	Annual Average Artificial Recharge in C2VSIM (TAF/Yr)	Operating Cost ($/AF)
GW-13	HAR13_GW-13	Chowchilla R riparian & Fresno R riparian	4	6.5
GW-15	HAR15_GW15	Kings R	138	
GW-16	HAR15_GW16	Kings R & Friant-Kern Canal	24	
GW-17	HAR15_GW17	Kings R & Friant-Kern Canal	23	
GW-18	HAR15_GW18	Kaweah R, Tule R riparian & Friant-Kern Canal	178	
GW-19	HAR15_GW19	California Aqueduct, Kern R and Friant-Kern Canal	79	
GW-20	HAR15_GW20	Kern R, Friant-Kern Canal & Cross-Valley Canal	66	
GW-21	HAR15_GW21	Kern R, California Aqueduct, Friant-Kern Canal & Cross Valley Canal	208	

2.2.10. Urban Return Flow to Groundwater (Term 12)

In urban areas, some of the water delivered to meet demands will be consumed while the rest returns to groundwater or surface water. In CALVIN these return flows are calculated by multiplying the water delivered to urban areas by amplitudes that separate return flow to surface and ground water. The calculations to update these amplitudes based on C2VSIM results are similar to those described in section 2.1. The CVGSM and C2VSIM urban return flow amplitudes for each sub-region of the Central Valley are in Table 2-11. In C2VSIM it is assumed that in the Sacramento region all urban water returns to surface water, while other Central Valley return flows become groundwater.

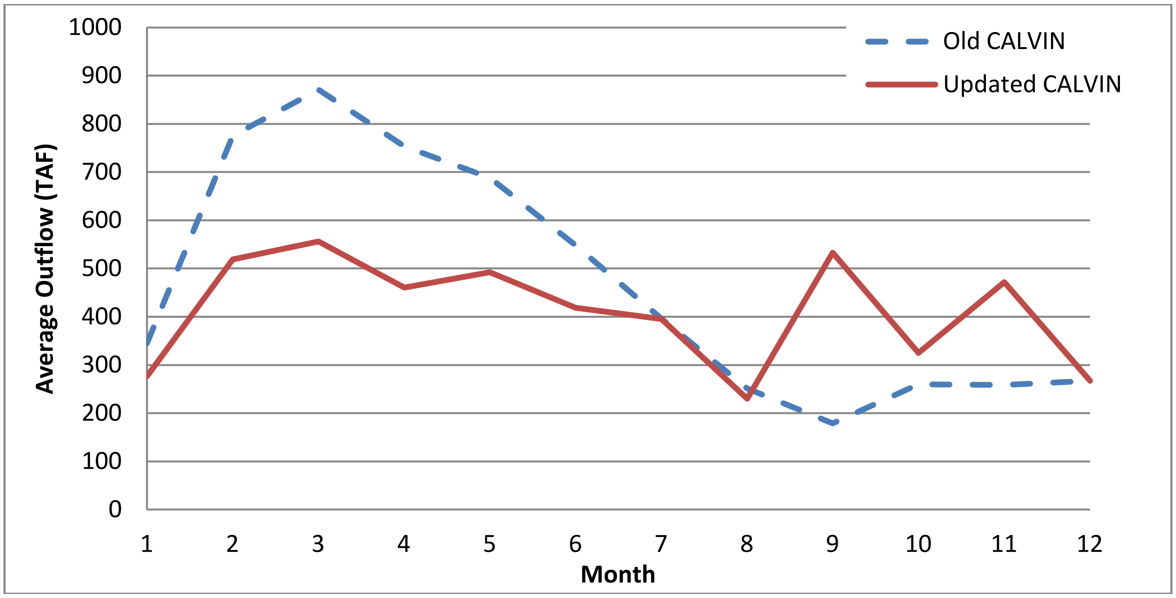
Table 2-11: Central Valley Amplitude for Urban Return Flow of Applied Water (from Zikalala, 2012)

	Amplitude of Urban Return Flow			
	to Groundwater		to Surface water	
CVPM	CVGSM	C2VSIM	CVGSM	C2VSIM
1	0.501	0	0	0.496
2	0.522	0.001	0	0.521
3	0.503	0.001	0	0.495
4	0.504	0.001	0	0.497
5	0.515	0.001	0	0.508
6	0.533	0.004	0	0.524
7	0.006	0.002	0.53	0.519
8	0.005	0.002	0.522	0.532
9	0.524	0.001	0	0.524
10	0.528	0.455	0	0
11	0.537	0.477	0	0
12	0.528	0.474	0	0
13	0.526	0.464	0	0
14	0.512	0.452	0	0
15	0.51	0.449	0	0
16	0.005	0.476	0.516	0
17	0.522	0.471	0	0
18	0.528	0.468	0	0
19	0.512	0.448	0	0
20	0.518	0.5	0	0
21	0.005	0.465	0.514	0

2.3. Updates to Delta Outflow and Delta Pumping constraints

The San Joaquin Delta is vital to the state's water resource infrastructure and the state's ecosystem. Because of its importance, minimum Delta outflows are required in each month. In CALVIN this environmental requirement is modeled through a minimum outflow constraint that forces the model to constantly release water into the San Francisco Bay. The Delta outflow requirement is modeled as time series that dictates the minimum amount of water that must be released from delta each month. The State Water Project Delivery Reliability Report of 2011 (DWR, 2011) provides a basis for updating CALVIN’s Delta constraints. To update this constraint it was decided to simply replace the current constraint time series with the time series of minimum outflows used in the CalSim II model. CalSim II was used to support DWR's 2011 reliability report and therefore already included the suggested updates to the Delta Outflow constraint. Figure 2-3 presents the average pumping capacity at Bank's pumping plant in both the old and new CALVIN models.

Figure 2-3: Average Monthly Required Delta Outflow in CALVIN, Before and After the Updates



In addition to the updated Delta outflow requirements, diversions from the Delta had to be restricted as well. Delta exports refer to water pumped south through the Banks and Tracy pumping plants into the southern Central Valley or to Southern California. To restrict the southern exports the maximum pumping capacity at Banks was updated to match the maximum capacity seen in CalSim II; Tracy was left untouched. In old CALVIN the Banks monthly capacity was dictated by a varying time series, but with the updates the Bank's capacity is now constrained by a set of upper bounds for each month. A comparison of the average Banks pumping capacities for each month appears in Table 2-12.

Table 2-12: Average Pumping Capacity at Bank's, Before and After the Updates

	Average Bank's Pumping Capacity in Old CALVIN	Average Bank's Pumping Capacity in Updated CALVIN
Month	TAF	
January	523	472
February	476	426
March	523	472
April	506	457
May	523	472
June	506	457
July	523	472
August	523	472
September	506	457
October	523	472
November	506	457
December	523	472
Annual	6161	5558

2.4. Updates to Agricultural Demands of the Central Valley

The Central Valley has extensive agricultural production and copious water deliveries are needed to sustain it. In the new CALVIN base case these agricultural demands were updated based on the latest runs of SWAP (the Statewide Agricultural Production Model). These updates reflect recent improvements to the SWAP model that include greater discretization of Central Valley subregions 3,10,14,15,19, and 21 to more accurately represent crop production in those areas. For more information on the SWAP model, see Howitt et al. (2012). Table 2-13 presents the annual average agricultural demands used in old and new CALVIN for each Central Valley subregion.

Table 2-13: Annual Average Ag Demands, Before and After the Updates

	Annual Average Ag Demands (TAF/Yr)	
CVPM	**Old CALVIN**	**Updated CALVIN**
1	126	139
2	497	473
3	2196	1315
4	956	884
5	1313	1485
6	619	732
7	429	413
8	802	737
9	926	1208
10	919	1403
11	855	777
12	772	760
13	1506	1679
14	1358	1129
15	1701	1828
16	345	368
17	797	739
18	1759	2119
19	887	842
20	829	640
21	1195	999
Total		
Sacramento	7864	7386
San Joaquin	4052	4620
Tulare	8871	8664
Central Valley	20787	20670

Chapter Three: The Updated CALVIN Model, with Improved Central Valley Groundwater Representation

3.1. Introduction

This report compares in some detail how the latest updates have affected the CALVIN model's optimized operation of California's water resource system. To determine how the updates changed the optimum solution, the current base case (S07I18) will be compared to the previous base case (R17I03). The comparison of the new and old CALVIN runs focuses on economic and water delivery results, but also examines groundwater storage throughout the Central Valley and the effects of environmental constraints, such as required Delta outflow. In addition, the updated base case is compared with a no overdraft case (S07I19) to explore how California's water resource system responded when Central Valley overdraft is prevented. The work presented here is based on the updates, calibrations, and modeling conducted in Zikalala (2012) and Chou (2012). Zikalala and Chou performed similar comparisons, but those comparisons were narrower and more focused.

Several trends can be seen in the updates themselves, including:

- Banks pumping capacity and required Delta outflow decreased
- Agricultural demands are reduced in Sacramento and Tulare, but increased in the San Joaquin basin
- Groundwater agricultural pumping capacity and pumping cost are reduced overall
- Agricultural water reuse rates are drastically reduced across most of the Central Valley
- Groundwater storage capacity increased
- Agricultural return flow split to groundwater increased (decreasing return to surface water), but total return flow amounts are reduced
- Groundwater inflows are reduced

The runs compared are S07I18 with R17I03 and S07I18 with S07I19. S07I18 is the latest CALVIN base case model run which slightly differs from the ones used in Chou (2012) and Zikalala (2012). In Chou (2012) the updated base case was S07I14, but it was later determined that the artificial recharge node for CVPM 16 was not connected. In Zikalala the updated base case was S07I16, but afterwards it was decided to change the Delta outflow requirement to match the CALSIM II 2009 results completely. R17I03 is the pre-update base case used in Bartolomeo (2011). Finally, S07I19 is the same as S07I18 except that overdraft is prevented over the 72 year modeling period by setting ending groundwater storage equal to initial storage.

3.2. Comparison of Results

This section presents and discusses the differences between the updated and old CALVIN models and the updated base case and the no overdraft scenario.

3.2.1. Agricultural water Demands, Deliveries, and Scarcities

Table 3-1 shows the agricultural demands for each run over the primary regions of the Central Valley (Sacramento, San Joaquin, and Tulare) as well as Southern California. As part of these updates, the agricultural demands for the Central Valley were updated based on new SWAP results; Southern California demands were not updated. Overall the state agricultural water demand fell by only 0.5% (about 120 TAF/yr). However, for individual regions changes are more significant with the Sacramento and Tulare losing about 500 TAF and 200 TAF in annual agricultural demands, respectively, while the San Joaquin basin gained around 550 TAF in agricultural demands. Both the new CALVIN base case and the No Overdraft run used the same agricultural demands.

Figure 3-1 compares the agricultural demands from new and old CALVIN for the 21 CVPM Central Valley regions. CVPM 1 through 9 are the Sacramento region, 10 through 13 make up the San Joaquin, and 14 through 21 form the Tulare. In the Sacramento region there were a few small gains and losses in most CVPM areas, with a large drop in CVPM 3, where 700 TAF of demands were eliminated. The San Joaquin basin had a significant increase of 500 TAF in CVPM 10 which explains most increase in the region's total demands. In the Tulare region, CVPM 15 and 18 had a total increase of about 400 TAF even though the region as a whole lost 200 TAF in demands. The demand, delivery, and scarcity data for all 21 CVPM and Southern California agricultural demand areas are given in Table A-1 of Appendix A.

Table 3-1: Annual Average Agricultural Demands by Region

	Old Calvin (R17I03)	New Calvin (S07I18)	
	Demand	**Change in Demand**	**Demand**
Agricultural Demand Area	TAF/yr	%	TAF/yr
Sacramento	7863.8	-6.1	7386.1
SJ and South Bay	4052.3	14.0	4619.8
Tulare	8871.2	-2.3	8664.1
Southern Cal	4308.6	0.0	4308.6
Central Valley	20787.3	-0.6	20670.1
Statewide	25096.0	-0.5	24978.7

Figure 3-1: Annual Average Agricultural Water Demands in Old and New CALVIN for each CVPM

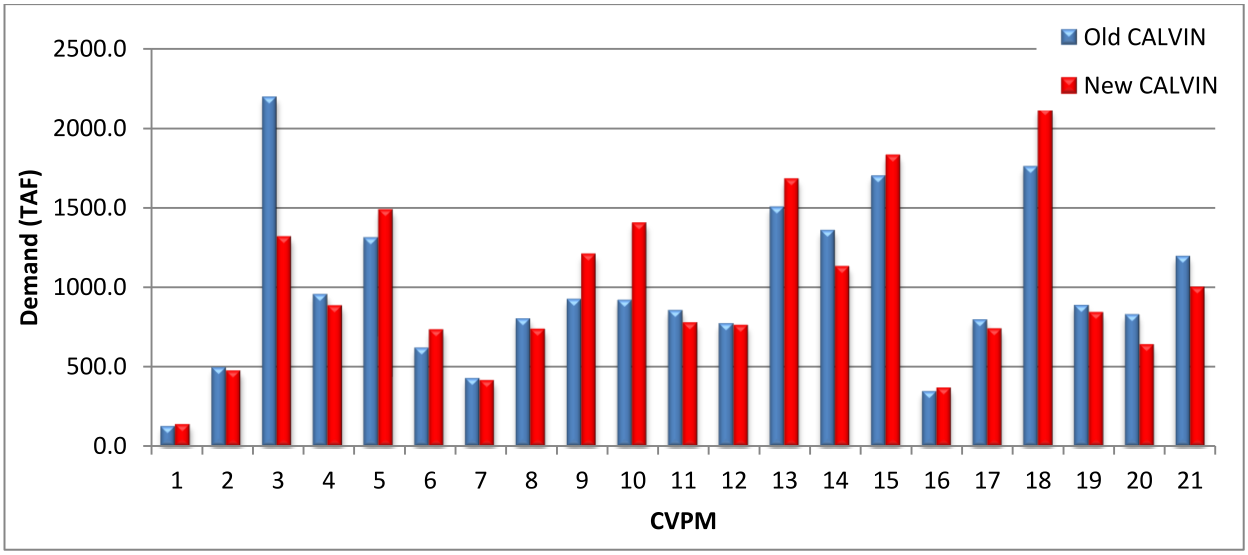


Table 3-2 gives the agricultural water deliveries for each run over each region and Table 3-3 shows the percent of the agricultural water demands satisfied. As a result of the updates, agricultural water deliveries statewide were reduced by 1.8 %, or about 450 TAF annually. The overall change is just the net change in deliveries. Sacramento and Tulare lost about 450 and 400 TAF of deliveries respectively, while the San Joaquin gained 450 TAF. In the end, the overall percent of demands met is smaller in the updated CALVIN. Why did deliveries fall when the demand was reduced as well, shouldn't this mean that there was more water available to meet excess demands? In the old CALVIN base case the model had too much water in the system to begin with. It originally required about 2 MAF of water to be removed at calibration nodes. In the new base case this calibration water has been eliminated so deliveries are likely to be reduced. This was a major reason for these updates.

As expected when overdraft is prevented, deliveries fall in all Central Valley regions since less groundwater supplies are available. Most reduction comes in the Sacramento basin, most likely as water is shipped south to meet more valuable demands south of the Delta where ground water was more valuable. When referring to no overdraft, it means no net overdraft over a 72 year model run. Any given year can have overdraft as long as it is replaced at some point in the future. This encourages conjunctive use with groundwater being drawn down in dry years and refilled in wet years.

Table 3-2: Annual Average Agricultural Deliveries by Region

	Old Calvin (R17I03)	New Calvin (S07I18)		No Overdraft (S07I19)	
Agricultural Demand Area	**Delivery**	**Change in Delivery**	**Delivery**	**Change in Delivery**	**Delivery**
	TAF	%	TAF	%	TAF
Sacramento	7848.8	-5.9	7382.0	-1.9	7242.7
SJ and South Bay	4030.3	10.9	4470.8	-0.5	4448.0
Tulare	8871.2	-4.7	8457.7	-1.5	8334.6
Southern Cal	3339.3	0.0	3339.3	0.0	3339.3
Central Valley	20750.3	-2.1	20310.5	-1.4	20025.3
Statewide	24089.6	-1.8	23649.8	-1.2	23364.5

Table 3-3: Percentage of Agricultural Demands met by Region

	Old Calvin (R17I03)	New Calvin (S07I18)	No Overdraft (S07I19)
Agricultural Demand Area	**Demands Met**	**Demands Met**	**Demands Met**
	%	%	%
Sacramento	99.8	99.9	98.1
SJ and South Bay	99.5	96.8	96.3
Tulare	100.0	97.6	96.2
Southern Cal	77.5	77.5	77.5
Central Valley	99.8	98.3	96.9
Statewide	96.0	94.7	93.5

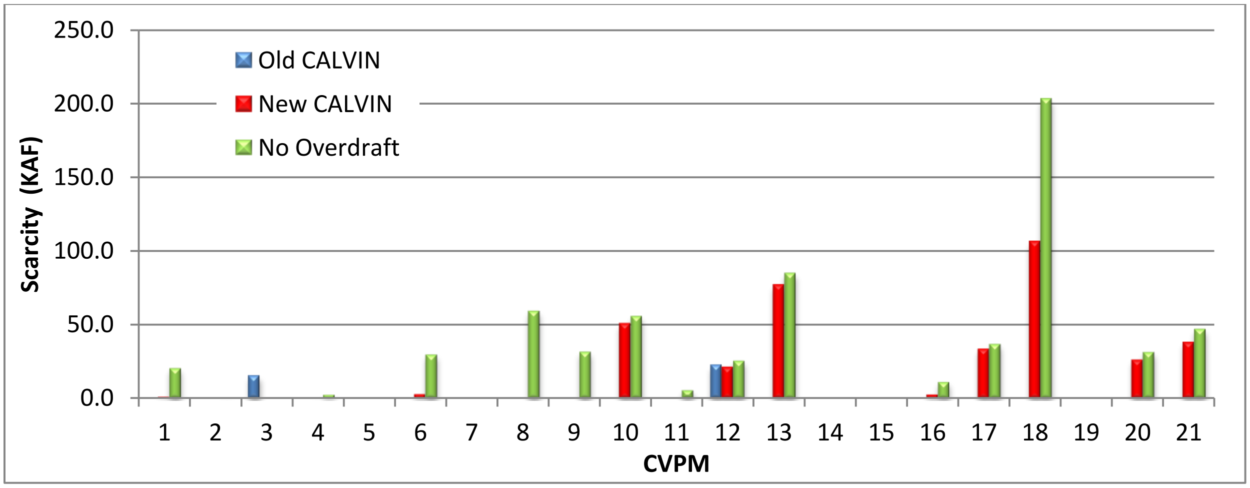
Table 3-4 shows the annual agricultural scarcity (demand - delivery) in each region. The Sacramento Valley actually has slightly less scarcity in the updated CALVIN than in old CALVIN. This could be related to the decrease in Banks pumping plant capacity, which makes it easier to meet north of Delta demands, but more difficult to meet the demands south of the Delta. Demands also fell significantly in the Sacramento Valley, making them easier to meet despite the overall decrease in water availability. Overall there is more scarcity due to the reduced, but more accurate, water supplies. Without the ability to overdraft there is further reduction in groundwater availability and scarcity increases over all regions of the Central Valley. The Tulare basin, which heavily depends on groundwater, sees the largest increase in scarcity for both cases.

Looking at Figure 3-2 we see a comparison of the scarcity for each CVPM demand area in all three runs. In old CALVIN the only scarcity is in CVPM 3 and 12. In the new model the scarcity in CVPM 3 disappears since the demands for that area were 700 TAF lower, which leaves the Sacramento region with very little water scarcity. The demand area with the greatest increase in agricultural water scarcity is CVPM 18, which now has over a 100 TAF of scarcity. CVPM 18 has the highest agricultural demand in the new CALVIN model and it also contains the Visalia Urban area and the Pixley wildlife refuge which reduce supplies available to agriculture. In the No Overdraft case the scarcity for CVPM 18 almost doubles to over 200 TAF since groundwater use is more restricted and surface water supplies need to be used more efficiently. Most other CVPM areas in the San Joaquin and Tulare regions that had scarcity in new CALVIN have only slight increases in the No Overdraft case. On the other hand, Sacramento sees increased scarcity in several areas as more water is being sent south to Delta pumping plants.

Table 3-4: Annual Average Agricultural Scarcity by Region

	Old Calvin (R17I03)	New Calvin (S07I18)	No Overdraft (S07I19)
Agricultural Demand Area	**Scarcity** TAF	**Scarcity** TAF	**Scarcity** TAF
Sacramento	15.0	4.1	143.5
SJ and South Bay	22.0	149.0	171.8
Tulare	0.0	206.5	329.6
Southern Cal	969.4	969.4	969.4
Central Valley	37.0	359.6	644.8
Statewide	1006.4	1328.9	1614.2

Figure 3-2: Annual Average Agricultural Scarcity for each CVPM Demand Area



For Urban demands, deliveries, and scarcities there was almost no change from Old CALVIN in either the updated model or the no overdraft case. Urban demands are more economically valuable than agricultural demands, so any additional scarcity between runs will be allocated to agricultural areas first. Table 3-5 gives the urban demands, deliveries, and scarcities over each region. The only area with any increase in urban scarcity was in Southern California, but this was very small. It is most likely caused by the decrease in Banks pumping plant capacity since Southern California receives a significant portion of its water supply from the north. The small increase in scarcity primarily occurs over San Bernardino and the E&W MWD. See Table A-2 of Appendix A for urban water demands, deliveries, and scarcities for each demand area.

Table 3-5: Urban Water Demands, Deliveries, and Scarcities

	Demands	Old Calvin (R17I03)		New Calvin (S07I18)		No Overdraft (S07I19)	
		Delivery	Scarcity	Delivery	Scarcity	Delivery	Scarcity
Urban Demand Area	TAF	TAF	TAF	TAF	TAF	TAF	TAF
Sacramento	1608.6	1608.6	0.3	1608.4	0.3	1608.4	0.3
SJ and South Bay	1571.4	1571.6	0.0	1571.4	0.0	1571.4	0.0
Tulare	1082.0	1082.2	0.0	1082.1	0.0	1082.0	0.0
Southern Cal	7041.4	6845.7	195.7	6845.7	195.7	6843.5	197.9
Central Valley	4262.0	4262.4	0.3	4261.9	0.3	4261.9	0.3
Statewide	11303.4	11108.1	195.9	11107.6	196.0	11105.3	198.2

3.2.2. Willingness to Pay

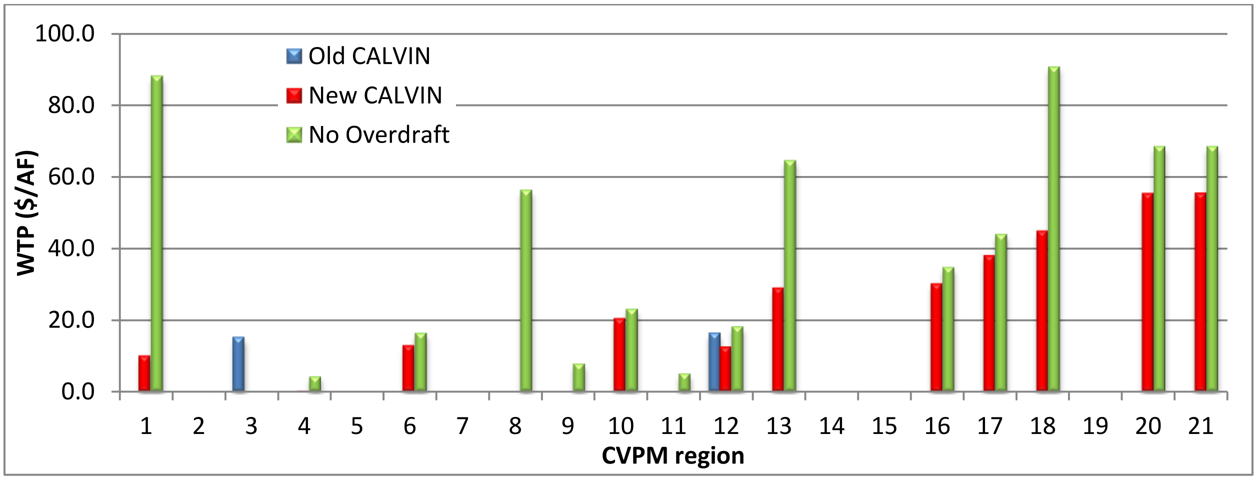
The willingness to pay (WTP) for an urban or agricultural demand area represents the amount of money users in that area would be willing to pay for 1 additional acre-ft of water. Figure 3-3 gives the annual average WTP for each Central Valley agricultural demand area and Table 3-6 shows the average maximum WTP for agricultural water in each region. In Old CALVIN there was very little WTP in the Central Valley, primarily because there was little scarcity. With the updated Central Valley hydrology and Delta constraints, water scarcity and WTP increased. The largest WTP values occur in the Tulare region where water supplies are most limited and reliance on Delta water exports is highest. San Joaquin also sees greater WTP after the updates. In the Sacramento region the average maximum WTP increases despite the total regional scarcity decreasing. On the Urban side there was almost no change in WTP except at the Castaic Lake Water Agency (CLWA), where it increased by 6 $/AF.

In the No Overdraft case the increased scarcity also increased WTP in all regions except Southern California which remains the same as in Old Calvin. Even the Sacramento region sees large increases in WTP for CVPM 1 and 8, which contain the urban demand areas Redding and Sacramento, respectively. This could mean that water originally going to agriculture has shifted to more valuable urban demands. Urban demand areas again have no change in WTP except in CLWA where it increased by another 35 $/AF. See Table A-3 and A-4 of Appendix A for agricultural and urban WTP data for all demand areas and Figures A-1 through A-3 for box plots of Average WTP for the Sacramento, San Joaquin, and Tulare regions.

Table 3-6: Average Maximum Sub-region Marginal WTP for Agricultural Water Deliveries

	Average Willingness to Pay ($/AF)		
	Old Calvin	New Calvin	No Overdraft
Sacramento	15.0	16.9	90.1
SJ and South Bay	16.1	31.4	67.0
Tulare	0.0	70.0	95.1
Southern Cal	640.4	640.4	640.4
Central Valley	21.6	70.0	125.9
Statewide	640.4	662.2	669.4

Figure 3-3: Annual Average Agricultural WTP for each CVPM Demand Area



3.2.3. Supply Sources

In managing the water supply it is important to know where the water being delivered comes from. Figure 3-4 shows the overall breakdown of deliveries, both agricultural and urban, in the Central Valley for each Calvin run. On the left are agricultural pie charts for water deliveries by type and from each run to the next we can see the proportion of groundwater used steadily dropping and at the same time the proportion of surface water used is growing. There is also a decrease in water reuse in response to the decreased agricultural reuse rates. In Old Calvin urban supplies were slightly dominated by groundwater use, unlike agricultural supplies which always favored surface water. With these updates, a bit more urban supply is taken from surface water. A small amount of desalination and water recycling occurs in some urban areas (discussed later).

Table 3-7 gives the breakdown of agricultural water deliveries from surface water, groundwater, and reuse water for each region. For surface water use there was a significant increase in all regions except Southern California, which remained unchanged. These increases were needed to balance the corresponding reduction in groundwater and reuse water. The Sacramento region had the most change, using 1 MAF more surface water as it cut groundwater use by 1 MAF/yr and its reuse by 250 TAF. The San Joaquin and Tulare regions both increased surface water use by about 300 TAF while reducing groundwater use by 70 TAF and 300 TAF, respectively. Water reuse rates have drastically fallen, with about a 75% reduction in reuse water for both the San Joaquin and Tulare. In the No overdraft case the shift from groundwater to surface water continues to grow in all regions as groundwater becomes more limited. The Sacramento region had a small drop in surface water deliveries, most likely because more of its surface water is being pumped south through the Delta. See Table A-5 of appendix A for agricultural supply breakdown for each agricultural demand area.

Table 3-7: Annual Avg. Supplies for Agricultural Deliveries by Region

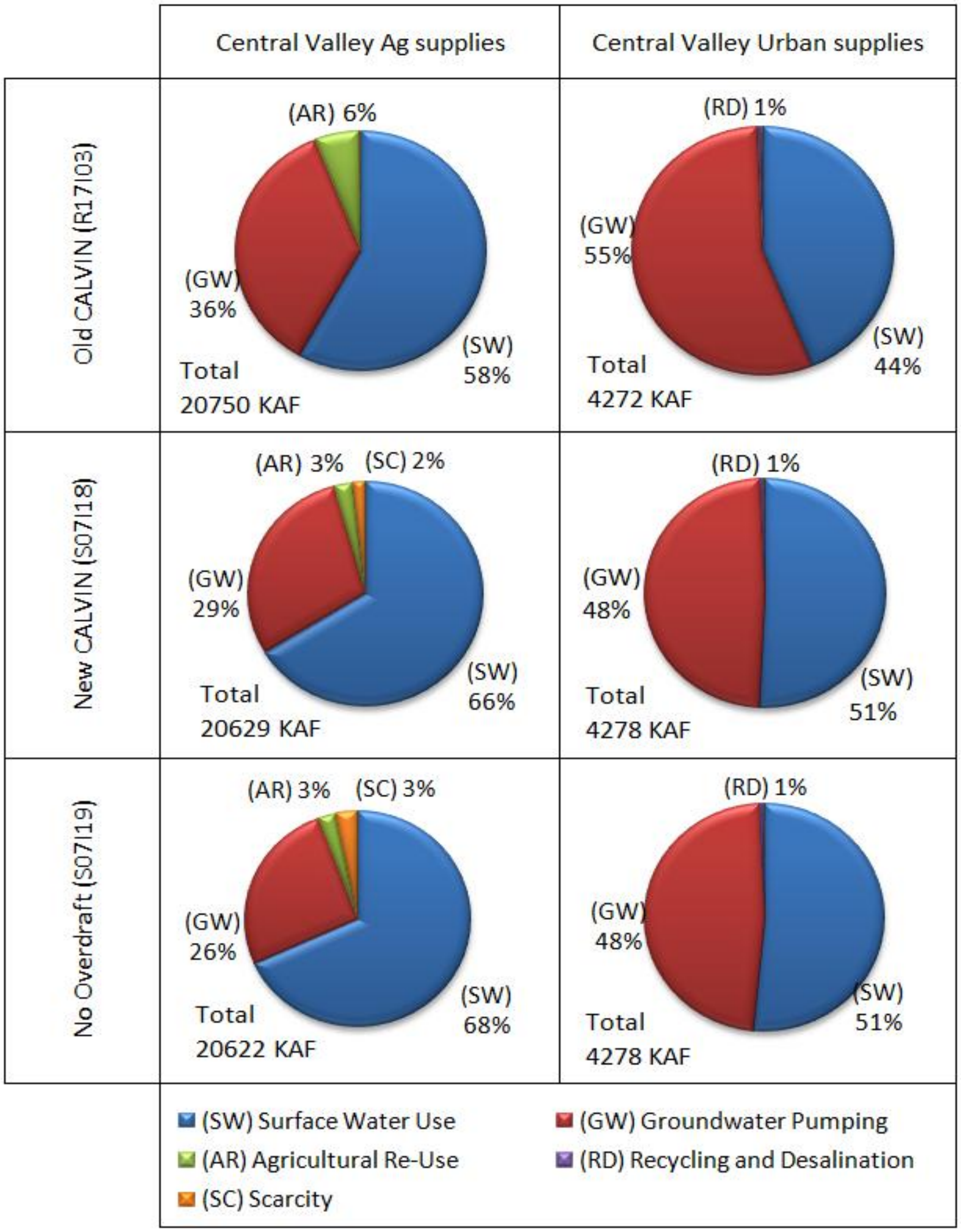
	Agricultural Surface Water TAF/yr			Agricultural Groundwater TAF/yr			Agricultural Reuse TAF/yr		
Region	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
North of Delta	4511	5528	5517	2406	1420	1290	658	383	382
SJ & South Bay	3012	3303	3470	1161	1089	900	303	78	78
Tulare	4533	4822	5083	3885	3590	3203	239	55	55
Southern Cal	3191	3196	3196	185	186	186	0	0	0
Central Valley	12057	13653	14071	7452	6100	5392	1201	517	515
Statewide	15248	16849	17266	7637	6286	5578	1201	517	515

On the Urban side, see Table 3-8, there is also a shift from groundwater use to surface water, although it is not as large as the shift in Agricultural supplies. Most of the shift is in the Sacramento region, and about 90% of it is in the Sacramento urban demand area itself where surface water took over 250 TAF of deliveries previously supplied by groundwater. Overall, in the No Overdraft case surface water use slightly increases, all in the Sacramento region, while groundwater use slightly decreases. However, the Tulare region itself uses a little more groundwater than it did in New Calvin. There is also a 13 TAF increase in recycled water use for Antelope Valley due to reduced SWP deliveries. Desalination use did not change in any of the runs due to its high cost. Only Santa Barbara-San Luis Obispo employs any desalination, averaging about 18 TAF per year. SB-SLO is forced to use desalination primarily because the Coastal Aqueduct, which brings water from the California Aqueduct to the SB-SLO area, is not large enough to meet the demand and the area has no modeled access to groundwater, which may be inaccurate. See Table A-6 of appendix A for urban supply breakdown for each urban demand area.

Table 3-8: Annual Avg. Supplies for Urban Deliveries by Region

	Urban Surface Water TAF			Urban Groundwater TAF			Urban Recycling and Desalination TAF		
Region	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
North of Delta	991	1266	1341	618	345	269	7	8	9
SJ & South Bay	554	518	518	1000	1038	1038	16	16	16
Tulare	329	387	346	752	695	736	44	44	44
Southern Cal	4233	4228	4213	2188	2191	2191	191	192	205
Central Valley	1874	2171	2205	2370	2078	2043	67	68	69
Statewide	6096	6399	6418	4559	4269	4233	258	260	274

Figure 3-4: Central Valley Agricultural and Urban Water Supply Breakdown for each Run



3.2.4. Water Scarcity costs, Operating costs, and Hydropower benefits

As a hydro-economic model, the CALVIN model tries to allocate water in the most economically valuable or least costly manner, within constraints. This requires balancing the operating costs needed to run the system and the penalties of water shortages in demand areas. Maximizing hydropower and other benefits helps mitigate some of these costs. Figure 3-5 shows the shares of operating costs for the entire Central Valley. Surface water pumping costs include only those generated from pumping plants, or any CALVIN node that has a PMP in its name.

Other costs in this case include surface water pumping not at a pumping plant, water quality costs for urban southern California, and any unexplained costs. Originally, groundwater pumping generated about half of the cost for the Central Valley, but with the updates it only accounts for a quarter of the total costs. The reduction of groundwater pumping costs has reduced total regional operating cost to $1129.3M/yr, about 20% less than before, In the No Overdraft case, groundwater pumping costs are further reduced thanks to more limited supplies and surface water pumping increases as the system relies more heavily on Delta pumping.

Figure 3-5: Central Valley Operating Cost Breakdown for each Run

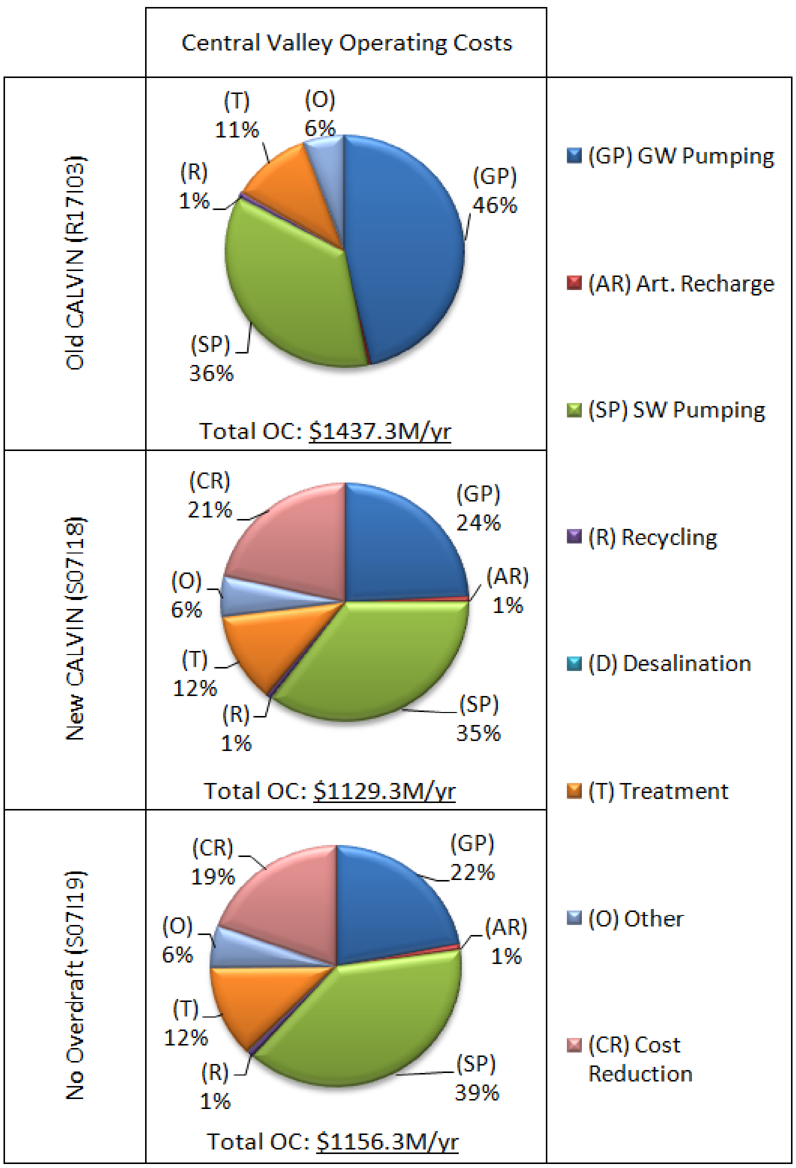


Table 3-9 shows operating costs in several categories for each region and model run. Most of the reduction in operating costs was due to reduced ground water pumping costs over all three regions, with the largest decrease in the Tulare, about $200M/yr. There are two reasons for lower groundwater pumping costs. First, unit pumping costs decreased for all regions in the updating (mostly due to lower estimated pumping heads) and, second, less groundwater is being used. Overall groundwater pumping costs are lower by almost 50 % of their per-update value. Despite increased surface water use, the cost of surface water pumping remained unchanged in all regions except the San Joaquin where it decreased by about $10M/yr, probably in response to the reduced Banks pumping plant capacity. Increased use of surface water for urban demands in the Sacramento region added about $15M/yr in treatment costs, mostly in the Sacramento demand area. Artificial recharge costs increased slightly in Tulare and the San Joaquin since it is now represented in those regions. As mentioned above, the desalination costs occur in SB-SLO because they lacked enough access to other water supplies.

With the No Overdraft constraint, operating costs increased by another $30M/yr. Most of the cost increase came from $60M/yr in additional surface water pumping costs, primarily at Banks and Tracy, but also at the Gianelli pumping plant so water could be stored in the San Luis Reservoir. With the constraints on overdraft, less groundwater could be used and groundwater pumping costs fell by another $30M/yr. There was also a small increase in Southern California water recycling costs from additional recycling in Antelope Valley.

Table 3-9: Annual Average Operating Costs for each Region

	GW Pumping	SW Pumping	Treatment	Art. Recharge	Desalination	Recycling	Other	Total
	$M/year							
Region	**Old Calvin**							
Sacramento	134.3	7.7	34.3	0.0	0.0	3.7	79.8	259.9
SJ & South Bay	99.9	252.3	110.0	7.1	0.0	8.1	0.0	477.4
Tulare	433.0	253.2	13.8	0.0	0.0	0.0	0.0	700.0
Southern Cal	148.5	150.4	655.3	12.5	37.2	193.0	976.6	2173.6
Central Valley	667.2	513.2	158.1	7.1	0.0	11.8	79.9	1437.3
Statewide	815.8	663.6	813.4	19.6	37.2	204.8	1056.4	3610.8
	New Calvin							
Sacramento	48.0	7.6	48.2	0.0	0.0	4.2	80.1	188.1
SJ & South Bay	72.9	243.1	107.4	7.3	0.0	8.1	0.0	438.8
Tulare	228.0	253.3	18.0	3.1	0.0	0.0	0.0	502.4
Southern Cal	148.5	150.4	655.3	12.5	37.2	193.4	976.7	2174.1
Central Valley	348.9	503.9	173.6	10.4	0.0	12.3	80.1	1129.3
Statewide	497.4	654.3	828.9	22.9	37.2	205.7	1056.8	3303.3
	No Overdraft							
Sacramento	38.2	7.5	54.2	0.0	0.0	4.5	80.2	184.8
SJ & South Bay	68.9	299.4	107.4	7.4	0.0	8.1	0.0	491.2
Tulare	210.1	251.4	15.0	3.8	0.0	0.0	0.0	480.3
Southern Cal	148.5	150.9	648.5	13.9	37.2	212.6	964.1	2175.8
Central Valley	317.2	558.4	176.6	11.3	0.0	12.6	80.3	1156.3
Statewide	465.7	709.3	825.1	25.2	37.2	225.2	1044.4	3332.1

Table 3-10 shows net system costs for each region and model run. Overall, with the updates, net system costs fell about $300 M/year throughout the Central Valley, with the largest regional decrease being about $200 M/year in Tulare. Sacramento costs fell by another $70 M/year and San Joaquin costs were reduced by $40 M/year. Most of these changes were from reductions in operating costs for each region. The agricultural scarcity costs increased in the Tulare and the San Joaquin, but fell in the Sacramento, leading to an overall increase of about $15 M/year. There was also a slight decrease in hydropower benefits for the Sacramento region and a small increase in benefits for the San Joaquin and in Southern California, for an overall increase of $5 M/year. Interestingly, hydropower benefits generated in the Sacramento Valley are enough to offset the region's total costs and make about $22.5 M/year.

When net overdraft is prevented, total system costs statewide rise by about $50M/year. This increase is split between increased agricultural scarcity penalties ($20 M/year) and increased operating costs ($30 M/year) in the Central Valley. On the Regional level operating costs increase in the San Joaquin but fall in Sacramento and Tulare, as discussed above. Urban scarcity costs increased by about $2 M/year, corresponding to the small increase in scarcity, also mentioned above. Finally, Hydropower benefits increased by about $4 M/year, most of which was in the San Joaquin region.

Table 3-10: Annual Average Net system Costs by Region

	Operating costs	Agricultural Scarcity Cost	Urban Scarcity Cost	Hydropower Benefits	Net System Costs
	$M/year				
Region	**Old Calvin**				
Sacramento	259.9	1.9	0.4	-214.8	47.4
SJ & South Bay	477.4	2.1	0.0	-39.1	440.5
Tulare	700.0	0.0	0.0	0.0	700.0
Southern Cal	2173.6	178.3	184.2	-460.1	2076.0
Central Valley	1437.3	4.1	10.4	-253.9	1187.8
Statewide	3610.8	182.4	184.5	-714.0	3263.8
	New Calvin				
Sacramento	188.1	0.2	0.4	-211.2	-22.5
SJ & South Bay	438.8	6.3	0.0	-43.3	401.8
Tulare	502.4	11.4	0.0	0.0	513.7
Southern Cal	2174.1	178.3	184.2	-465.0	2071.6
Central Valley	1129.3	17.9	0.4	-254.4	893.0
Statewide	3303.3	196.2	184.6	-719.4	2964.6
	No Overdraft				
Sacramento	184.8	9.9	0.4	-210.0	-15.0
SJ & South Bay	491.2	7.7	0.0	-48.8	450.2
Tulare	480.3	23.0	0.0	0.0	503.3
Southern Cal	2175.8	178.3	186.1	-464.3	2075.9
Central Valley	1156.3	40.6	0.4	-258.8	938.5
Statewide	3332.1	218.9	186.5	-723.1	3014.4

3.2.5. The Delta Response

The Sacramento-San Joaquin Delta is the central hub in California's water supply network and is vital for exporting water from the northern, water rich parts of the state to drier central and southern areas. The two primary pumping plants in the Delta that pump water south into the San Joaquin, Tulare, and Southern California regions are Banks and Tracy. The State Water Project's Banks pumping plant pumps water into the California aqueduct, which serves as the only connection between northern and southern California over the Tehachapi mountains, while the federal Central Valley Project's Tracy pumping plant sends water into the Delta Mendota canal. Table 3-11 shows upper bound constraints on both Banks and Tracy. Water from Tracy also can enter the California aqueduct by going through the O'Neill pumping plant and water from Banks can get to the Delta Mendota canal through the O'Neill power plant. The Delta also is important environmentally with hundreds of species of fish, birds, and other animals depending on it. To protect these species and local water quality for agricultural and urban users, a minimum monthly Delta outflow is required, given in Table 3-11.

In CALVIN there is a preference to pump water through Banks rather than Tracy, due to lower overall pumping costs at Banks. This may not be easy to see at first glance since direct pumping through Tracy is actually cheaper; Banks pumping costs $33.157/AF, while Tracy pumping costs $31.97/AF. However, once you add in the cost and benefit provided by the O'Neill PMP, Banks becomes cheaper. To pump into the California aqueduct from Banks costs $33.157/AF and to pump from Tracy it costs $ 31.97 + $6.66 = $38.63/AF. To pump into the Delta-Mendota canal from Tracy costs $31.97/AF and from Banks it costs $33.17 – $5.18 = $27.99/AF. Wherever the water goes Banks is preferred and thus Tracy will primarily be used when Banks is hitting an upper bound constraint.

Table 3-11: Delta Constraints

	Bank's Pumping Constraint		**Tracy Pumping Constraint**		**Total Delta Pumping Constraint**		**Minimum Delta Outflows**	
	Annual Average	Max	Annual Average	Max	Annual Average	Max	Annual Average	Max
Model	TAF/yr	TAF/mo	TAF/yr	TAF/mo	TAF/yr	TAF/mo	TAF/yr	TAF/mo
Old CALVIN	6158	523	2169	283	8327	806	5593	1713
New Calvin	5475	472	2169	283	7644	755	4944	1320

Table 3-12 summarizes Banks and Tracy pumping over all three Calvin runs and Table 3-13 shows total Delta pumping for the three runs. With the lower monthly pumping capacity, Banks overall average pumping falls by about 400 TAF/yr. At the same time Tracy pumping increases by about 300 TAF/yr to offset some of the reduction at Banks. In the No Overdraft case the southern Central Valley depends much more on surface water pumping from the Delta. To replace the lost groundwater, pumping through Banks increases by about 200 TAF/yr, while Tracy pumping almost doubles to 1500 TAF/yr. During droughts, in all cases, both pumping stations average less than their usual flow because northern areas have less water available to send south. During droughts, most areas use more groundwater, even in the no overdraft case. Overall, Banks hits its capacity constraint about 50% of the time in the new base case and 2/3 of the time in the No overdraft case; despite this, the marginal cost or values of expansion remains very small in all cases. On the other hand, Tracy almost never reaches its upper bound and has a very low value in expansion. Overall total Delta pumping fell with the updates by 40 TAF/yr and then increased by about 900 TAF/yr in the No Overdraft case. For reasons explained above, whenever capacity is reached at the Tracy pumping plant, Banks has already reached its capacity.

Table 3-12: Banks and Tracy Pumping Plant Usage for each CALVIN Run

	Overall Avg. Flow	Drought Avg. Flow	Non-Drought Avg. Flow	Marginal value of Capacity Expansion	Capacity Reached
	TAF/yr	TAF/yr	TAF/yr	$/AF/Month	% of Months
	Banks Pumping				
Old CALVIN	4906	4,059	5,111	1.43	49%
New CALVIN	4537	3,172	4,867	2.20	51%
No Overdraft	4709	3,370	5,032	5.42	66%
	Tracy Pumping				
Old CALVIN	462	122	544	0.01	1%
New CALVIN	788	374	888	0.26	6%
No Overdraft	1499	380	1,769	0.88	8%

Table 3-13: Total Delta Pumping for each CALVIN Run

	Total Delta Pumping			
	Overall Avg. Flow	Drought Avg. Flow	Non-Drought Avg. Flow	Capacity Reached on both Plants
	TAF/yr	TAF/yr	TAF/yr	Months
Old CALVIN	5368	4181	5655	1%
New CALVIN	5325	3546	5755	6%
No Overdraft	6208	3750	6802	8%

Figures 3-6, 3-7, and 3-8 give the average pumping through Banks, Tracy, and overall for the Delta for each month over each CALVIN run. In the older CALVIN most flow through Banks and all flow through Tracy occurred in the spring and summer, March to September. This has changed in the updated base case and the no overdraft case. For Banks, in both CALVIN runs, fall and winter flows have risen while spring and summer flows fell. The largest average monthly flow through Banks is now in January, which had the second smallest flow in old CALVIN. At Tracy in the updated base case most average monthly flows have increased or remained unchanged, except for March, and flows in May through August have risen significantly. For the No Overdraft case, the average Tracy pumping increased in all months, especially in late winter to early spring.

Winter pumping increased in the new base case because more water is available at that time. In Old CALVIN more water was available overall, so more water was available in the summer for seasonal Delta export demands. With the updates, that extra water is eliminated and Delta pumping is spread over more months. By pumping water in the winter when it is more abundant it can be stored somewhere along the California aqueduct for use in the summer when demands are highest. Most winter Delta diversions are stored in San Luis Reservoir.

In addition to the three CALVIN runs, monthly average flows from the CalSim II model are graphed. In CalSim II the average monthly flow at Banks is almost always smaller than in any of the CALVIN cases, while Tracy pumping is almost always larger than in any of the CALVIN cases. Average Tracy flows in CalSim II are still usually smaller than average Banks flows for the corresponding month, but the difference is nowhere near as large as in CALVIN's.

Figure 3-6: Average Banks Pumping each Month

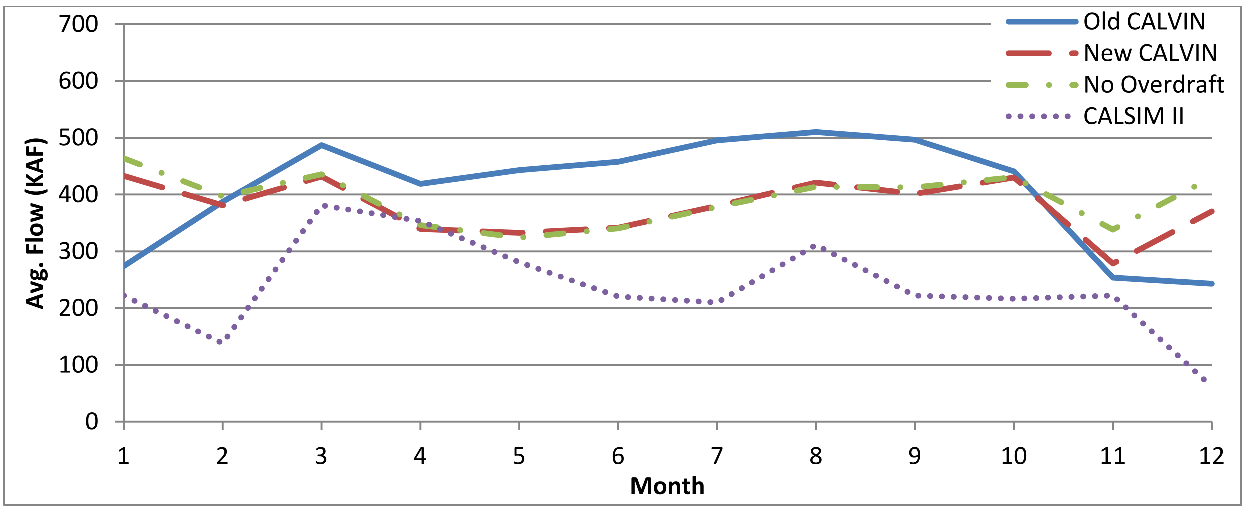


Figure 3-7: Average Tracy Pumping each Month

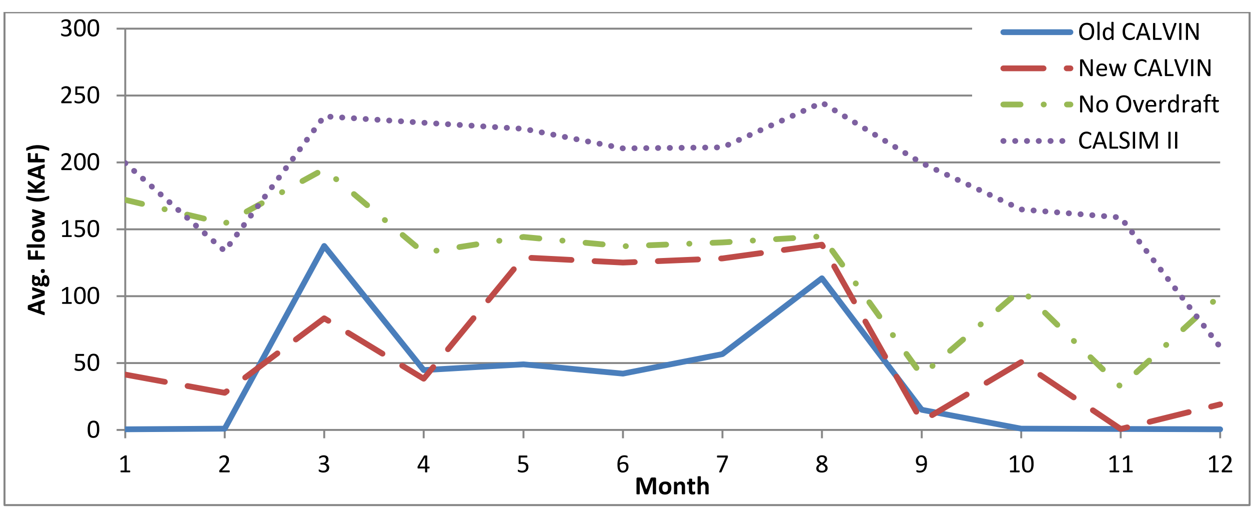
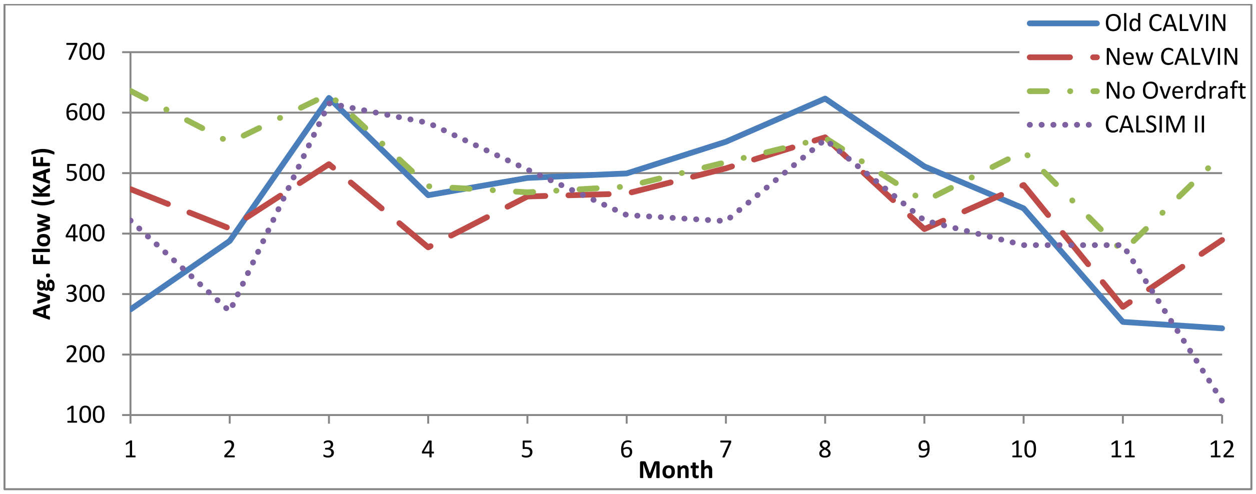


Figure 3-8: Average Total Delta Pumping each Month



3.2.6. Surface Water Storage

In California most rainfall occurs in winter while most water demand is in the summer. To make sure water is available in the summer it must be stored in reservoirs. Figures 3-9, 3-10 and 3-11 show average monthly surface reservoir storage over each region of the Central Valley for each CALVIN run. In the updated base case, Sacramento Valley average monthly storage fell in all months, with the largest decreases in the winter. Since more water is exported to drier regions in winter, less storage is needed. In the Tulare, storage remained mostly unchanged in the summer and fell in the winter. For the San Joaquin, unlike the other regions, there was increased storage in the spring. This increased storage is in San Luis Reservoir where the increased Delta exports from winter are stored for summer use. In the No Overdraft case the trends continue as groundwater becomes limited. Sacramento and Tulare both see a little more reduction in storage over all months, while San Joaquin storage has larger increases in spring storage and a significant drop in summer and early winter storage.

Figure 3-9: Average Monthly Storage over the Sacramento Region

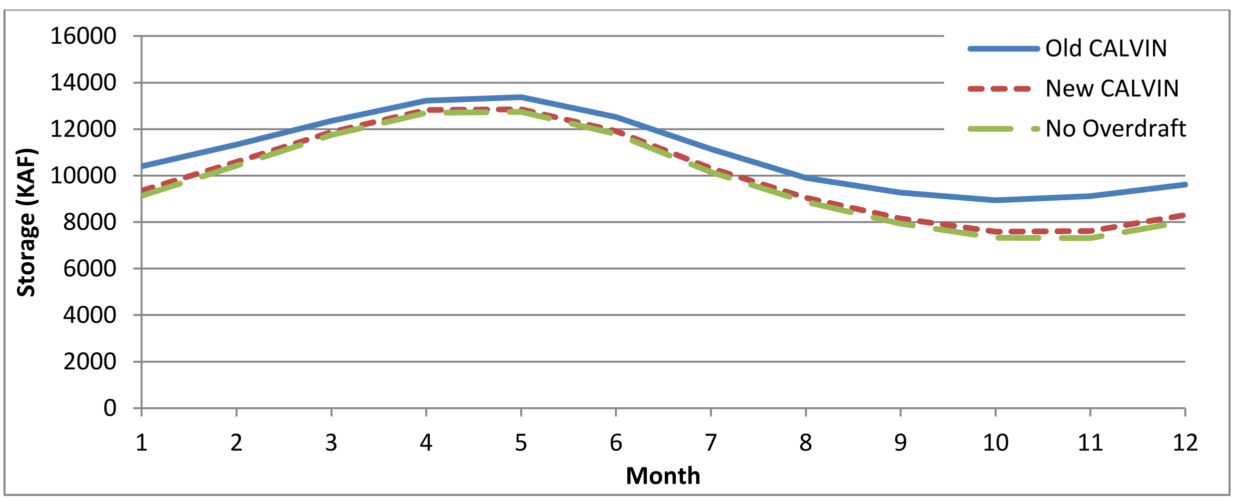


Figure 3-10: Average Monthly Storage over the San Joaquin Region

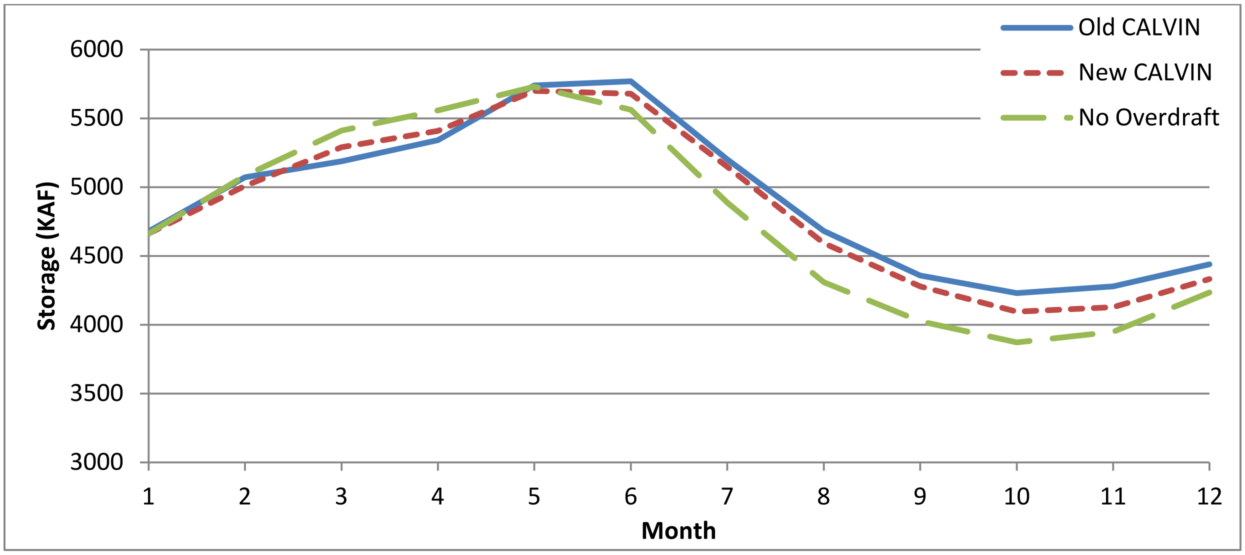


Figure 3-11: Average Monthly Storage over the Tulare Region

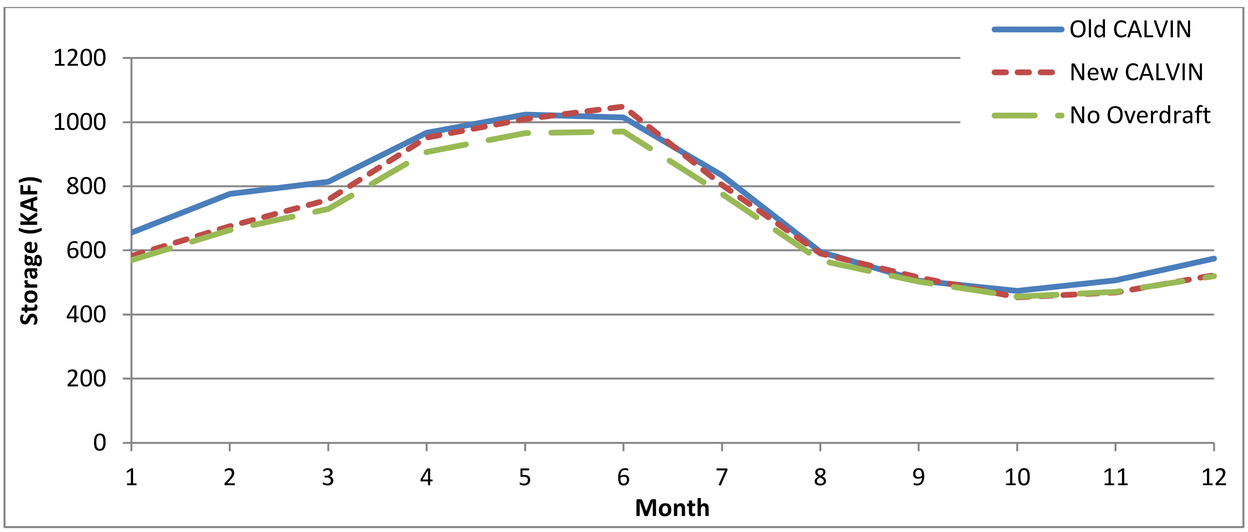
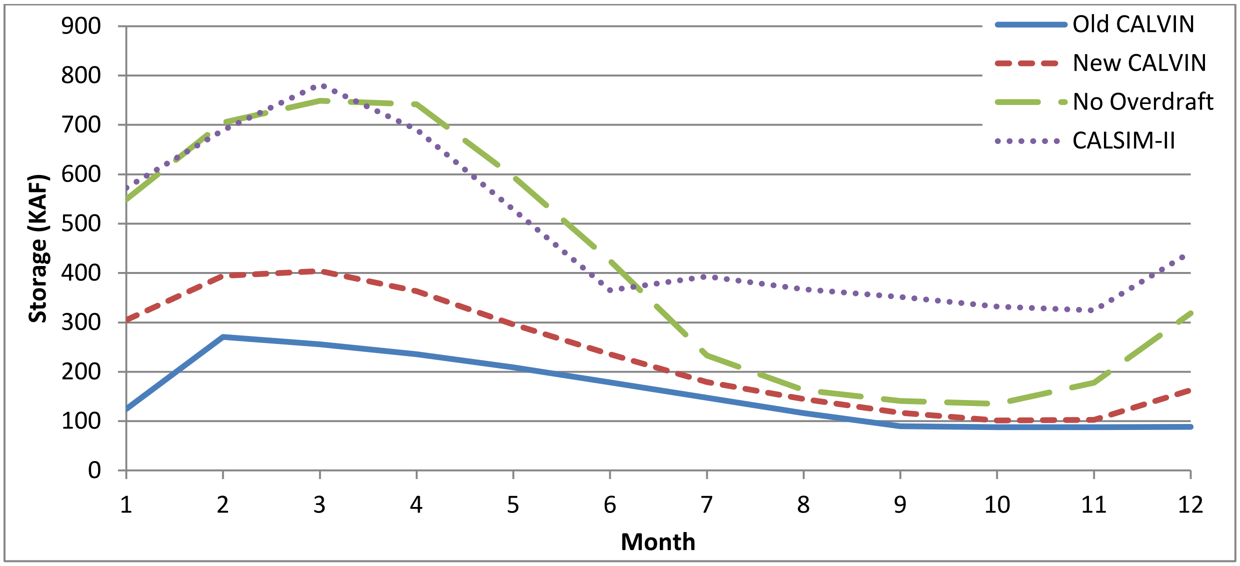


Figure 3-12 highlights the San Luis reservoir average storage by month over each CALVIN run and for CalSim II. The San Luis reservoir has a capacity of about 2 MAF and is supplied from the California Aqueduct through the Gianelli pumping plant. In the updated base case and in the No Overdraft case there was a large increase in the winter through spring storage. In Old CALVIN the reservoir was used exclusively to store water for Santa Clara urban demands, but since the updates it has become the primary storage location for winter Delta exports as mentioned above. CalSim II models the San Luis reservoir storage based on actual operations, and it best matches the results for the No Overdraft case; however, in CalSim II the storage remains around 375 TAF throughout the summer, while in CALVIN releases continue until storage drops 150 TAF.

Figure 3-12: Monthly Average Storage at San Luis Reservoir



3.2.7. Southern California

Even though all updates occurred in the Central Valley, there are effects in Southern California. Figure 3-13 plots the average imports into Southern California for each month, as measured at Edmonston pumping plant. In both the updated base case and the No Overdraft scenario, spring imports increase, while late summer and winter imports decrease. These new deliveries come in response to the shifted availability of Delta exports; since more water is pumped from the Delta in winter, it reaches Southern California in spring. However, rather than use this water in spring, the model stores it for the coming summer. Figure 3-14 gives the average reservoir storage in Southern California by month. There is about a constant 75 TAF increase in storage from March to June, mostly in Castaic Lake and Diamond Valley Reservoir, with a little in Pyramid Lake. Overall, annual average imports to Southern California are nearly the same in all three CALVIN runs (2032 TAF/yr in Old CALVIN, 2033 TAF/yr in New CALVIN, and 2018 TAF/yr in the "No Overdraft" case), which explains why scarcity remains unchanged in the region between runs. As was shown above the scarcity cost remains unchanged as well, signifying that the model still allocates water to the same demands.

In addition to the three CALVIN runs, monthly average imports to Southern California from CalSim II are graphed as well. Overall, the annual average imports in CalSim II measure 1568 TAF/yr, which is about 460 TAF less than in CALVIN. In CalSim II the pattern of imports is the opposite of that seen in CALVIN, with more imports made during the Spring and Summer before dropping off in the Fall and Winter.

Figure 3-13: Average Imports to Southern California from the Central Valley each Month

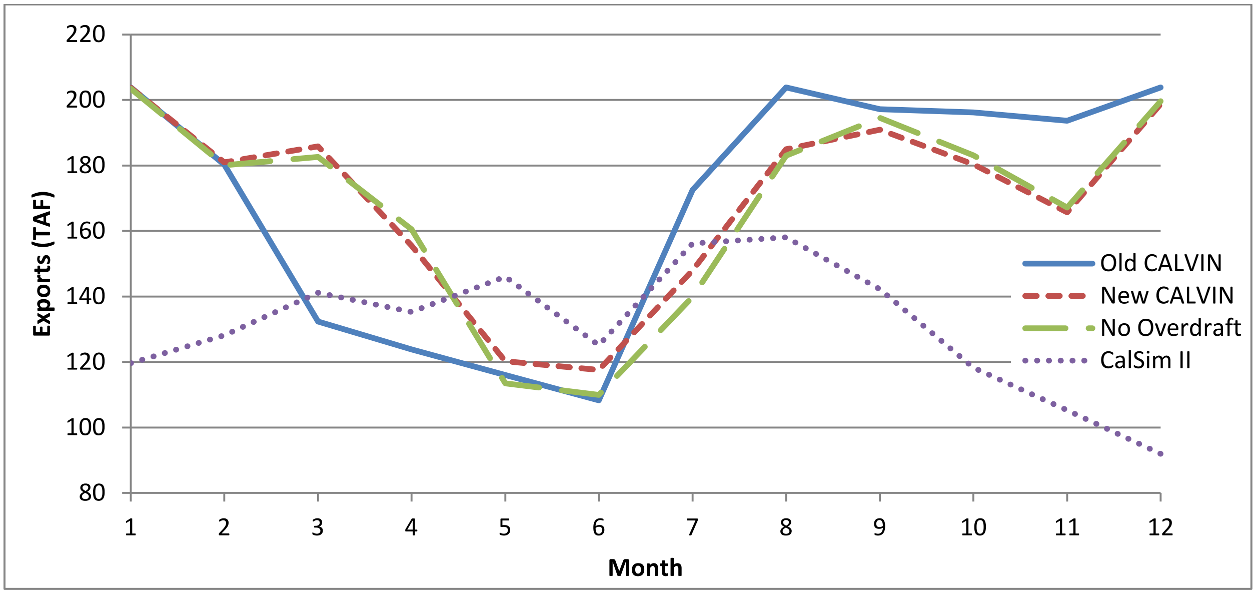
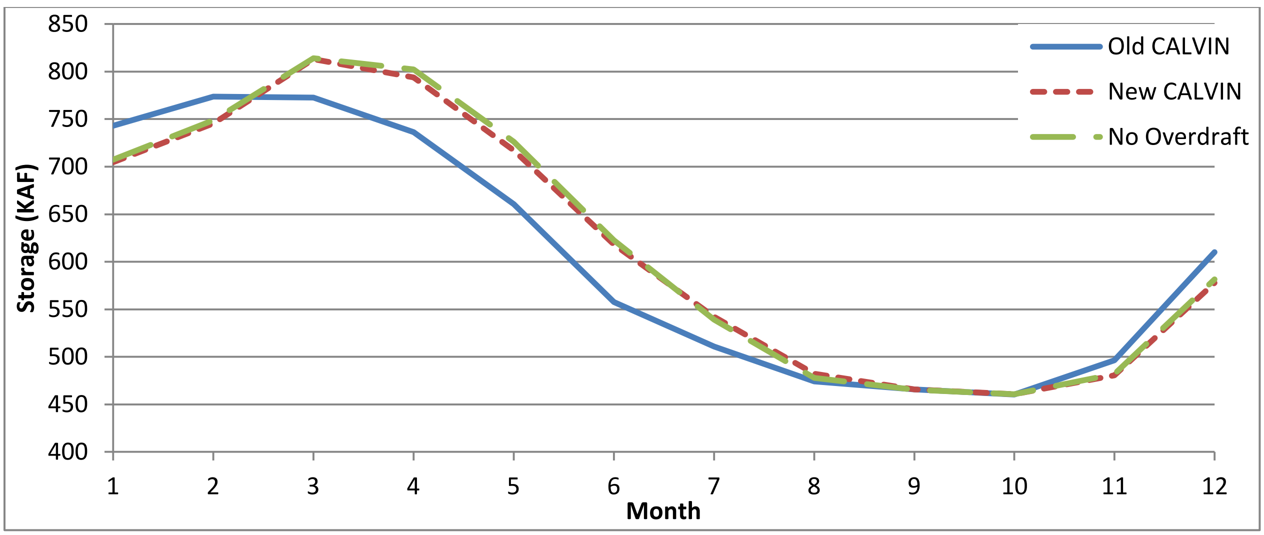


Figure 3-14: Average SW Storage in Southern California by Month



3.2.8. Groundwater Overdraft and Storage

Groundwater Overdraft refers to pumping more groundwater than will be refilled by natural and artificial means. Overdraft is a significant concern in the San Joaquin and Tulare basins where farmers supplement scarce surface water supplies with groundwater. Groundwater mining has led to significant problems in these regions such as subsidence, habitat destruction, increased pumping costs, and dried up wells. As of 2009 there was a reported 2 MAF per year of groundwater overdraft throughout California, primarily in the Tulare (California Department of Water Resources 2009). Various modeling efforts have estimated Tulare basin overdraft at about 1.2 - 1.6 MAF/year (Chou 2012). However, groundwater is an important water source during drought years when surface water availability decreases. Water districts are widely encouraged to adopt conjunctive use practices, to rely on groundwater during drought years and surface water during wet years. The most severe drought years represented in CALVIN are 1929-34, 1976-77, and 1987-92 along with several less severe droughts years between 1921 and 1992.

Figures 3-15, 3-16, and 3-17 plot total net groundwater storage change, recorded each year in October, for each Central Valley region over time. In these figures a negative change in groundwater storage signifies groundwater overdraft. Old CALVIN had much lower estimates of overdraft for the Central Valley from the 1997 CVGSM model. Most overdraft occurs during droughts, while in the years leading up to a drought overdraft decreases a little since CALVIN sees the drought coming and tries to prepare for it. The largest overdraft occurs during the first severe drought period from 1929-34 with 20 MAF of overdraft in Sacramento, 15 MAF in the San Joaquin, and 40 MAF in Tulare. Over the next 57 years, overdraft occurs more slowly. In the end there is about 15 MAF of overdraft in the Sacramento and the San Joaquin and 55 MAF in the Tulare. In the No Overdraft case early on there is still a large amount of overdraft, but there is also more recharge for the rest of the modeling period. Since there must be 0 net overdraft at the end of the 72 year period, the model must plan groundwater use so recharge balances out groundwater pumping. However, with hydrologic foresight, the model knows how much natural recharge it will get before each year begins, which will help it decide how much to overdraft during any given drought over the long-term. By using the C2VSIM model, Zalakala (2012) found that the CALVIN no–overdraft case is optimistic, and some overdraft would still occur with operations and deliveries suggested by CALVIN.

Figure 3-15: Sacramento October Net Groundwater Storage over 72 years

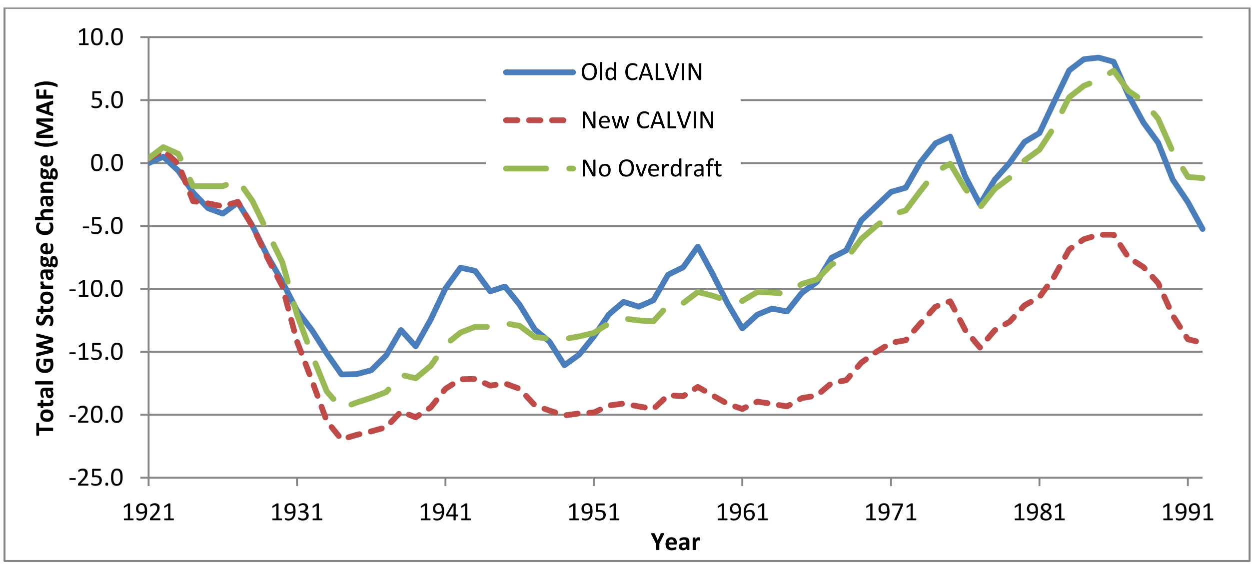


Figure 3-16: San Joaquin October Net Groundwater Storage over 72 years

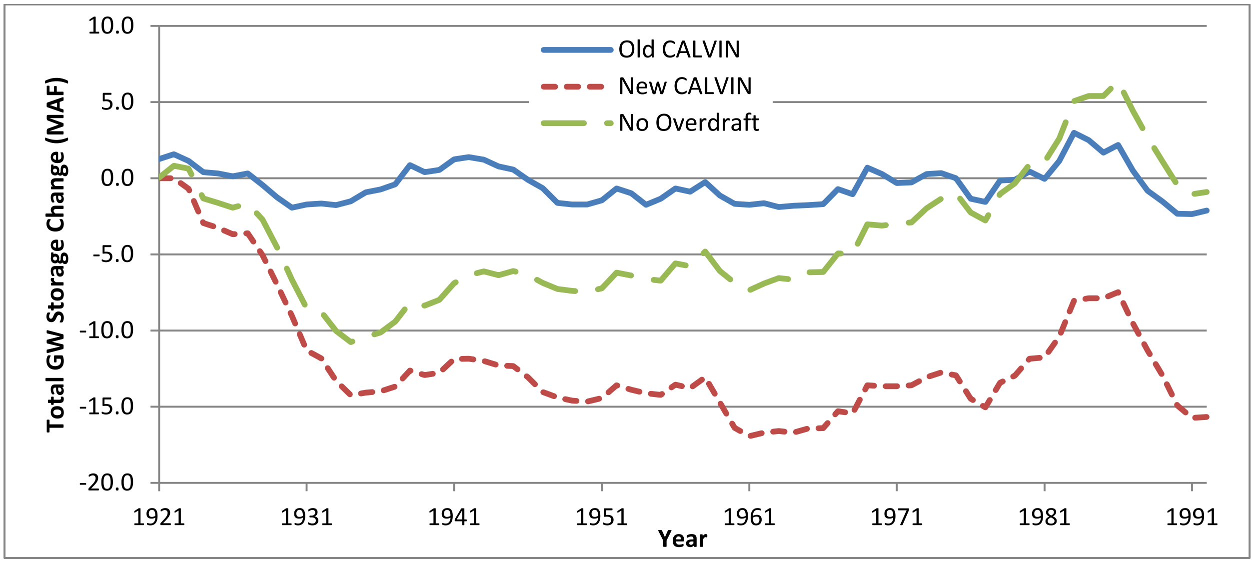
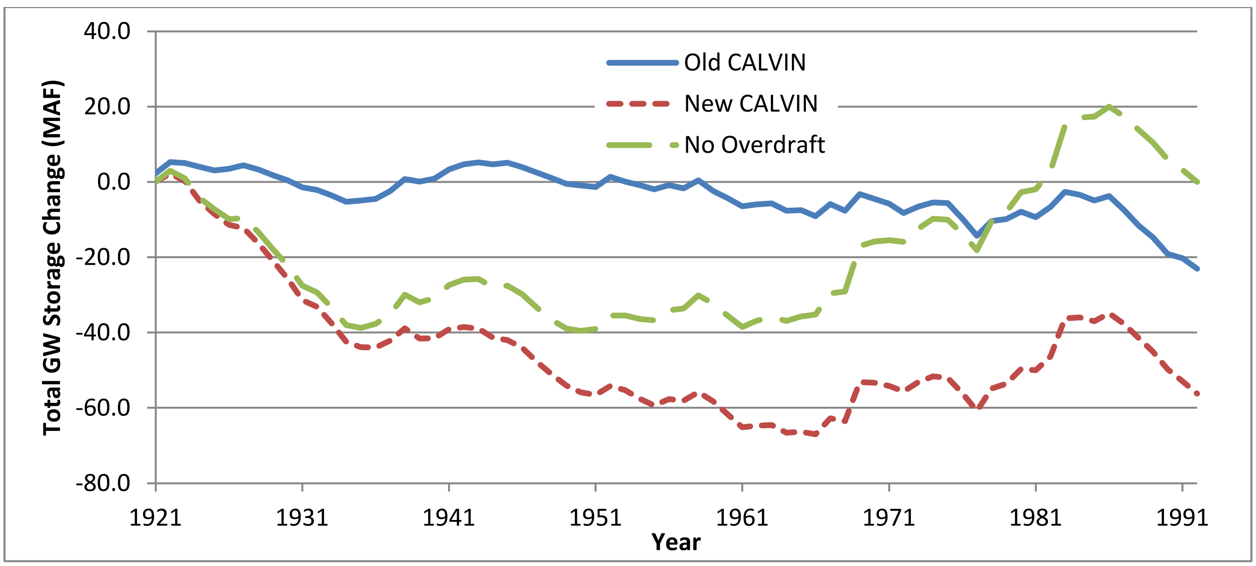


Figure 3-17: Tulare October Net Groundwater Storage over 72 years



3.2.9. Artificial Recharge

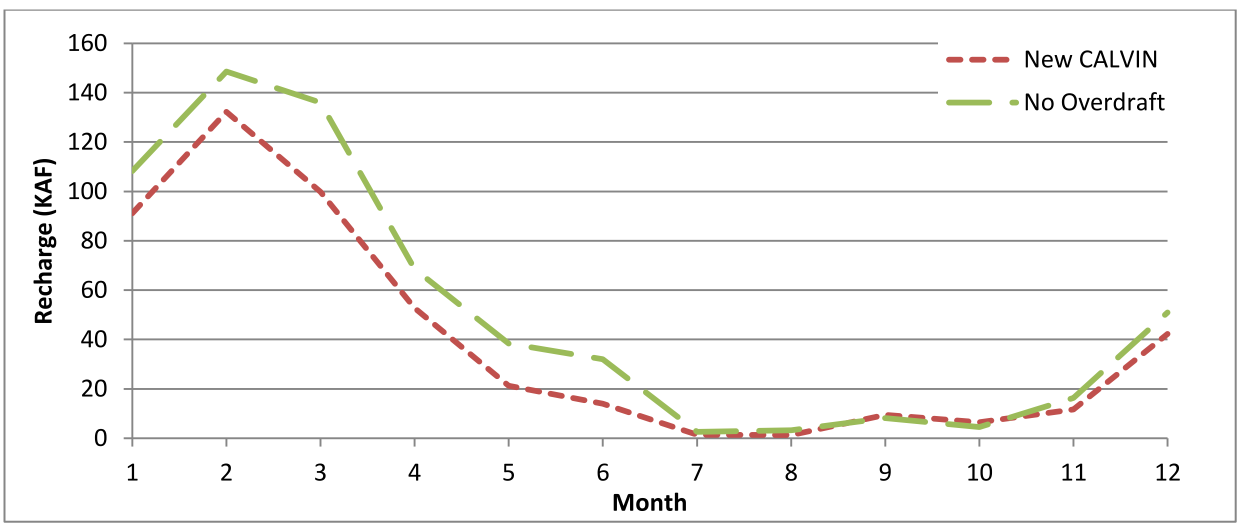
As mentioned in chapter 2, one update to CALVIN was to add artificial recharge capabilities to some Central Valley regions, primarily in Tulare basin. This gives CALVIN another tool to help manage groundwater overdraft and store surface water during wet years in aquifers. Artificial recharge is accomplished by spreading water on the ground allowing it to percolate through the soil into the aquifer. However, artificial recharge costs money and water that could be allocated to meet other demands.

Table 3-14 summarizes annual average artificial recharge and its cost for both the new CALVIN base case and the No Overdraft case. With groundwater constrained, more recharge occurs in the No Overdraft case for most regions, except it is slightly smaller in CVPM 18 and 19. CVPM 18 uses the most artificial recharge, about 2/3 of the total recharge for the base case and half the total for the No Overdraft case. This area has the most agricultural demand for the Tulare region and also heavily depends on groundwater pumping. Figure 3-18 graphs the monthly average artificial recharge in the Central Valley for applicable CALVIN runs. Most artificial recharge occurs in winter and spring when water is most available and before the summer demands.

Table 3-14: Central Valley Average Artificial Recharge Summary

	Recharge TAF/year		Cost $M/year	
	New CALVIN	No Overdraft	New CALVIN	No Overdraft
CVPM 13	30.4	54.9	0.2	0.4
CVPM 15	31.2	89.4	0.2	0.6
CVPM 16	0.0	14.2	0.0	0.1
CVPM 17	90.5	116.6	0.6	0.8
CVPM 18	323.5	306.5	2.2	2.1
CVPM 19	6.8	6.7	0.0	0.0
CVPM 20	0.0	0.0	0.0	0.0
CVPM 21	1.2	29.2	0.0	0.2
Total	483.6	617.4	3.3	4.2

Figure 3-18: Monthly Average Artificial Recharge in the Central Valley



3.2.10. Marginal Costs of Constraints

Marginal Costs of constraints, also called shadow prices or Lagrange multipliers, are the change in the optimal economic value produced if a constraint is changed by one unit. If a maximum capacity constraint is reached and the model would like to exceed that limit, the marginal cost indicates the value of expansion for that constraint. On the other hand, if a minimum capacity constraint is reached and the model would want to reduce flow even further, then the marginal cost will be the economic value for reducing that constraint by one unit. A non-zero marginal cost on a non-negative flow constraint means that the model would like to reverse the flow in that link. Marginal costs are especially valuable in identifying reservoir or conveyance infrastructure that could be expanded to improve water allocation and system costs. If the marginal cost of a constraint is zero, then that constraint does not limit the optimal solution.

In CALVIN lower bound constraints are usually from environmental requirements such as minimum instream flows and wildlife refuge demands. Table 3-15 gives the marginal costs for the environmental constraints that had some value in reduction. With the updates and again in the No Overdraft case the value of water and capacity tends to be greater with more limited water supplies. Most minimum in stream flow constraints had very small average marginal costs. However, some, such as the first Feather River section, are usually binding, but only have a small value in reduction. The minimum flow constraints with the largest marginal costs in the Central Valley are on the Trinity River and on Clear Creek. With most minimum instream flows, the water can still be used elsewhere downstream. Even if the constraint interferes with economically ideal operation, the water still has economic value, it just could be more valuable traveling somewhere else. The Trinity River constraint requires water to flow out of the system and become unavailable for additional use. In addition, the Trinity River marginal cost also accounts for the lost hydropower benefits of water diverted away from Whiskeytown Reservoir.

Refuge demand marginal costs are generally higher because only a small portion of the water going to the refuge can be reused to meet demands downstream. Refuges behave like additional consumptive demand areas with demands that must be met, forcing the model to allocate additional water that may be economically beneficial elsewhere. Interestingly, with the updates, the marginal cost for Sacramento West refuge decreases by more than 50% in the new base case, because the Sacramento West refuge is located off the same node as the CVPM 3 agricultural demands. With the updates the CVPM 3 agricultural demands decreased by 900 TAF/yr, so the available surface water in the area can be spread farther and expensive groundwater pumping becomes less important. In comparison, the Pixley refuge is located off the same node as CVPM 18 agricultural demands, which increased by about 350 TAF/yr. Here, the refuge demands have more of an effect on water supply and force the model to use more expensive groundwater. The marginal cost for Pixley doubles with the updates and increases by another $30/AF when groundwater use is limited.

The other environmental constraints such as the Delta outflow requirement, Mono Lake, and Owens lake function as sinks requiring water that cannot be used again. In addition, Mono Lake and Owens Lake marginal costs are high because the water they divert could be used to generate valuable hydropower at Owens Valley PWPs 1 and 2, are of high quality with low treatment costs, and supply high-value Los Angeles water demands.

Table 3-15: Marginal Costs for Environmental Constraints

River	CALVIN Links	Average marginal cost $/AF Old CALVIN	Average marginal cost $/AF New CALVIN	Average marginal cost $/AF No Overdraft	% of months constraint is binding (%) Old CALVIN	% of months constraint is binding (%) New CALVIN	% of months constraint is binding (%) No Overdraft
Sacramento	D5-D73	2.65	4.15	4.98	43%	41%	41%
	D61-C301	0.61	0.64	0.69	17%	26%	26%
	D507-D509	0.31	1.02	1.58	8%	7%	7%
Feather	C23-C25	0.49	0.50	0.50	95%	97%	97%
	C25-C31	0.39	2.07	2.85	23%	29%	29%
	C32-D42	0.05	0.15	0.23	6%	7%	7%
Yuba	C83-C31	0.05	0.02	0.03	6%	6%	6%
American	D9-D85	0.66	3.17	4.53	43%	57%	60%
Mokelumne	SR-CR-C38	1.98	5.20	8.07	56%	43%	42%
	D98-D517	0.14	0.25	0.45	14%	6%	6%
	D517-D515	0.52	2.28	6.89	17%	42%	42%
Stanislaus	D653A-D653B	4.14	5.53	8.10	58%	59%	61%
Tuolumne	SR-81-D662	1.94	1.70	2.51	20%	16%	15%
	D662-D663	2.23	3.76	5.67	45%	54%	55%
Merced	D645-D646	7.71	7.73	18.63	45%	38%	41%
	D649-D695	6.25	13.35	23.47	48%	67%	69%
Clear Creek	SR-3-D73	17.44	18.98	19.94	100%	100%	100%
Trinity	D94&D40-SINK	36.23	45.71	52.38	100%	100%	100%
Refuge							
Sacramento East	C311-HSURC311	2.44	9.53	14.54	100%	100%	100%
Sacramento West	C303-HSURC303	35.75	11.22	16.77	99%	99%	99%
San Joaquin	D723-HSURD723	32.47	42.71	50.76	100%	100%	100%
Pixley NW	C60-HSURC60	43.29	89.10	122.60	74%	100%	100%
Kern NW	C95-HSURC95	53.93	62.07	70.64	100%	100%	100%
Other							
Req. Delta Outflow	D541-REQ DELTA	2.68	9.37	14.16	100%	100%	100%
Mendota Pool	D732-HSURD732	27.74	39.27	45.97	100%	100%	100%
Mono Lake	SR-GL-SR-ML	1397.67	1406.14	1417.15	99%	99%	99%
Owens Lake Dust mitigation	SR-OL-SINK	1068.84	1076.72	1087.02	100%	100%	100%

Table 3-16 summarizes the marginal values for conveyance infrastructure including canals, aqueducts, and pipelines that have some value for expansion. Several links have a maximum capacity of zero meaning they do not actually exist, but the marginal cost shows how much value they could provide the system if constructed; these links are highlighted in bold. Most marginal costs remain relatively unchanged between Old and New CALVIN and between the updated base case and the No Overdraft scenario. The largest value in expansion is for the Coastal Aqueduct which serves Santa Barbara-San Luis Obispo (SB-SLO) with surface water from the California Aqueduct. As mentioned above the Coastal Aqueduct cannot deliver enough water to meet SB-SLO demands, which forces SB-SLO to use expensive desalination. If the Coastal Aqueduct was expanded the model could reduce expensive desalination, which is why the marginal cost is so high (CALVIN does not include several local SB-SLO sources, exacerbating scarcity there). Otherwise, the most significant changes between the runs occur for the Hetch Hetchy Aqueduct and an Imperial-San Diego Canal.

The Hetch Hetchy Aqueduct primarily brings water from Hetch Hetchy reservoir to the San Francisco urban demand area. In CALVIN the Hetch Hetchy Aqueduct is represented by multiple links, each with the same capacity, so when one reach binds, the others do not. The first link includes hydropower benefits, so it has a higher value of expansion. In the new base case, the first link has a higher marginal cost, while in the second link it decreased; in the No Overdraft case this is reversed. With the updates the model prefers to send more water through the first link to generate additional hydropower, but in the No Overdraft case supplies at the end of the aqueduct are stretched thin and the model would rather have more capacity on the second link. In addition, when the second link does not bind, the model would like to have a connection to New Don Pedro reservoir.

The Imperial-San Diego Canal is a proposed east to west connection between Imperial Valley and San Diego for transferring Colorado River water to San Diego urban demands. If this aqueduct were constructed it could reduce the need for expensive water recycling in San Diego. However, it would also have high pumping costs to cross the La Rumorosa Range of the San Pedro Martír Mountains. Old CALVIN had an unrealistically high monthly average marginal value for this aqueduct because pumping costs were not yet included (about $450/AF to $600/AF (Bartolomeo 2011)). New CALVIN has decreased this monthly average marginal value by about $480/AF, which is within the range of pumping costs suggested by Bartolomeo. During the winter the model wants to run the canal backwards, sending water from San Diego to El Centro urban demands. With the updates, water exports from northern to southern California have increased in the spring, but are smaller in late summer and early winter. The Imperial-San Diego canal still has value in the summer when San Diego has to use recycling, but in the winter, with reduced northern exports, water would be more useful elsewhere in Southern California. Therefore, in the winter, the model would like to transfer water from San Diego to El Centro and possibly other parts of Southern California.

Table 3-16: Marginal Value of Expansion for Conveyance Infrastructure

Infrastructure	CALVIN Link	Max flow capacity	Avg. Marginal Annual Value of Expansion			% of Months Capacity is Binding		
			$/AF			%		
		TAF/mo	Old CALVIN	New CALVIN	No Overdraft	Old CALVIN	New CALVIN	No Overdraft
Winters, Moore, W. Adams Canals	C16-HSU6C16	38.5	1	7	6	20%	36%	33%
South Folsom Canal	C107-C39	9.5	0	0	7	0%	5%	15%
	C173-T43GALT	0	0	0	13	0%	0%	50%
North Bay Aqueduct	D55-C22	10.76	94	97	97	12%	45%	40%
EBMUD-CCWD intertie (to EBMUD)	C310-HWTC310	5.6	96	101	109	100%	100%	100%
New Don Pedro to HH Aqueduct	**SR-81-C88**	0	219	297	268	56%	74%	68%
Hetch Hetchy Aqueduct	C44-C88	28.54	256	335	305	56%	74%	68%
	C88-C78	28.54	204	122	149	44%	26%	32%
Pacheco Tunnel	SR-12-D714	29.52	5	5	5	38%	39%	41%
Delta Mendota Canal	D701-D703	282.92	0	0	2	3%	7%	24%
	D722-D723	202.96	0	2	2	5%	24%	26%
Friant-Kern Canal	C76-C688	277	1	1	1	13%	8%	6%
California Aqueduct	BANKS PMP-D801	472	1	2	5	49%	51%	66%
Cross Valley Canal (Eastward)	D752-C74	49.2	1	18	37	50%	90%	94%
Coastal Aqueduct	D848-D849	4.37	1395	1387	1378	100%	100%	100%
Santa Ana Pipeline	C129-D876	28.79	3	6	6	66%	72%	71%
LA Aqueduct	C120-SR-LA	47.57	2	3	3	51%	50%	50%
	OWENS2 PWP-C122	48	1	3	5	11%	13%	13%
Colorado Aqueduct	C134-IRON PMP	110.48	24	25	30	6%	6%	7%
	EAGLE PMP-JULIAH PMP	110.48	375	383	389	94%	94%	93%
Inland Feeder	C129-N2	61.38	3	5	5	75%	73%	75%
San Diego Canal	N6-SR-LSK	104.35	240	241	240	72%	72%	72%
Imperial-San Diego Canal	**C152-C156**	0	521	43	50	100%	61%	61%

Table 3-17 gives the annual average marginal value for expanding reservoir capacity of all reservoirs modeled in CALVIN. This neglects the cost of expanding the reservoirs which would reduce the overall benefit of creating additional storage. Most reservoirs have little value for expansion. These low marginal values are produced because most reservoirs are filled for only a few months of the year and not in every year. Several reservoirs never reach their maximum storage, including San Luis Reservoir even though it is used more in New CALVIN and the No Overdraft case. The largest marginal value of expansion is about $350/yr per AF for Lake Skinner, which is just upstream of E&W MWD and San Diego urban demand areas. Most of Lake Skinner's expansion value is in the spring, when the model wants to store extra water near Los Angeles to prepare for summer demands.

Overall in the New CALVIN model (and the No Overdraft case) the marginal value of expansion increased for most reservoirs. Since there is less water in the system for New CALVIN and the No Overdraft case the model wants to store more water during winter for summer use and the reservoir fill to capacity more often. However, there are several reservoirs where the value of expansion decreases in the new model runs. Most of these reservoirs serve areas that have high agricultural demands in the Tulare and San Joaquin regions. With reduced water availability the model must sacrifice long term storage to meet short term demands, therefore expanding storage is a little less valuable. With the no overdraft case, most reservoirs do not fill as frequently, which tends to reduce the value of reservoir expansion, even if the value of stored water in filled years is higher.

Table 3-17: Marginal Value of Expansion for Surface Water Reservoir Capacity

	CALVIN Node	Max Storage	Avg. Annual Value of Expansion $/AF			% of Years Reservoir at Maximum Storage %		
		TAF	Old CALVIN	New CALVIN	No Overdraft	Old CALVIN	New CALVIN	No Overdraft
Clair Engle Lake	SR-1	2096	2.1	3.2	3.8	51%	32%	29%
Whiskeytown Lake	SR-3	240	3.9	5.9	7.2	100%	100%	100%
Shasta Lake	SR-4	4552	4.1	6.1	7.4	94%	88%	82%
Black Butte Lake	SR-BBL	149	5.6	11.8	15.3	96%	93%	90%
Lake Oroville	SR-6	3538	6.4	9.4	10.8	100%	100%	100%
Folsom Lake	SR-8	975	6.5	8.6	10.5	100%	93%	85%
Clear Lake & Indian Val.	SR-CL-IVR	600	1.3	3.7	4.8	42%	38%	38%
Lake Berryessa	SR-LB	1601	0.2	0.9	1.2	10%	10%	10%
New Bullards Bar	SR-NBB	930	9.0	12.6	14.7	100%	99%	96%
New Hogan Lake	SR-NHL	266	1.6	4.0	5.5	46%	42%	42%
EBMUD Aggregate	SR-EBMUD	153	0.1	1.1	2.5	6%	15%	18%
Los Vaqueros Res	SR-LV	104	0.3	1.6	2.5	22%	26%	32%
Pardee Reservoir	SR-PR	209	1.1	2.7	4.9	93%	82%	78%
Camanche Res	SR-CR	438	1.1	2.7	4.9	53%	43%	47%
New Melones Res.	SR-10	2393	5.0	5.1	5.5	85%	81%	67%
San Luis Reservoir	SR-12	2038	0	0	0	0%	0%	0%
Millerton Lake	SR-18	519	4.7	4.9	5.2	46%	38%	43%
Lake McClure	SR-20	1024	6.2	7.5	11.4	75%	61%	43%
Hensley Lake	SR-52	90	11.8	8.1	3.6	39%	43%	36%
Eastman Lake	SR-53	148	5.9	3.3	1.3	19%	21%	19%
New Don Pedro	SR-81	2030	4.2	4.3	4.8	74%	79%	64%
Lloyd/ Eleanor	SR-LL-LE	134	10.6	10.3	11.0	39%	33%	35%
Santa Clara Aggregate	SR-SCV	170	0.5	0.5	0.5	1%	1%	1%
Turlock Reservoir	SR-TR	301	4.3	4.4	4.9	69%	61%	46%
SF Aggregate	SR-ASF	225	0	0	0	0%	0%	0%
Hetch Hetchy	SR-HHR	67	3.4	3.4	3.9	47%	42%	33%
Lake Isabella	SR-LI	528	2.6	5.1	6.5	25%	33%	28%
Lake Kaweah	SR-LK	120	45.7	10.6	7.5	100%	100%	100%
Lake Success	SR-LS	78	44.6	9.0	6.2	89%	78%	68%
Pine Flat Res.	SR-PF	991	2.9	2.5	2.5	99%	86%	82%
Lake Perris	SR-27	132	0	0	0	0%	0%	0%
Pyramid Lake	SR-28	171	0.5	0.6	0.6	99%	97%	94%
Castaic Lake	SR-29	324	0.5	0.8	1.0	76%	63%	81%
Diamond Valley	SR-DV	825	0	0	0	0%	0%	0%
Grant Lake	SR-GL	48	68.7	69.1	69.6	8%	8%	8%
LAA Storage	SR-LA	103	0	0	0	0%	0%	0%
Long Valley	SR-LC	184	0	0	0	0%	0%	0%
Lake Mathews	SR-LM	182	0.01	0	0	6%	0%	0%
Lake Skinner	SR-LSK	44	351.2	356.7	357.6	100%	100%	100%

3.2.11. The Marginal Value of Water throughout California

CALVIN also produces marginal values for additional water (called duals) at each node in the network at each time step. These numbers represent how much economic benefit could be produced by injecting 1 AF of water at a particular node and time-step. The Dual value is driven by how the additional water would be optimally used in the system to meet demands, lower operating costs, and generate hydropower. In general, nodes closer to demand areas place more value on additional water (avoiding operating and opportunity costs elsewhere). In reality, water cannot just be injected anywhere, but these numbers can give an idea of the best places and times to bring in new supplies.

Table 3-18 shows monthly average values of additional water across California at major reservoirs, pumping plants, and junctions. In the Sacramento region dual values were generally small in old CALVIN and increased a little with the updates and again in the No Overdraft case. Several important reservoirs are given as examples for the region with Camp Far West being the least valuable place for extra water in all three cases and Clair Engle being the most valuable. In the Bay Area/Delta the value of additional water in reservoirs is generally high in all three cases because of the large nearby urban demands. On the other hand, the value of additional water at Banks and Tracy is less because of pumping costs and because the plants have upper bound constraints that limit use of additional water. In the San Joaquin and Tulare regions the benefit from additional water is generally higher than in the Sacramento since these regions have greater water scarcity. Finally, Southern California has great value for additional water throughout the region in all three cases since there is a lot of urban scarcity and the costs of bringing in additional water are high.

Table 3-19 gives the monthly average value of additional water at nodes with river inflows, basically the value of increasing the river source by 1 AF. In old CALVIN values were typically low, between 0 and $50 for an additional AF, except in Southern California where there was still plenty of urban and agricultural scarcity. The Mono Basin and Upper Owens River inflows were an exception with dual values exceeding $1000/AF because they enter upstream of multiple hydropower plants and can then be used to meet expensive Los Angeles urban demands. In new CALVIN and in the No Overdraft case the value of additional water has increased throughout the system in response to the higher scarcity and reduced groundwater availability. The most significant increases occur for rivers in the Tulare region where agricultural demands are hit the hardest by the groundwater restrictions. Interestingly, the Colorado River does not change value between the three model runs, meaning that in all three cases the water will be used in the exact same way, producing the same benefit.

Table 3-18: Monthly Average Marginal Value for Additional Water Across California

	CALVIN Node	Description	Value of additional water $/AF		
			Old CALVIN	New CALVIN	No Overdraft
Sacramento Region	SR-CFW	Camp Far West Reservoir	4.5	12.2	18.1
	SR-4	Shasta Lake	16.1	25.1	31.3
	SR-EL	Englebright Lake	7.5	15.9	21.7
	SR-1	Clair Engle Lake	43.8	53.3	60.0
Bay Area /Delta	D523	Sac and SJ infow to Delta	3.0	10.4	15.8
	BANKS PMP	Banks pumping plant	3.0	10.4	15.8
	TRACY PMP	Tracy pumping plant	3.0	10.4	15.8
	SR-EBMUD	EBMUD Aggregate	155.6	169.1	183.1
	SR-15	Lake Del Valle	152.2	156.2	163.7
	SR-ASF	SF Aggregate	443.2	445.7	453.1
	SR-SCV	Santa Clara Aggregate	422.8	425.1	432.5
San Joaquin Region	SR-53	Eastman Lake	34.1	52.6	100.8
	SR-18	Millerton Lake	51.6	80.5	112.4
	SR-HHR	Hetch Hetchy Reservoir	23.0	29.3	39.1
	SR-12	San Luis Reservoir	73.2	76.8	84.4
Tulare Region	SR-LI	Lake Isabella	56.0	80.0	107.2
	SR-LK	Lake Kaweah	39.1	75.0	102.9
	SR-LS	Lake Success	35.6	73.7	102.1
	SR-PF	Pine Flat Reservoir	34.9	51.5	68.1
Southern California	EDMONSPMP	Pumping across the Tehachapi Mts.	179.4	187.6	196.1
	C149	Colorado diversions to Imperial and Coachella	214.5	214.5	214.5
	IRON PMP	Colorado diversions to LA and San Diego	238.0	238.9	244.4
	SR-LSK	Lake Skinner	1115.1	1125.4	1135.4
	SR-29	Castaic Lake	499.5	509.7	520.5

Table 3-19: Monthly Average Marginal Value of Additional Water for River Inflows

CALVIN Node	Description	Monthly Avg. inflow	Monthly Avg. Value of additional water $/AF		
		TAF	Old CALVIN	New CALVIN	No Overdraft
C27	M&S Fork Yuba River inflow	35.53	7.5	15.9	21.7
C35	Greenhorn Creek and Bear River inflows	34.83	4.5	12.2	18.1
C37	Cosumnes River inflow	30.47	3.8	15.6	39.9
C77	Feather River inflow	324.98	18.2	27.5	33.8
D17	N&M Forks American River inflow	114.47	10.5	20.5	27.3
SR-1	Trinity River inflow	101.43	43.8	53.3	60.0
SR-4	Sacramento River inflow	460.46	16.1	25.1	31.3
SR-8	S Fork American River inflow	109.24	10.5	20.5	27.3
SR-NBB	N Fork Yuba River inflow	101.08	35.2	43.9	49.9
SR-NHL	Calaveras River inflow	12.85	5.8	16.4	22.8
SR-PR	Mokelumne River inflow	56.74	5.6	18.1	31.3
SR-10	Stanislaus River inflow	88.12	21.4	28.4	37.9
SR-18	San Joaquin River inflow	140.06	51.6	80.5	112.4
SR-20	Merced River inflow	76.84	28.1	43.7	73.9
SR-52	Fresno River inflow	7.02	31.5	50.8	100.0
SR-53	Chowchilla River inflow	5.78	34.1	52.6	100.8
SR-HHR	Tuolumne River inflow	62.25	23.0	29.3	39.1
SR-LI	Kern River inflow	56.97	56.0	80.0	107.2
SR-LK	Kaweah River inflow	34.71	39.1	75.0	102.9
SR-LS	Tule River inflow	11.00	35.6	73.7	102.1
SR-PF	Kings River inflow	132.83	34.9	51.5	68.1
C146	Whitewater River inflow	0.00	244.5	244.5	244.5
SR-CR3	Colorado River inflow	366.67	214.5	214.5	214.5
SR-GL	Mono Basin inflow	9.92	1397.7	1406.1	1417.2
SR-LC	Upper Owens River inflow	11.95	1304.6	1312.5	1322.8

3.3. <u>Concluding Remarks</u>

The most significant improvement to the CALVIN model, as a result of the updates to groundwater representation, is the elimination of the 2.2 MAF of calibration flows in the Central Valley. Before the updates, CALVIN had to pump more groundwater than was required for demands to avoid infeasibilities during the model run. An infeasibility occurs when it is impossible for the model to satisfy one of its constraints. With the updates, groundwater use for Central Valley agricultural fell from about 8281 TAF to 6100 TAF per year, about 2181 TAF and almost all of the 2252 TAF of earlier calibration flows. By removing this extra water, annual agricultural water scarcity in the new base case has increased to about 360 TAF, compared to only 37 TAF of scarcity in the old base case.

Some of the other conclusions from comparison between the old and new CALVIN models are:

- Groundwater use has fallen throughout the Central Valley, and Central Valley Urban supplies have shifted from primarily groundwater to surface water dependent
- Reduced groundwater use saves about $300 million/Year in groundwater pumping costs per year
- More Delta pumping occurs in late winter to be stored for spring and summer use
- Exports to Southern California have increased in the spring and decreased in the fall
- Southern California stores more water in Spring to prepare for Summer demands
- The Imperial-San Diego canal has lost its value

For the No Overdraft case examined, much can be learned about how the system responds to limited groundwater supplies. To replace the lost groundwater supply in the San Joaquin and Tulare regions, the system relies more heavily on Delta exports. On average, Delta pumping increases by about 900 TAF/yr. Most of the increase occurs during the winter when more surface water is available, so it must be stored in the San Luis Reservoir to await summer demands. Even with the additional Delta exports there isn't enough surface water to make up for the lost groundwater and scarcity increases by about 300 TAF/yr. Between the additional scarcity and increased surface water pumping, net system costs increase by about $30 M/yr. Although some areas still rely heavily on groundwater, groundwater is most important during droughts, when surface water is limited. Groundwater use must be balanced so there is enough natural and artificial recharge between droughts to refill aquifers. One difficulty with enforcing a no overdraft policy is balancing long-term recharge and pumping, especially with imperfect forecasts and climate change. If California's climate changes into a warmer, drier climate, the number of drought years will increase and demand for groundwater will also increase.

These updates are not the last for CALVIN. To maintain and improve the model, updates must continue as more accurate data becomes available. This is just one step in the never ending effort to improve a model so that it better represents reality and becomes more useful for decision making. One place that needs to be examined more carefully is the South Coast area of SB-SLO to determine if it is forced to use desalination or if it has a less expensive solution not represented in CALVIN. To improve the system further, the Central Valley surface water representation, such as rim inflows, accretions, and depletions, should be updated. In addition, updating Southern California groundwater may also be useful. There is also some concern that estimates the hydropower benefits generated in Southern California are too high, especially for the LA Aqueduct, so it might be beneficial to reexamine those values. With the changes to the system revisiting some of the past scenarios, such as those in Ragatz (2011) (varying urban water conservation, varying Delta export level, different climate scenarios) should be done to create a more accurate portfolio of results.

Unfortunately, no model is perfect and to use them effectively engineers must understand their limitations. As George Box put it, “All models are wrong, but some are useful.” Blindly accepting a models output as true can be just as bad, even worse, than having no model at all. Despite their limitations, computer models are still useful and will be more important in the future. Water resource management is no longer a small or medium scale issue; to effectively meet rising water demands all aspects of water resources need to be integrated into a single unit, allowing engineers to manage the entire system at the same time. Computer models will be instrumental in the planning and implementation of new water use practices such as water markets and conjunctive use. However, there will be a time when the old models become too cumbersome and are outclassed by newer, more capable versions. At some point modelers must decide that it is time to move on rather than continue updating indefinitely.

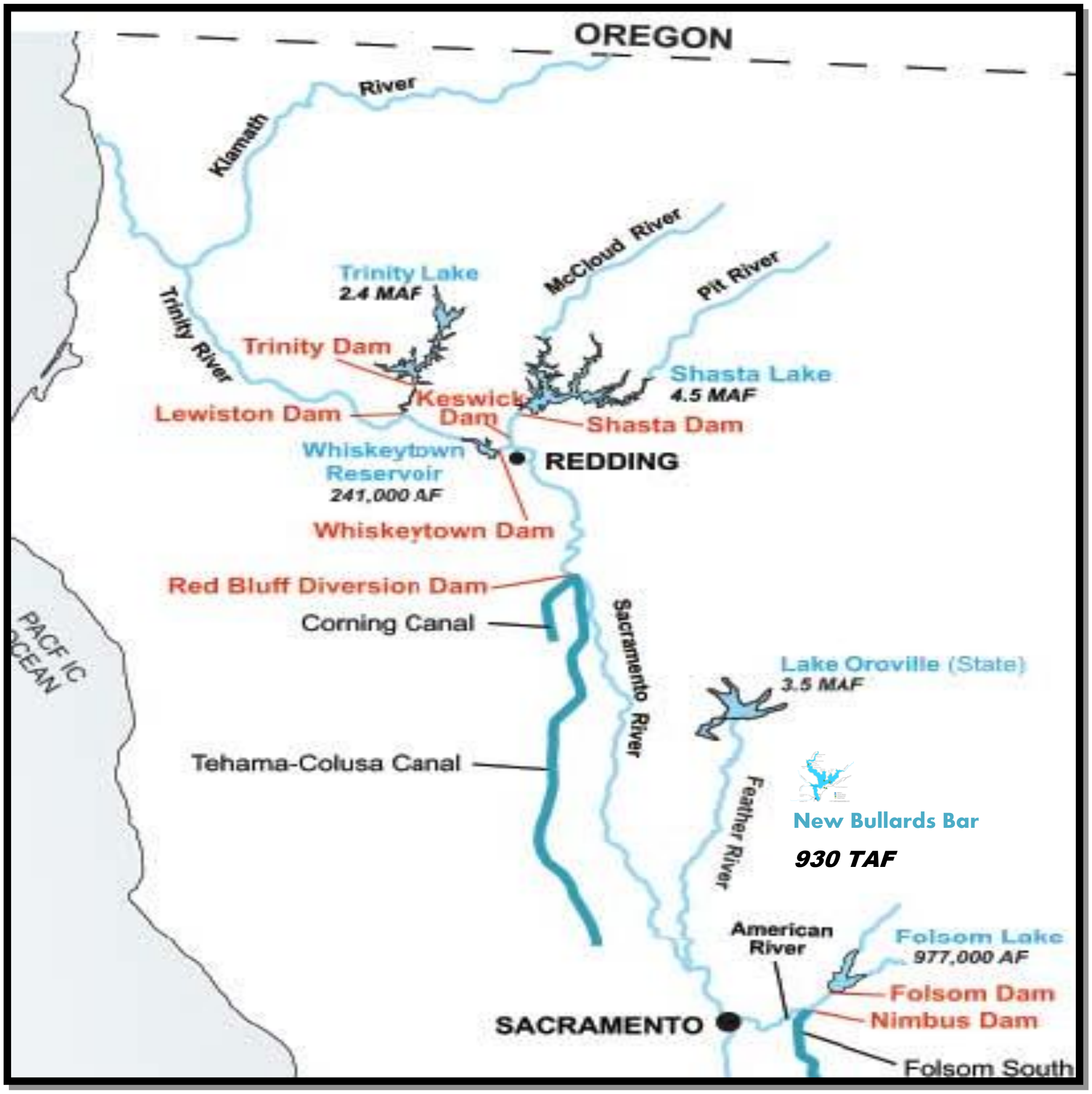
Chapter Four: Optimized Storage Balancing and Reservoir Reoperation for the Sacramento Valley

4.1. Introduction

This chapter has two objectives. The first objective was to infer a set of optimized storage allocation and reservoir release rules from the results of the updated CALVIN model for some of the most important reservoirs in California's Sacramento Valley. These results were taken from run S07I18, the new base case for the updated CALVIN model described in chapter 3. The second objective was to infer similar operating rules from CalSim II model results. Unlike CALVIN, CalSim II uses predefined operating priorities adapted from existing rules as part of the model. After inferring the two rule sets the goal was to compare them, at least for economics, and to see how different the operations actually are. CalSim II rules results are from Existing Conditions Run 2005A01A used in the SWP water supply reliability report.

The Sacramento Valley is the most northern part of California's Central Valley, surrounded by the Northern Coast Ranges to the west, the southern Siskiyou Mountains to the north, and the northern Sierra Nevada to the east (water.usgs.gov). In addition, it is the wettest part of the Central Valley with its water traveling south through the Sacramento River into the San Joaquin Delta to be distributed to rest of the Central Valley, Bay Area, and Southern California during the dry season. The region is heavily dammed with reservoirs on most major tributaries to prevent flooding, control water supply, and generate hydropower. Most smaller reservoirs are not used for storage or flood control, but for hydropower generation so their operations are pretty well defined. On the other hand, the larger reservoirs have more numerous options for release and more severe impacts on water supply and the environment. This chapter seeks to examine and improve the operating rules for the five largest reservoirs in the Sacramento Valley, which are Shasta, Oroville, Trinity (Clair Engle), Folsom, and New Bullards Bar (NBB).

Figure 4-1: Important Rivers and Reservoirs of the Sacramento Valley (Source:http://www.usbr.gov/mp/2011_accomp_rpt/mpr_highlights.html)



All models and analysis have limitations. In creating operating rules based on any model, the limitations and assumptions of that model must be considered. In CALVIN the model has hydrologic foresight to see when floods and droughts are coming, so it can operate each reservoir to best deal with each situation (Draper 2001). In reality, the system could never be operated that well, no matter what rules were used. The derived rules will at best approximate the results of their model; not every action will be explained and there will be variability. In addition, creating rules from model results is somewhat subjective reflecting this variability. Two people looking at the same results could see different patterns and infer different rules, which can then be compared in terms of performance.

Beyond these inherent problems, there are also limitations specific to the CALVIN and CalSim models. Both models use monthly time steps, so the best rules that can be derived are monthly rules. Real operations happen continuously every day, so these rules can only provide targets on total release and storage over a month. This also requires having projections of the monthly inflow which adds additional uncertainty to the operations. The second problem is that CalSim is designed to operate just the Central Valley Project and State Water Project while CALVIN operates the entire state. Though the models have comparable inflows, some demand areas are not represented in CalSim that are in CALVIN. This could mean that optimized rules from CALVIN can't compare with the rules from CalSim since they can depend on information not in CalSim. Finally, the optimized rules in this case are optimized for statewide economics only, within environmental constraints. There could be other sets of operating rules that are optimized for other objectives, like minimizing the likelihood of floods. CalSim itself may already be using rules of some kind determined for other objectives.

Before examining the reservoirs themselves, note the annual variability in water supplies for California, as operations may differ during years of drought and flood. With so much variability it would be beneficial to have some kind of index that separates years based on water availability. For this reason the Department of Water Resources classifies each year with a water year type, based on the Sacramento River index or on the San Joaquin River index (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST). Based on this index there are five types of water year: Wet, Above Normal, Below Normal, Dry, and Critical.

However, for this research, there were a few problems with applying the DWR water year type (WYT) index. First, it is a Year-type index, while model results are monthly, so using WYT to classify results ignores information on monthly water variability. The second problem is that the WYT index is based on the Sacramento River index which only accounts for the aggregate flow in the Sacramento River. This ignores spatial information on water availability over the Sacramento region as different tributaries to the Sacramento River may experience their own local shortages or floods. Finally, in deriving operating rules it is important that they are based on information that is already known; unfortunately, WYT is based on flows over the entire water year. This means in October, the first month of a new water year, there is uncertainty in what the WYT will be.

To deal with the above drawbacks, a new index was defined based on the water availability over the previous 12 months at each reservoir, in other words a Past Year Type (PYT) index. Though it doesn't predict how wet it will be in the future there is some correlation between years so it may have some value. Like the WYT, the PYT is divided into the same five year types, but it is calculated based on the inflow to each reservoir. The index will be assigned at each reservoir by calculating the total inflow over the past year (IOPY) for each month and then separating the months into percentiles. Table 4-1 below shows how these percentiles will be assigned a PYT.

Table 4-1: Past Year Type assignment

Reservoir IOPY Percentile	PYT Description	PYT number
0 to 20	Critical	1
20 to 40	Dry	2
40 to 60	Below Normal	3
60 to 80	Above Normal	4
80 to 100	Wet	5

4.2. Modeled Results for Sacramento Valley Reservoirs

This section provides a brief qualitative description of how CALVIN and CalSim operate the reservoirs mentioned above and how these operations differ.

4.2.1. Shasta Reservoir

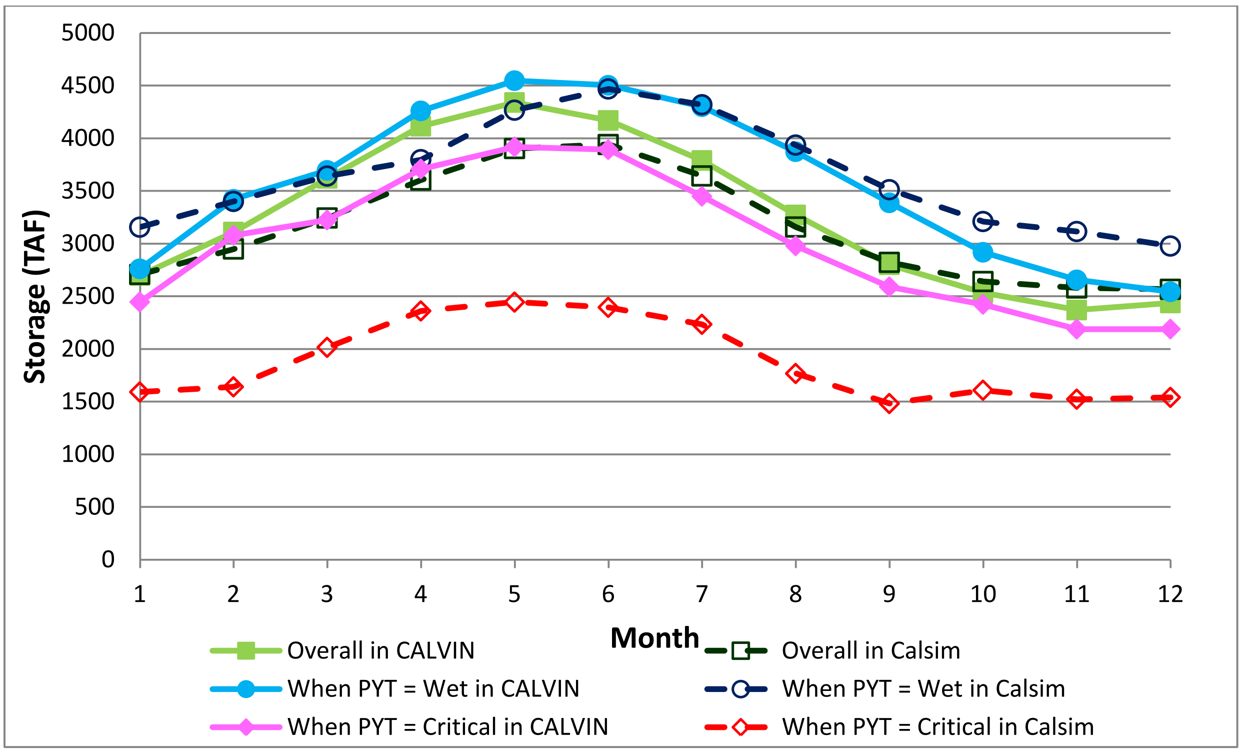
Shasta is the largest reservoir in California, and primarily serves the CVP for seasonal, drought, and flood storage on the upper Sacramento River. The maximum capacity is 4552 TAF, with a dead pool of 116 TAF. The modeled results for Shasta from both CALVIN and CALSIM are presented below in Table 4-2 and Figure 4-2. Table 4-2 shows that overall average monthly storage is slightly higher in CALVIN than CalSim. In addition, in CALVIN Shasta has a higher average maximum storage and a lower average minimum storage. This produces an average annual drawdown volume that is 600 TAF greater in CALVIN. For Critical months less water is available, so the average storages tend to decrease in both models. However, since CalSim doesn't have the foresight to see it coming and plan ahead, the difference from normal years is much greater. Average drawdown in CALVIN falls by about 250 TAF while in CalSim it falls by 400 TAF; Thus CALVIN is releasing 750 TAF more from Shasta during really dry periods. On the other hand, in very wet months more water is available so the storages tend to increase from normal years in both models. For these wet periods the drawdown in both models is nearly the same as in normal years, although the total amount of water released may be greater because inflow is greater. Overall, CALVIN works Shasta reservoir harder.

Figure 4-2 shows average Shasta storage by month for both models. For CALVIN the drawdown season usually begins in May while the refill season begins in November. In CalSim drawdown usually begins in June while refill begins in December, except in really dry years when most drawdown occurs between July and September and most of the refill is between February and April. In general, CALVIN refills more storage in the early months of the year while CalSim relies more on the spring runoff; CalSim may be a little more conservative during that period since it doesn't know when a flood will come. With this extra refill CALVIN can use more of Shasta's storage, which leads to greater drawdown. Most of this additional drainage in CALVIN occurs in September and October when CalSim has leveled off its drawdown.

Table 4-2: Shasta Storage Summary in both CALVIN and CalSim

	Shasta reservoir							
	Avg. Monthly Storage		Avg. Annual Max storage		Avg. Annual Min Storage		Avg. Annual Drawdown	
For:	TAF							
	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim
All Years	3271	3146	4339	3940	2369	2566	1970	1374
Critical Months(PYT = 1)	2952	1847	3918	2444	2188	1481	1730	963
Wet Months (PYT = 5)	3533	3634	4547	4468	2543	2976	2004	1491

Figure 4-2: Average Monthly Shasta Storage for each Month in CALVIN and CalSim



4.2.2. Trinity Reservoir

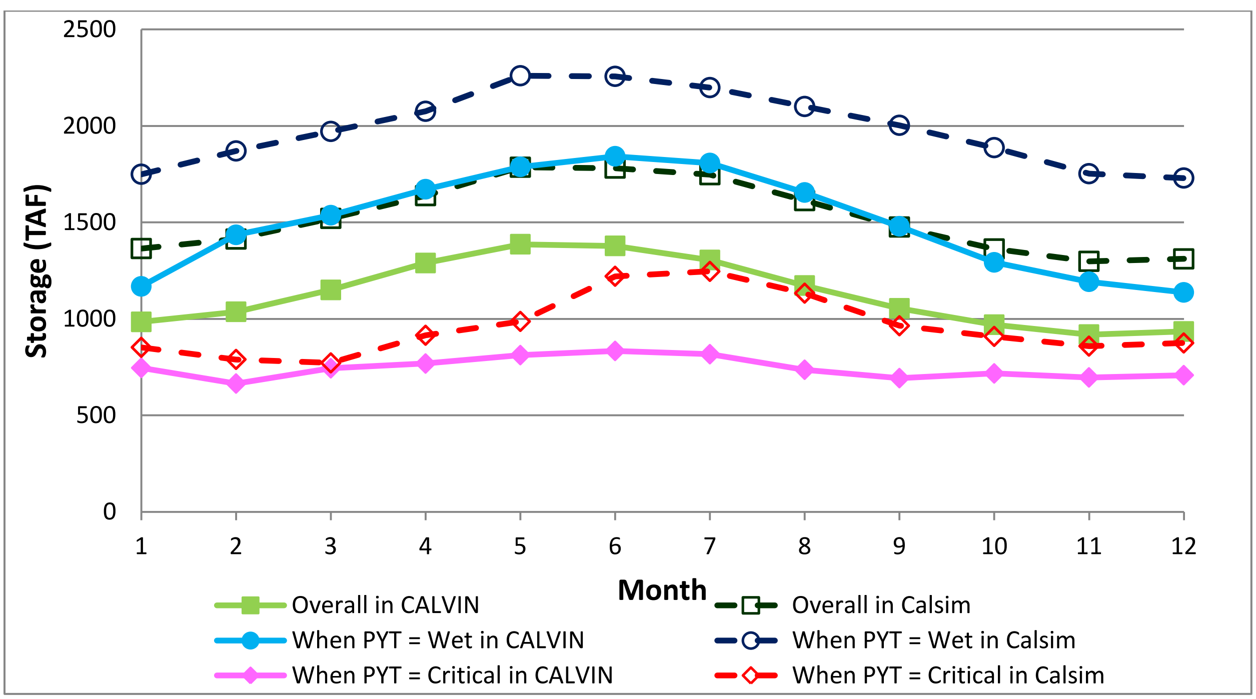
Trinity Reservoir is an important part of the federal Central Valley Project on Trinity River, primarily used for storing future irrigation water and producing hydropower. The maximum capacity is 2447 TAF and the dead pool is 400 TAF. The modeled results for Trinity from both CALVIN and CalSim are presented below in Table 4-3 and Figure 4-3. On average, CalSim stores about 400 to 600 TAF more water in Trinity than CALVIN, as long as the past year wasn't very dry. In very dry years the storage is bit closer between the models, but CalSim still averages 400 TAF more storage when it is at its peak before the drawdown season. In CalSim, Trinity averages about 500 TAF of drawdown each year, regardless of past year type. CALVIN averages 500 TAF in drawdown as well, but varies depending on the PYT, with more storage released in very wet years and relatively little storage released in very dry years.

Figure 4-3 compares average Trinity storage by month for both models. Overall, both models seem to follow the same drawdown and refill pattern for Trinity storage, except that CalSim keeps 500 TAF more storage in the reservoir throughout the year. The overall drawdown season is from May to November while the refill season covers the rest of the year. For wet periods the average drawdown and refill patterns in CalSim are similar to the overall average patterns, but in CALVIN the refill period tends to be longer, starting in December and ending in June. In addition, as seen above, the average drawdown in CALVIN during these wet periods is a bit larger than in CalSim. Finally, when PYT is Critical CALVIN has almost no drawdown or refill, instead keeping storage at about 750 TAF. On the other hand, in CalSim drawdown takes place from July to March, with a period of fast drawdown from July to September and then a period of slower drawdown up to March. Refill thus takes place from March to June, with most coming in as spring runoff in May.

Table 4-3: Trinity Storage Summary in both CALVIN and CalSim

	Trinity Reservoir							
	Avg. Monthly Storage		Avg. Annual Max storage		Avg. Annual Min Storage		Avg. Annual Drawdown	
For:	TAF							
	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim
All Years	1132	1526	1387	1786	918	1298	468	488
Critical Months(PYT = 1)	742	963	834	1246	664	771	169	474
Wet Months (PYT = 5)	1504	1985	1843	2260	1137	1730	706	530

Figure 4-3: Average Monthly Trinity Storage for each Month in CALVIN and CalSim



4.2.3. Oroville Reservoir

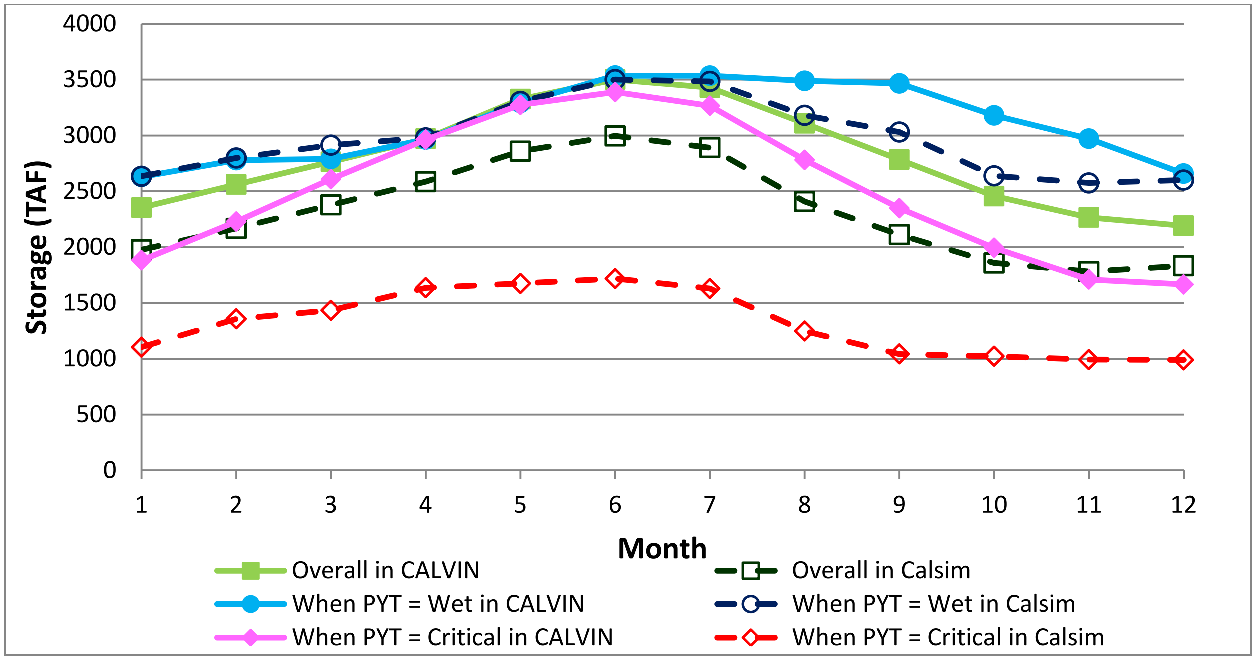
Oroville is the second largest reservoir in California and the major reservoir of the State Water Project, storing water along the Feather River for water supply, hydropower, and floods. The maximum capacity is 3538 TAF and the dead pool is 29.6 TAF. The modeled results for Oroville from both CALVIN and CalSim are presented below in Table 4-4 and Figure 4-4. In general, CALVIN stores about 500 TAF more water in Oroville than CalSim. Despite this additional water, the models have similar average annual drawdowns. In very wet periods the average storage and annual drawdown are relatively close between the models. However, during dry periods the difference between average monthly storages more than doubles to about 1150 TAF. Furthermore, the average peak storage in CALVIN comes close to full while CalSim doesn't even fill halfway. In CALVIN, Oroville has very high storage depletion penalties during the early summer, making storage more valuable than release at that time, so the model always tries to bring the reservoir to full or close to full by June. As the summer passes these penalties fall and releases become more valuable which leads to a very large annual average drawdown. The depletion penalties for all the reservoirs examined here are presented in Appendix D.

Figure 4-4 shows average Oroville storage by month for both models. In CALVIN the refill season is from December through May and the drawdown season is from June through November; however, if the previous year was wet, then the reservoir is kept full until September. CalSim has similar storage patterns except drawdown is finished by October and storage remains mostly unchanged until December. CALVIN always tries to have Oroville full by early summer, even when water has been scarce. CALVIN averages the same storage in April and May for both critical and wet periods, and averages only slightly lower storages for June when it has been dry. However, going into July, if it has been dry, then most other reservoirs will be low on storage, which will force Oroville to start draining. If it was wet, Oroville can remain full throughout the summer and only starts draining in September to empty Oroville's flood storage space. CalSim, on the other hand, averages lower storage overall than CALVIN for most months during critical periods.

Table 4-4: Oroville Storage Summary in both CALVIN and CalSim

	Oroville Reservoir							
	Avg. Monthly Storage		Avg. Annual Max storage		Avg. Annual Min Storage		Avg. Annual Drawdown	
For:	TAF							
	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim
All Years	2810	2321	3502	2996	2192	1780	1309	1216
Critical Months(PYT = 1)	2440	1291	3389	1718	1665	989	1723	729
Wet Months (PYT = 5)	3138	2986	3537	3501	2629	2574	907	927

Figure 4-4: Average Monthly Oroville Storage for each Month in CALVIN and CalSim



4.2.4. Folsom Reservoir

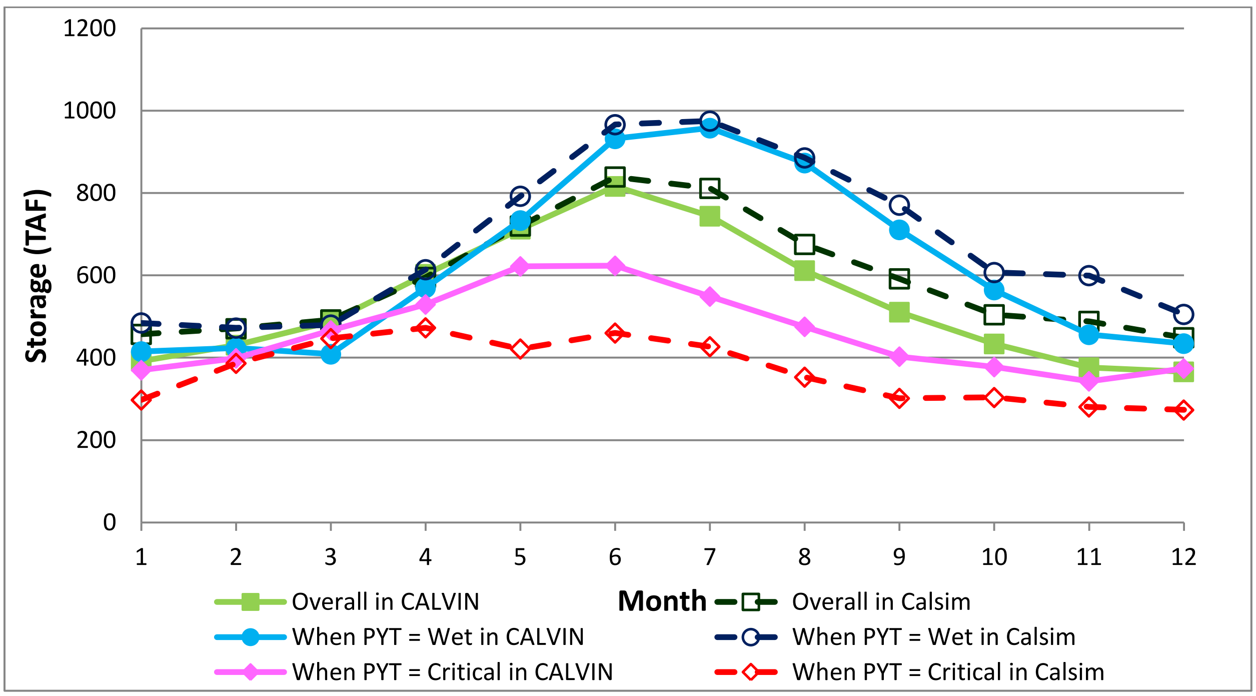
Folsom is part of the Central Valley Project storing water along the American River to help manage water supply, generate hydropower, and control floods for the city of Sacramento. The maximum capacity is 1120 TAF and the dead pool is 83 TAF. The modeled results for Folsom from both CALVIN and CalSim are presented below in Table 4-5 and Figure 4-5. On average, CalSim stores about 50 TAF more water in Folsom per month than CALVIN does, except in dry periods when CAVLIN averages 80 TAF more. Despite this, CALVIN averages more annual drawdown overall, by 50 TAF, and in wet and dry periods, by 50 and 80 TAF, respectively. Both average monthly storage and average annual drawdown in both models increases when PYT is wet and decreases when PYT is dry.

Figure 4-5 shows average Folsom storage by month for both models. In CALVIN the drawdown season usually occurs from June to December, but shifts with water availability. When the previous year was dry, CALVIN still begins drawdown in June, but with less supply the season ends a month sooner, by November. Peak storage occurs a month earlier as well, in May, but there isn't much drawdown until June. If the previous year was wet Folsom reaches peak storage a month later than usual, in July, but most of the water is drawn down by December. However, in wet years refill begins later and storage remains at a minimum until March so there is more empty storage to catch spring runoff and prevent Spring flooding. CalSim behaves similarly to CALVIN for the drawdown and refill patterns, except that there is more total drawdown in CALVIN. However, in dry periods there is a dip in monthly average storage for May rather than a peak like in CALVIN. This dip occurs because in 1977, the driest year on record, CalSim storage is extremely low in May, bringing the average down.

Table 4-5: Folsom Storage Summary in both CALVIN and CalSim

	Folsom Reservoir							
	Avg. Monthly Storage		Avg. Annual Max storage		Avg. Annual Min Storage		Avg. Annual Drawdown	
For:	TAF							
	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim
All Years	540	591	816	839	366	449	450	390
Critical Months(PYT = 1)	439	355	623	473	343	273	281	200
Wet Months (PYT = 5)	640	697	958	975	409	472	549	503

Figure 4-5: Average Monthly Folsom Storage for each Month in CALVIN and CalSim



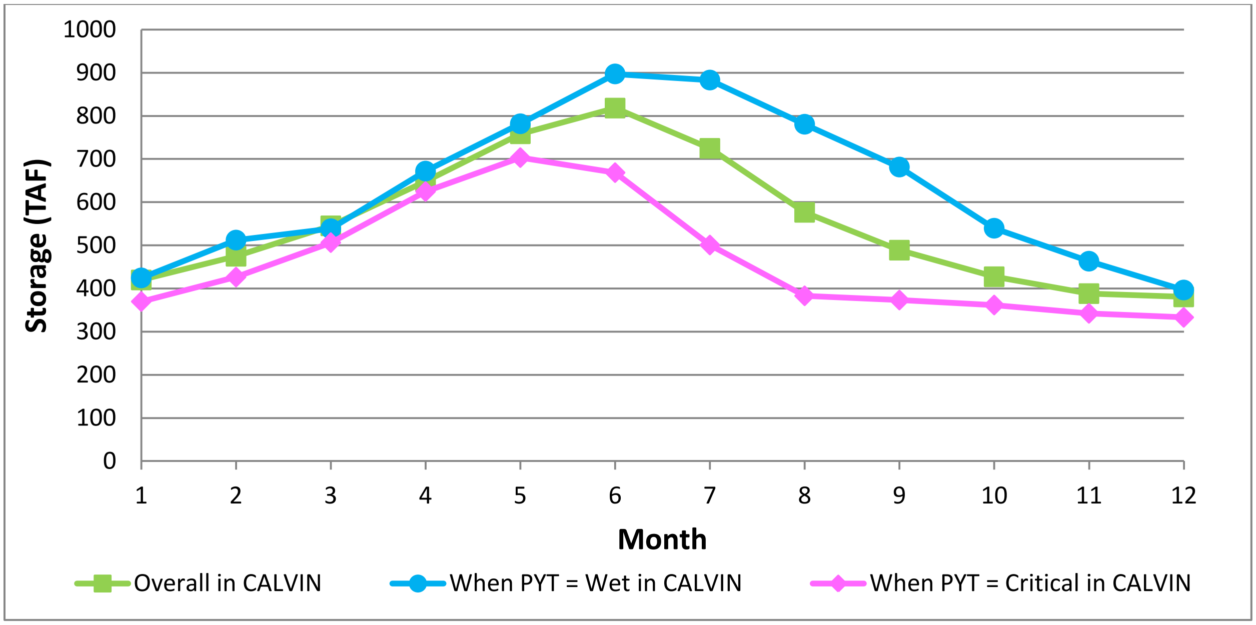
4.2.5. New Bullards Bar Reservoir

New Bullards Bar (NBB) is a locally owned reservoir on the Yuba River and it is used for storing irrigation water, generating hydropower, and providing flood storage. NBB is similar in size to Folsom with a maximum capacity of 930 TAF. The Yuba River eventually joins the Feather River which places NBB in parallel with Oroville, except they are not operated together because Oroville is part of the SWP. The modeled results for NBB from CALVIN are presented below in Table 4-6 and Figure 4-6. Unfortunately, there were no CalSim results for NBB so only the optimization model results are presented here. Skipping to Figure 4-6 we can at least see the patterns of drawdown and refill from CALVIN. Overall the drawdown season for NBB lasts from June to December and refill is just the reverse. If the previous year was wet then the pattern is similar except that there is more refill in May and drawdown is small until July. However, if the previous year was dry, then refill in the early months of the year is similar to the overall refill pattern, but storage peaks earlier, in May. From May to August there is a period of rapid drawdown, since Oroville releases only a minimum during this period and NBB makes up for it. In the last part of the year, from August to December, drawdown slows significantly to keep NBB storage from getting to low.

Table 4-6: New Bullards Bar Storage Summary in CALVIN only

	New Bullards Bar Reservoir							
	Avg. Monthly Storage		Avg. Annual Max storage		Avg. Annual Min Storage		Avg. Annual Drawdown	
For:	TAF							
	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim	CALVIN	CalSim
All Years	554	N/A	818	N/A	380	N/A	438	N/A
Critical Months(PYT = 1)	442	N/A	703	N/A	333	N/A	370	N/A
Wet Months (PYT = 5)	641	N/A	897	N/A	396	N/A	501	N/A

Figure 4-6: Avg. Monthly New Bullards Bar Storage for each Month in CALVIN only



4.3. Storage Allocation Rules

This section presents storage allocation rules inferred from CALVIN and CalSim results for the Sacramento Valley. The rules will be derived for reservoir systems moving from north to south, starting with Shasta and Trinity, then adding Oroville, and finally adding Folsom.

Optimized storage allocation rules between Oroville and New Bullards Bar are also described, although comparison with CalSim could not be done because CalSim does not include New Bullards Bar reservoir. Finally, there is a quick look at storage allocation between groundwater and surface water storage in the Sacramento Valley. Since there are many figures for these rules, most appear in Appendix B with only a few in this chapter to serve as examples.

4.3.1. Shasta - Trinity System

Figure 4-7 shows the overall storage allocation plot for the Shasta-Trinity system in CALVIN, where system storage is the total storage between the two reservoirs. The black lines superimposed on the plots represent the most extreme storage allocation rules that describe Shasta- Trinity operations. From here these curves are called storage allocation rule curves. The slope of these curves can be thought of as a relative drawdown or refill proportion between the two reservoirs at any specific total system storage; the sum of these proportions must equal 1.

In Figure 4-7, starting with high system storage and following the storage allocation curve to the left, we can derive the drawdown rule. When system storage is high, say greater than 6.3 MAF, all reservoir drawdown comes from Trinity, while Shasta remains at capacity. As system storage decreases to 6.3 MAF the storage allocation curves splits into two paths, one denoted by the solid line and the other by the dashed line. If we draw down along the solid line, then Trinity continues releasing from storage until its storage has been reduced to about 700 TAF. At this point system storage is around 5.3 MAF and Trinity storage is getting low. Next, CALVIN starts draining from Shasta, with minimal Trinity releases. When Trinity storage falls to 400 TAF it has reached its dead pool and cannot draw down further, so Shasta must supply all drawdown.

On the other hand, if drawdown follows the dashed curve then Shasta will release water much sooner. In this case, Trinity continues drawdown, but at a much lower proportion than it would have otherwise. When system storage falls to about 3 MAF then drawdown priority shifts slightly back to Trinity, while Shasta continues draining at a lower rate. Finally, when Trinity storage falls to 400 TAF, the dashed curve meets the solid curve again and 100% of the drawdown comes from Shasta. To describe the refill rules we would start at low system storage and move right along the curves, but the result would just be the reverse of the previously stated drawdown rules. These results are for all months and all years of model outputs.

To decide which of the above rule curves to use, let's limit the months shown on the storage allocation plot to just the months with a PYT of Wet and a PYT of Critical, as shown in Figures 4-8 and 4-9. In Figure 4-8, when the previous year is wet, storage in Shasta and Trinity tend to follow the dashed line. In this case, when the drawdown season starts the model wants to start draining from Shasta sooner because there is more chance that the coming refill season will be wet like the previous year. If it is wet then the model needs to draw down Shasta to prepare for floods and to limit spill later in the year due to the lack of storage capacity. Trinity has much smaller inflows, so having too much water there is less of a problem. Going the other way, during the refill season the model can delay Shasta's refill since there will be more spring runoff at the end of the season. This allows Trinity to store more water for future droughts.

However, in Figure 4-9, if the previous year has been dry, there is less concern for coming floods and spills and more concern for water supply. In this case the model prefers to follow the solid line where most of Trinity's storage is released before tapping into Shasta's. In general, there are two reasons why CALVIN would prefer to release from one reservoir over another. The first reason is for economics, either in the form of incentives, such as hydropower benefits, or as deterrents, such as storage depletion penalties or operating costs. Since it is an optimization model trying to minimize total cost, CALVIN will use the cheapest water first. The other reason is to meet constraints, which forces the model to release water from a specific reservoir so water will reach a specific place at specific times, even if it is economically worse to do so. Examples of this are minimum flow constraints and demand areas that only one reservoir can serve. For every acre-foot of water released from Trinity it will produce additional hydropower benefits by passing through Whiskeytown Reservoir; this makes releases from Trinity more valuable than releases from Shasta. During the refill season Shasta storage is more valuable than Trinity storage because Shasta has higher storage depletion penalties (in reality, Shasta also needs to collect cold water during winter for summer fish flows).

Figure 4-7: CALVIN Storage Allocation Between Shasta and Trinity for all Months

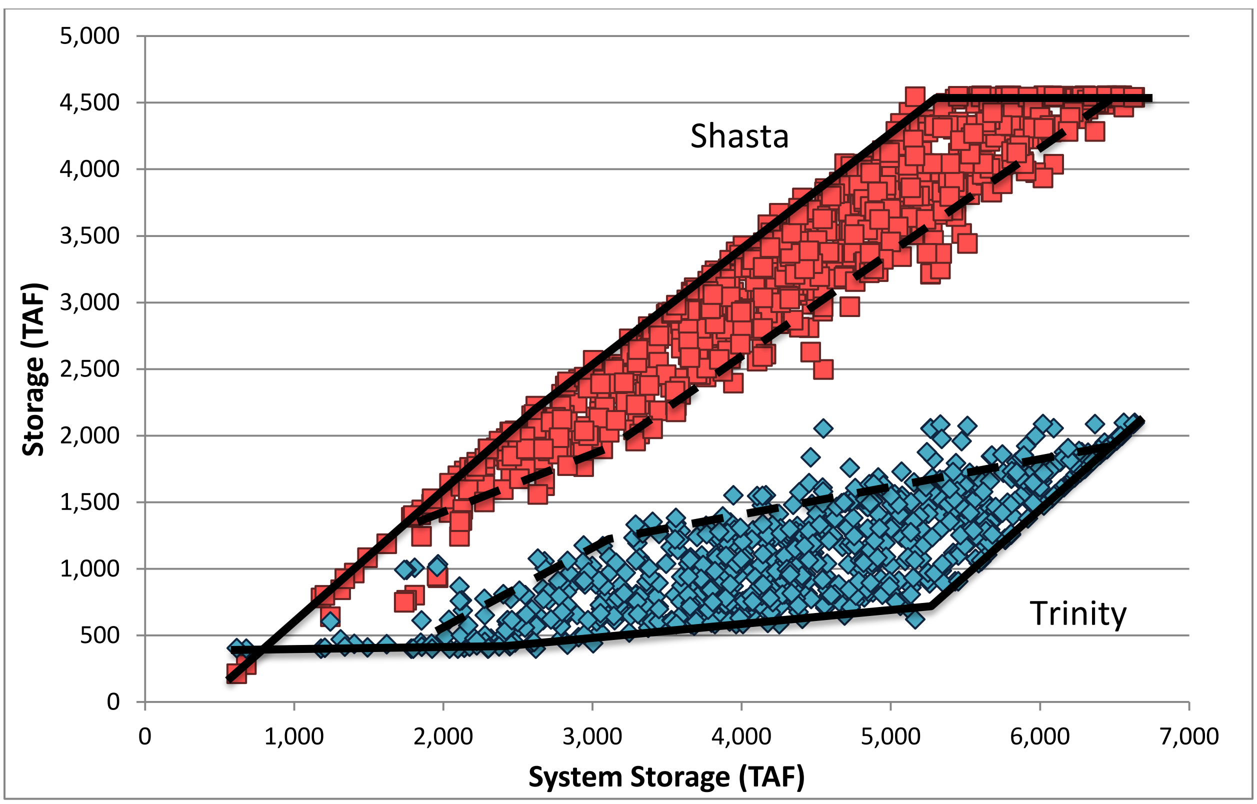


Figure 4-8: CALVIN Storage Allocation Between Shasta and Trinity when PYT = Wet

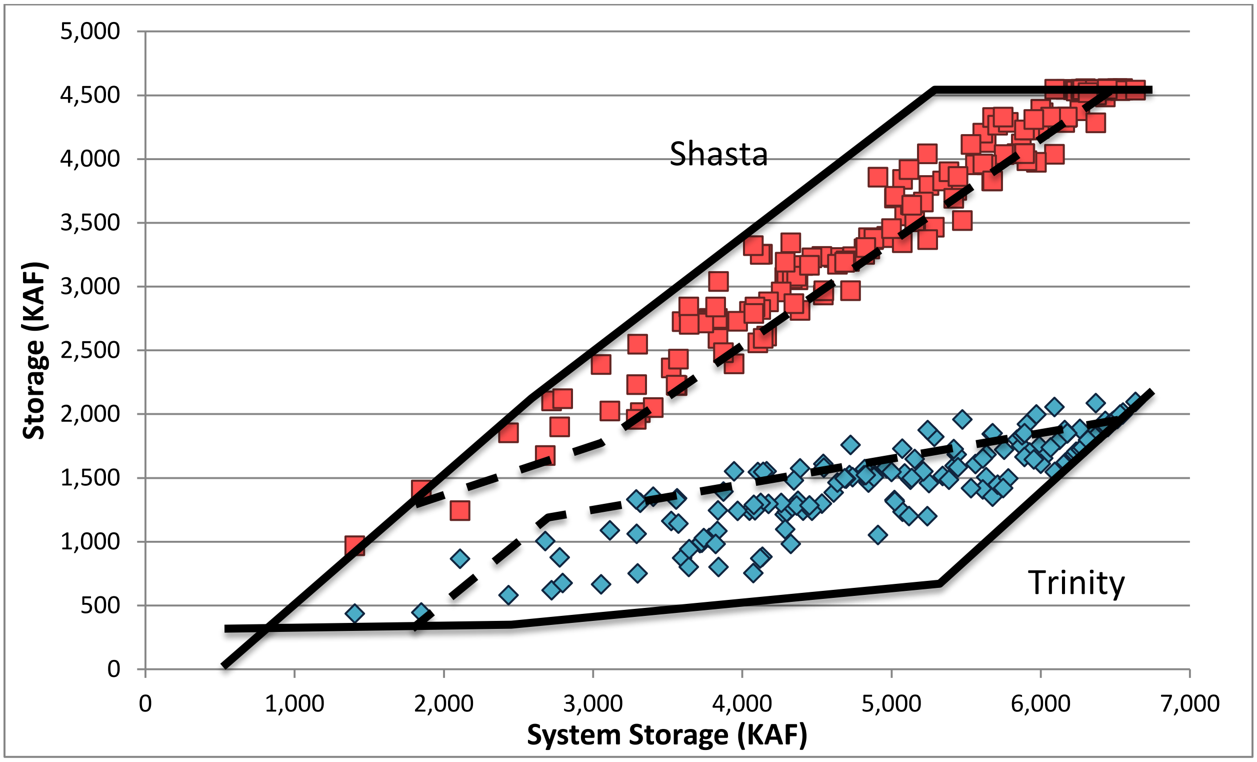


Figure 4-9: CALVIN Storage Allocation Between Shasta and Trinity when PYT = Critical

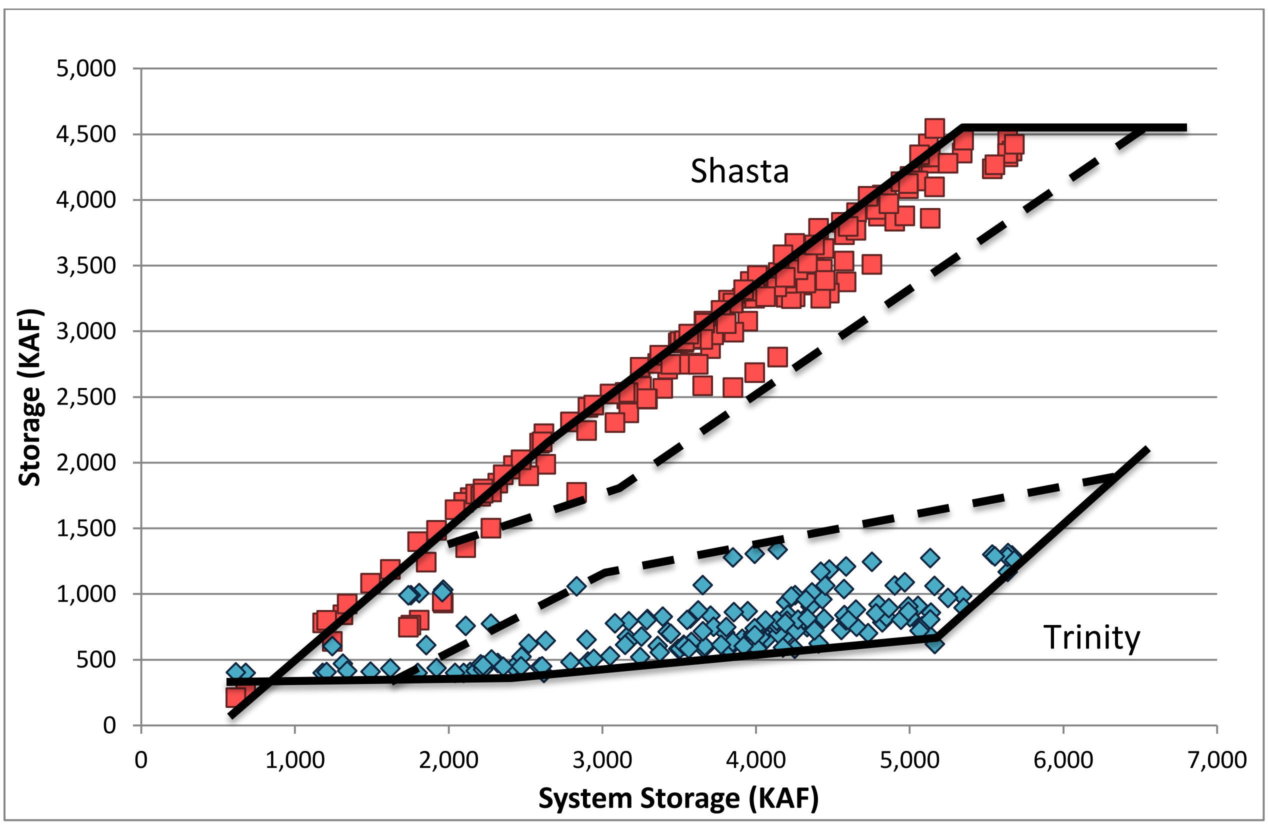
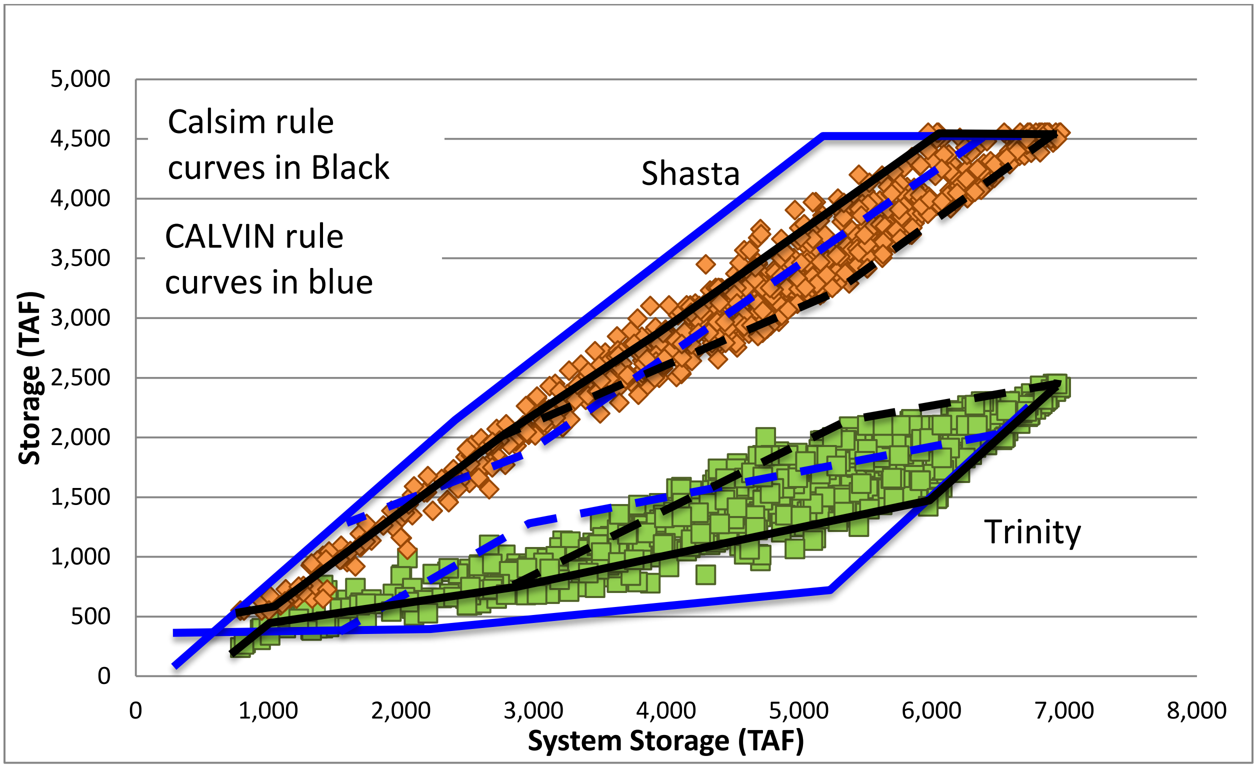


Figure 4-10 below shows the overall storage allocation plot for the Shasta-Trinity system in CalSim, which has a similar pattern. Starting at high system storage and moving left along the rule curves, once again there are two paths, a solid line for dry PYT and a dashed line for wet PYT. As before, in dry periods the model starts draining Trinity first, this time to about 1.5 MAF of storage, while keeping Shasta full. As system storage decreases further, CalSim begins to rely more on Shasta storage, releasing at a rate 4 AF from Shasta to every 1 AF from Trinity. Finally, when both reservoirs are left with about 500 TAF in storage each, CalSim once again favors draining Trinity. Though earlier it was mentioned that Trinity has a dead pool of 400 TAF, in CalSim, at least for this run, it has a dead pool of 240 TAF. In the wet periods, CalSim starts by draining primarily from Shasta, while Trinity is drained more gradually. At a system storage of about 5.4 MAF, drawdown priority shifts slightly back to Trinity, while Shasta continues draining at a lower rate. When the system storage is about 3 MAF the two curves meet and further drawdown is the same as it would be in dry years.

The optimized storage allocation rule curves from CALVIN are superimposed on the plot in blue so the two rule sets can be compared. As mentioned above, the two rule curves are similar in shape, but CalSim storage is shifted down in Shasta and up in Trinity. In addition, the CalSim operations are somewhat closer to the operations suggested for wet periods from the CALVIN results. However, CalSim operations begin releasing from Shasta sooner in both wet and dry years. These rules could indicate that the CalSim model is more conservative in dealing with floods and follows operations that minimize their likelihood. Floods are an instantaneous large cost to the system so it makes sense to avoid them. CALVIN can be less conservative since it can see them coming, but it may be wise to error on the side of safety in the real system.

Figure 4-10: CalSim Storage Allocation Between Shasta and Trinity for all Months



The overall storage allocation rules described above help identify general patterns in optimal reservoir operation, but dividing the plots by month reveals more detail. Tables 7 and 8 summarize of the monthly storage allocation rules for the Shasta-Trinity system in CALVIN and CalSim, respectively. The rules here are summarized by each reservoir's release/refill proportion for a given range of system storage. The system storage boundaries on the left side of the tables are the largest and smallest system storage values seen in the model, using these rules outside that range would require extrapolation or additional modeling. The release/refill proportions were calculated by dividing the monthly plots into sections and using linear fits on each part of the plot. This can be somewhat subjective; if someone else looked at these results they would probably come up with a somewhat different set of proportions. Many supporting plots are in Appendix B.

Table 4-7 shows that for the November through April refill season, CALVIN always gives refill priority to Shasta if system storage is low. In the drawdown season the model gives initial release priority to Trinity since it generates more hydropower and as Trinity gets low priority shifts to favor Shasta. In October this pattern is disrupted because Shasta has a minimum storage constraint at around 1900 TAF in October (to maintain cold water storage), which forces the model to shift release priority back to Trinity when Shasta storage hits 1900 TAF. If system storage is low enough, which only happens in the driest years, the constraint will be relaxed and Shasta will continue releasing water. September operations also are affected by this cold water pool constraint since the model has to have enough Shasta storage going into October as well.

For CalSim, from Table 4-8, in the early refill season the model gives initial priority to Shasta, with the reservoir taking about 75 % of the refill when system storage is low. When system storage rises to about 3300 TAF the model begins filling the two reservoirs at nearly the same rate. During the spring, operations are similar those in the early refill season. However, when the system storage is very high Shasta takes on more refill. During the initial months of the drawdown season Trinity, accounts for most early drawdown, while Shasta only takes over if the system storage is low. As the season wears on, storage in Trinity will be depleted by its early use and Shasta will account for more drawdown

Table 4-7: Monthly Storage Allocation Rules for Shasta-Trinity in CALVIN

	Shasta + Trinity CALVIN				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	System Storage rule (numbers in TAF)	Shasta release proportion	Trinity release proportion
January	1244	5342	<4300	0.82	0.18
			>4300	0.07	0.93
February	2279	5678	<4800	0.75	0.25
			>4800	0.21	0.79
March	2609	5892	<5300	0.66	0.34
			>5300	0.03	0.97
April	3374	6180	<5250	0.81	0.19
			>5250	0.02	0.98
May	3446	6451	<5600	0.71	0.29
			>5600	0.08	0.92
June	2945	6549	<5700	0.62	0.38
			>5700	0.22	0.78
July	2225	6636	<6250	0.58	0.42
			>6250	0.16	0.84
August	1621	6370	<5850	0.61	0.39
			>5850	0.19	0.81
September	1340	5908	<2700	0.19	0.81
			between 2700 and 5500	0.69	0.31
			>5500	0.08	0.92
October	1207	5418	<2300	0.99	0.01
			Between 2300 and 2700	0.00	1.00
			Between 2700 and 4450	0.77	0.23
			>4450	0.18	0.82
November	680	5268	<4300	0.78	0.22
			>4300	0.05	0.95
December	616	5333	<4250	0.80	0.20
			>4250	0.05	0.95

Table 4-8: Monthly Storage Allocation Rules for Shasta-Trinity in CalSim

	Shasta + Trinity CalSim II				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	System Storage rule (numbers in TAF)	Shasta release proportion	Trinity release proportion
January	1014	5210	<3350	0.76	0.24
			>3350	0.52	0.48
February	1320	5550	<3400	0.77	0.23
			>3400	0.52	0.48
March	1412	5985	<4300	0.74	0.26
			Between 4300 and 5650	0.40	0.60
			> 5650	0.91	0.09
April	2083	6349	<4850	0.72	0.28
			Between 4850 and 6150	0.40	0.60
			>6150	1.00	0.00
May	2308	6852	<5300	0.77	0.23
			Between 5300 and 6600	0.36	0.64
			>6600	0.83	0.17
June	2351	6972	<3600	0.91	0.09
			Between 3600 and 6500	0.63	0.37
			>6500	0.07	0.93
July	1998	6947	<3650	0.90	0.10
			Between 3650 and 6350	0.59	0.41
			>6350	0.39	0.61
August	1331	6420	<3000	0.93	0.07
			>3000	0.57	0.43
September	1010	5850	<2700	0.88	0.12
			>2700	0.56	0.44
October	939	5375	<4250	0.71	0.29
			Between 4250 and 5150	0.28	0.72
			>5150	1.00	0.00
November	790	5100	<3300	0.76	0.24
			>3300	0.51	0.49
December	817	5102	<3350	0.77	0.23
			>3350	0.48	0.52

4.3.2. Shasta-Trinity-Oroville System

Figure 4-11 below shows the overall storage allocation plot for the Shasta-Trinity-Oroville system in CALVIN, with Shasta and Trinity treated as one subsystem. Once again, there are two storage allocation curves; however, this time the dashed line is the refill rule and the solid line is the drawdown rule. To show this, Figures 4-12 an 4-13 present the same storage allocation plot, but Figure 4-12 is limited to months in the main part of the refill season, January to April, while Figure 4-13 is limited to months in the main part of the drawdown season, June to September.

In Figure 4-12, storage during the drawdown season tends to fall on the solid line. Assuming the system starts at full and following the solid curve, Shasta-Trinity (mostly Trinity) has drawdown priority for the first 3 MAF, while Oroville is left at capacity. In CALVIN, Oroville has higher storage depletion penalties for the summer, so each acre-foot released from Oroville costs more than an acre-foot released from Shasta or Trinity. Therefore, Oroville is only drawn down during the early summer when other reservoirs are low. However, during August and September, storage depletion penalties at Oroville decrease. In addition, as the refill season approaches, the model will need to clear some storage in Oroville to prepare for floods. If at this time the storage between Shasta and Trinity is low enough, then Oroville releases will become more valuable than its storage and the model will draw from the reservoir at a slightly higher rate than it drains Shasta and Trinity. This will continue until Oroville storage falls to about 850 TAF and system storage is around 2700 TAF, at which point further depletion of Oroville incurs large penalties for any month, so the model must rely on withdrawals from Shasta and Trinity once again.

During the refill season, storage allocation follows the dashed line in Figure 4-13. Starting at low system storage and moving right along the dashed line, Oroville does not begin refilling until Shasta and Trinity have at least 2 MAF of storage. From there the dashed curve diverges from the solid line and Oroville begins filling, at first about half as fast as the Shasta-Trinity system. Once Oroville has around 2.2 MAF of storage, its refill rate increases and the reservoir fills to 3 MAF. At this point Oroville stops refilling to keep some open storage available during April and May to catch potential floods caused by spring runoff. When spring runoff arrives the reservoir fills to capacity to avoid storage depletion penalties in the summer. In addition, as the years become drier the dashed refill line approaches the solid line. Since drier years have less inflow during the refill season, the reservoir must begin refilling earlier and faster than usual.

Figure 4-11: CALVIN Storage Allocation Between Shasta, Trinity, and Oroville for all Months

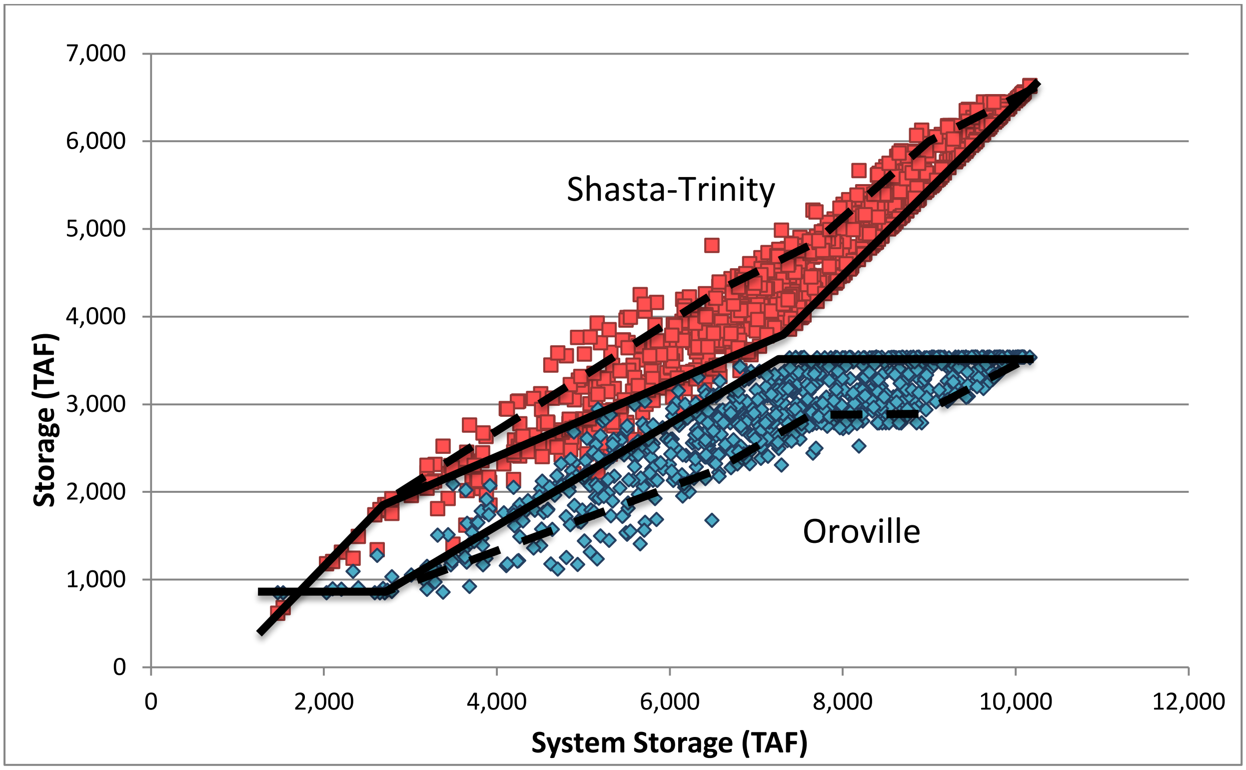


Figure 4-12: CALVIN Shasta-Trinity-Oroville Storage Allocation during the Drawdown Season, June-September

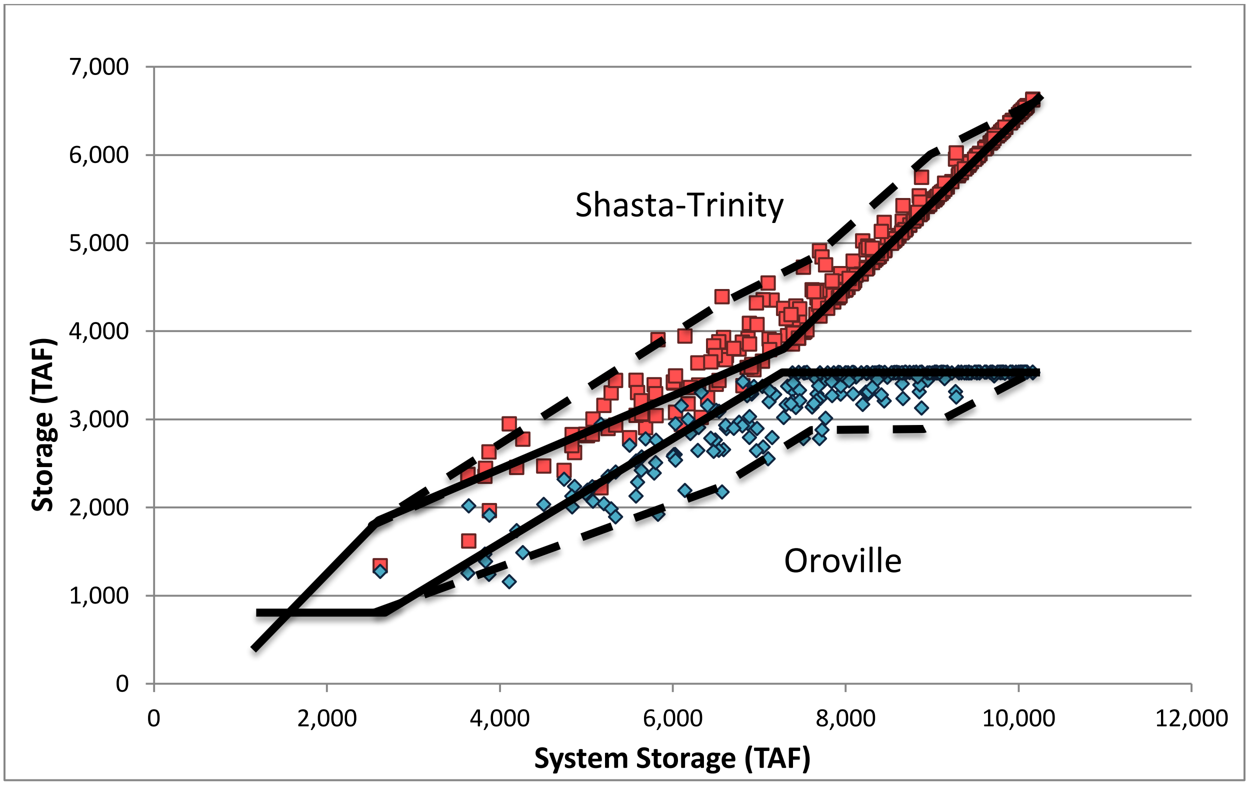
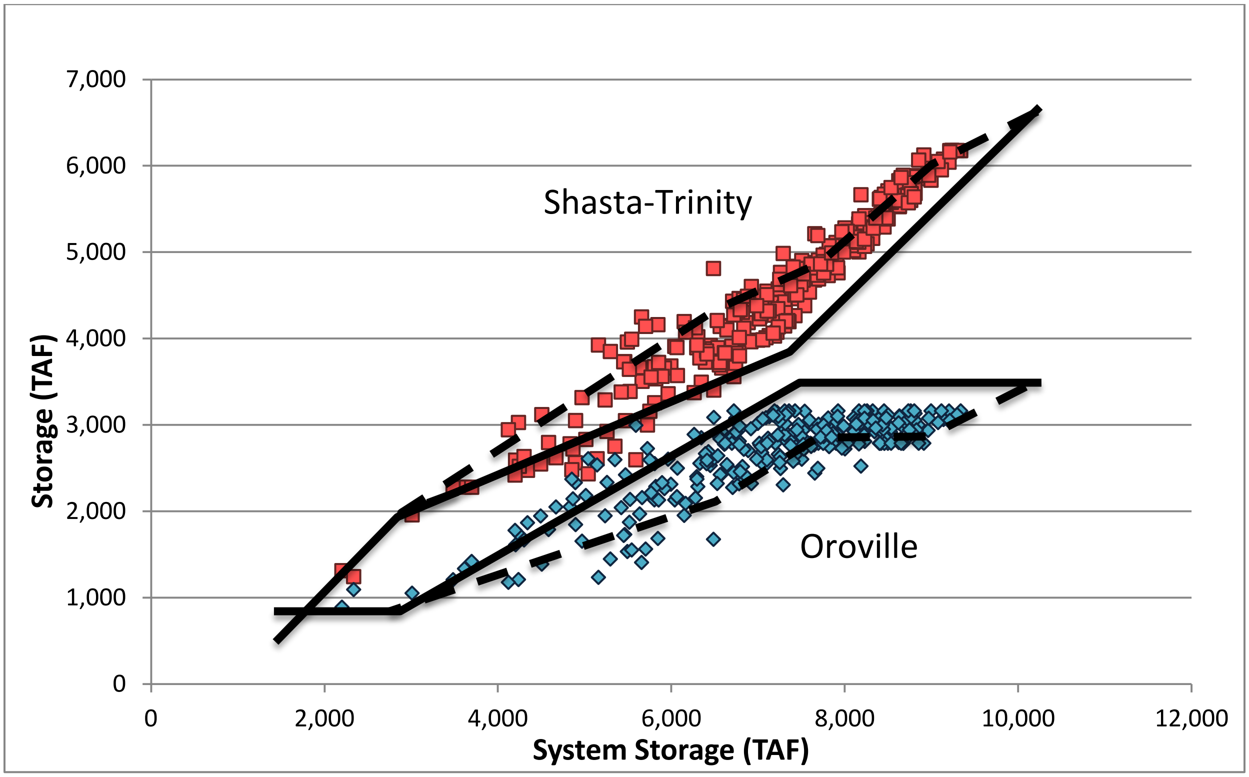


Figure 4-13: CALVIN Shasta-Trinity-Oroville Storage Allocation during the Refill Season, January-April



Examining CalSim storage allocation for the Shasta-Trinity-Oroville system in Figure 4-14, it is well approximated by a single average allocation curve for both drawdown and refill. For the drawdown season starting at high system storage, the Shasta-Trinity system begins with release priority given, while Oroville is kept full. However, after the first 500 TAF of drawdown, the two systems begin draining in about equal proportions. When Oroville storage falls to about 1.3 MAF at a system storage of 4.8 MAF, Oroville drawdown and refill slows. From here most of the drawdown comes from the Shasta-Trinity system, while Oroville makes minimal storage releases. Refill season storage allocation behaves the same, following the curve from left to right.

The CalSim results follow the (dashed line) CALVIN storage allocation curve well. CalSim's refill operations are close to CALVIN's optimal results for economics already, at least in wet years; another indication that CalSim's current operations are established for wet conditions. However, for the drawdown season, CalSim starts draining Oroville sooner. This frees additional storage capacity before the winter floods and inflows. As mentioned above, CALVIN benefits from hydrologic foresight, so it can see when floods are coming (although winter storage capacities in CALVIN are reduced to exclude each reservoir’s authorized flood storage capacity), but CalSim can’t see ahead. CalSim’s only option is to always be prepared by leaving significant storage open for the winter.

Figure 4-14: CalSim Shasta-Trinity-Oroville Storage Allocation Compared with CALVIN-based Rules for all Months

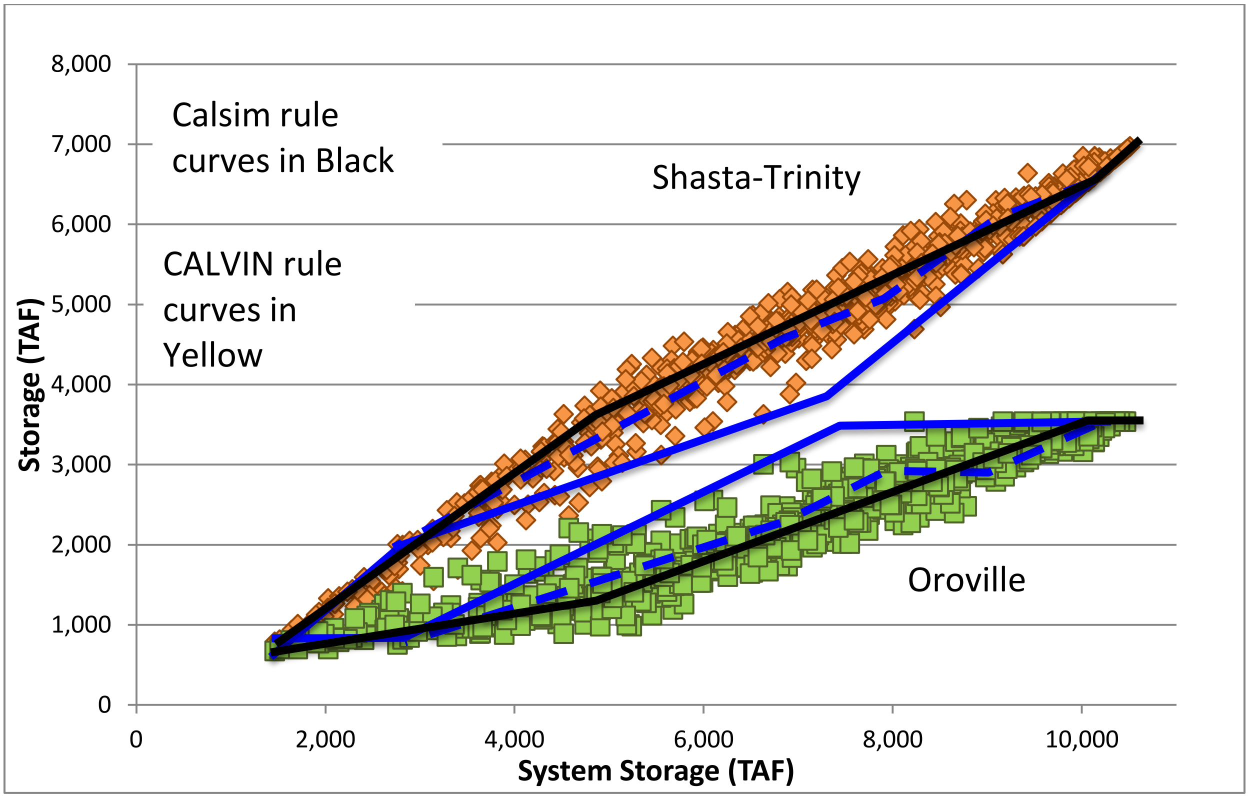


Table 4-9 summarizes monthly storage allocation rules for the Shasta-Trinity-Oroville system in CALVIN. In the waning months of the drawdown season, September through November, if total storage is high, the model favors draining the first 1 to 1.5 MAF of storage from Shasta or Trinity. However, as the storage between Shasta and Trinity falls the model shifts to balance drawdown equally between both reservoir systems. As the refill season begins, if system storage is low, initial refill priority is with the Shasta-Trinity system. As total storage increases, the refill is divided about equally between the two systems until Oroville is near its capacity, at which point all subsequent refill goes to Shasta-Trinity. In March, Oroville should be near capacity, so most refill goes to Shasta and Trinity. Coming to the end of the refill season, in April through June, Oroville should be kept at capacity. Oroville remains at capacity usually until July or August and then only starts drawdown if the storage in Shasta-Trinity is low.

Table 4-10 summarizes monthly storage allocation rules for the Shasta-Trinity-Oroville system in CalSim. From September to December, as the drawdown season comes to a close, Oroville is favored for the first 500 to 1000 TAF of drainage. Eventually, CalSim shifts to favor making more releases from Shasta-Trinity, at first about 60% to 40% and when storage is really low about 90% to 10%. As the refill season begins, initial refill priority is given to Shasta-Trinity in January and as the system storage increases CalSim slightly favors refilling Oroville. However, in February and March, as it gets closer to the drawdown season and Oroville approaches capacity, CalSim favors more refill going to Shasta or Trinity. In April, May, and June, like in CALVIN, all refill and drawdown is balanced with the same proportions: about 2/3 from Shasta-Trinity and 1/3 from Oroville. Unlike in CALVIN, CalSim doesn't need to keep Oroville full and can start draining it when it needs to. July has a similar pattern to June except it releases the first 500 TAF from Shasta-Trinity alone. Finally, in August CalSim begins to give more drawdown priority to Oroville at high systems storage before shifting back to the same 2/3 to 1/3 balance seen over the previous 4 months.

Table 4-9: Monthly Storage Allocation Rules for Shasta-Trinity-Oroville in CALVIN

	(Shasta/Trinity) + Oroville CALVIN				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	Systems Storage rule (numbers in TAF)	Shasta/Trinity release/refill proportion	Oroville release/refill proportion
January	2203	8226	<2900	0.88	0.12
			between 2900 and 7000	0.57	0.43
			>7000	0.90	0.10
February	3699	8769	<4650	0.12	0.88
			Between 4650 and 5550	0.94	0.06
			Between 5550 and 6900	0.45	0.55
			>6900	0.91	0.09
March	4897	8970	<8000	0.68	0.32
			>8000	0.97	0.03
April	5664	9339	always	0.94	0.06
May	6573	9900	always	0.98	0.02
June	6100	10087	always	0.95	0.05
July	5171	10166	<8300	0.77	0.23
			>8300	0.97	0.03
August	3641	9898	<8150	0.61	0.39
			>8150	0.93	0.07
September	2617	9438	<7900	0.53	0.47
			>7900	0.94	0.06
October	2102	8764	<7650	0.52	0.48
			>7650	0.98	0.02
November	1529	8408	<7350	0.56	0.44
			>7350	0.97	0.03
December	1466	8070	<2550	0.99	0.01
			between 2550 and 6650	0.55	0.45
			>6650	0.85	0.15

Table 4-10: Monthly Storage Allocation Rules for Shasta-Trinity-Oroville in CalSim

	(Shasta/Trinity) + Oroville CalSim II				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	Systems Storage rule (numbers in TAF)	Shasta/Trinity release/refill proportion	Oroville release/refill proportion
January	1887	8113	<6050	0.81	0.19
			>6050	0.38	0.62
February	2438	8641	<6050	0.80	0.20
			>6050	0.49	0.51
March	2596	9429	<4800	0.90	0.10
			>4800	0.60	0.40
April	3249	9512	Always	0.68	0.32
May	3616	10213	Always	0.67	0.33
June	3623	10510	Always	0.66	0.34
July	2763	10485	<10000	0.64	0.36
			>10000	1.00	0.00
August	2031	9958	<9550	0.65	0.35
			>9550	0.22	0.78
September	1709	9388	<4400	0.84	0.16
			between 4400 and 8850	0.60	0.40
			>8850	0.01	0.99
October	1634	8726	<4000	0.88	0.12
			between 4000 and 7700	0.64	0.36
			> 7700	0.12	0.88
November	1465	8263	< 3750	0.91	0.09
			between 3750 and 7300	0.64	0.36
			> 7300	0.07	0.93
December	1517	8052	<4700	0.86	0.14
			between 4700 and 7100	0.57	0.43
			>7100	0.17	0.83

4.3.3. Shasta-Trinity-Oroville-Folsom System

Figure 4-15 below shows the overall storage allocation plot for the Shasta-Trinity-Oroville-Folsom system in CALVIN, with Shasta, Trinity, and Oroville treated as one subsystem. Unfortunately, this plot gives little detail on storage allocation for Folsom since it is so much smaller than the other three reservoirs combined. For example, a drawdown of 500 TAF is half of Folsom's storage, but is only 1/20th of the combined Shasta-Trinity-Oroville system storage capacity. Figure 4-16 is the same plot with only Folsom storage allocation.

Like the previous system, Folsom storage allocation is different for refill and drawdown. Here the dashed line represents the refill curve and the solid line represents the drawdown curve. When drawdown starts, the first 1 MAF of storage is drained from the Shasta-Trinity-Oroville system (mostly from Trinity), while Folsom is kept full. When system storage falls below 10 MAF, but is still above 8 MAF, Folsom will start drawing down slowly, accounting for about 20% of the total drawdown. Below 8 MAF of total storage, drawdown at Folsom slows further to only 8% of the total drawdown, so that Folsom's small storage will last through the season. During the refill season, Folsom doesn't begin refilling until the system storage is about 4.5 MAF, allowing the other reservoirs, with more valuable storage, to recover first. As system storage increases, Folsom operations form a stair case pattern. Throughout the refill season Folsom has monthly capacity constraints that leave open storage for spring runoff. The goal of the model is to fill Folsom to capacity each month, if it is able, and then stop refilling until the following month. In general, Folsom should be filled to 575 TAF by March, 675 TAF by April, 800 TAF by May, and finally to the overall capacity of 975 TAF by June.

Figure 4-17, below, presents the overall storage allocation for Folsom from the CalSim model. The black lines are the CalSim storage allocation curves and the blue lines are the CALVIN storage allocation curves. While system storage is above 5 MAF, drawdown operations are very similar to those from CALVIN. When drawdown begins, CalSim takes the first 1 MAF of drawdown from Shasta-Trinity-Oroville, then starts drawing down Folsom, like in CALVIN. However, when system storage falls to 5 MAF, then Folsom should be around 300 TAF and the model will stop draining Folsom unless total storage falls below 3 MAF. Folsom storage is important for several reasons, including hydropower, Sacramento water supply, and migrating fish, so CalSim tries to maintain storage above 300 TAF, except in the driest years. In those dry years, the total storage will fall below 3 MAF and Folsom is forced to quickly release its remaining storage.

During refill, if total storage is below 8 MAF then refill operations are the same as the drawdown operations, only backwards. When system storage is below about 2 MAF, Folsom is kept at the dead pool. As system storage increases to 3 MAF, Folsom storage quickly rises to 300 TAF, but then refill slows. Between a total storage of 4.5 and 8 MAF Folsom begins filling faster. Above 8 MAF of system storage refill operations closely resemble those seen in CALVIN. Each month Folsom quickly fills to meet its monthly storage capacity and then ceases refill until the following month. This continues until Folsom reaches its overall capacity as the drawdown season begins.

Table 4-11 summarizes monthly storage allocation rules for Folsom compared with other major reservoirs of the Sacramento Valley. Since Folsom is smaller than the other reservoirs its allocation drains and refills more slowly, the largest drawdown/refill proportion is only 0.18. At the beginning of the drawdown season, in June, if system storage is high then Folsom will drain slowly; however, when Folsom storage is low, the drawdown rate is reduced to save water for later months. In July through September the system is operated similarly to June, except that at very high system storage the model prefers to withdraw solely from Shasta, Trinity, or Oroville. Near the end of the drawdown season, in October and November, drawdown at Folsom will continue at a constant rate until the reservoir is emptied. As the refill season begins, in December and January, CALVIN gives initial refill priority to Oroville, Trinity, and Shasta, just in case their storage is extremely low after the drawdown season. For the rest of the refill season though CALVIN attempts to refill Folsom slowly until it reaches its monthly capacity.

Table 4-12 summarizes monthly storage allocation rules for Folsom vs. the other major reservoirs of the Sacramento region in CalSim. At the beginning of the drawdown season, in June, the model gives drawdown priority to the Shasta-Trinity-Oroville subsystem until there is less than 10 MAF of system storage, then it begins to slowly drain Folsom. For the rest of the drawdown season the non-Folsom reservoirs should maintain the drawdown priority while system storage is high. Eventually Folsom should begin releasing water, but when its storage gets low it should reduce the release rate to preserve storage, much like in the CALVIN operations. However, if the system storage gets extremely low in July or August then Folsom should increase its release rate once again. In November, since the other reservoirs should already be low on storage, Folsom can begin draining immediately, but once the system storage falls to about 5 MAF then it should start preserving storage for the next year. Finally, for December through May, which represents the refill season, CalSim displays the same simple pattern that was seen in CALVIN: keep filling Folsom slowly until it reaches capacity.

Figure 4-15: CALVIN Storage Allocation Between Shasta, Trinity, Oroville, and Folsom for all Months

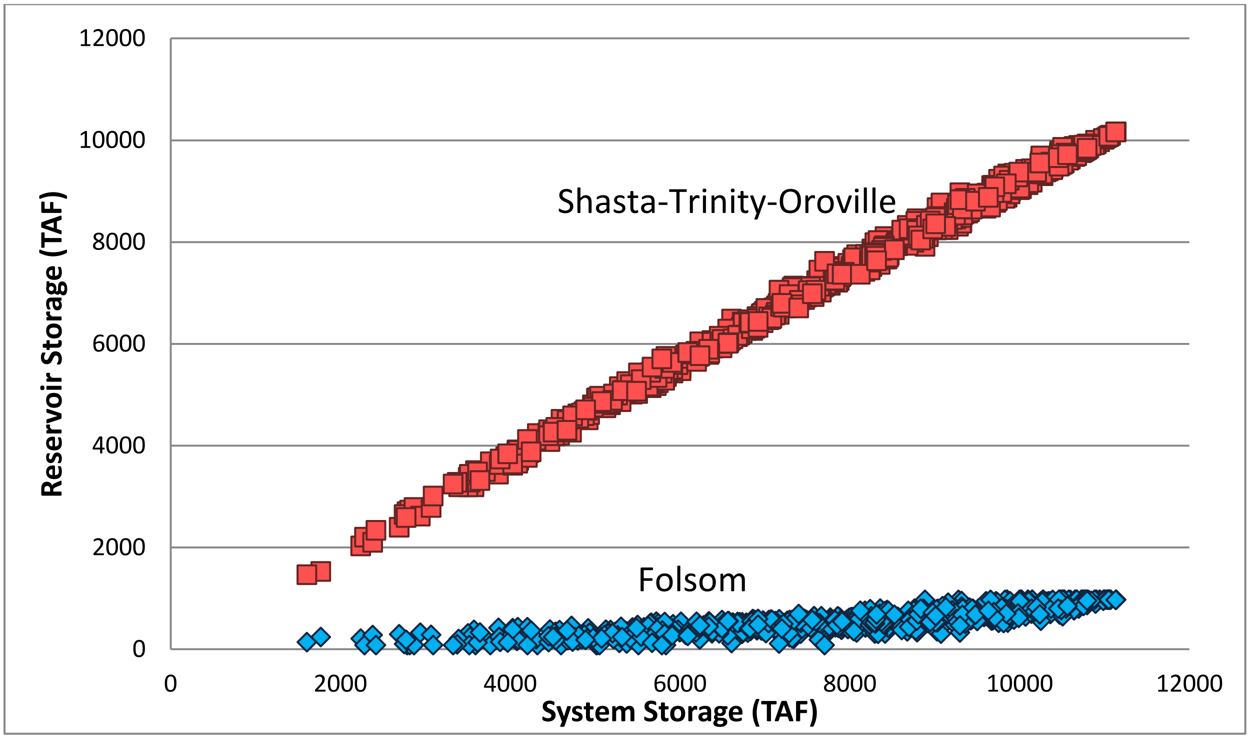


Figure 4-16: CALVIN Storage Allocation for Folsom in all Months

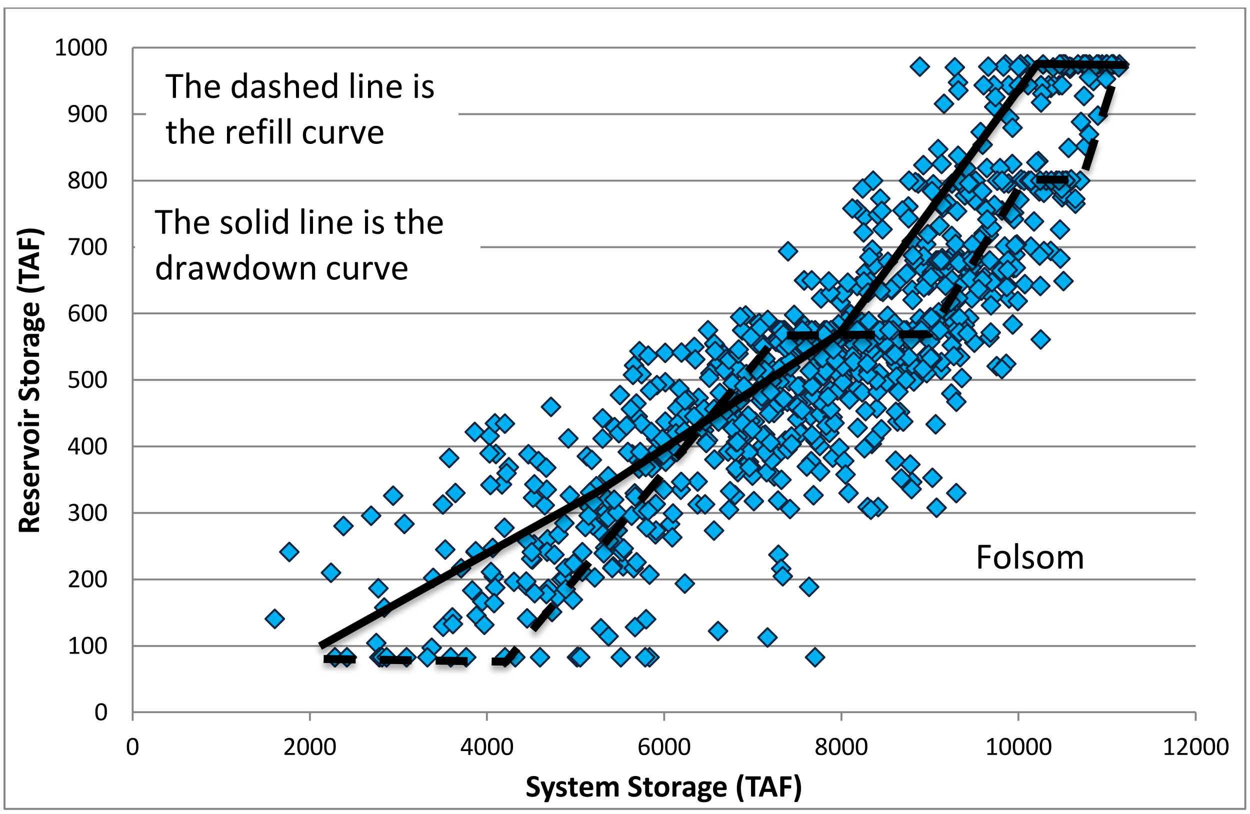


Figure 4-17: CalSim Storage Allocation for Folsom in all Months

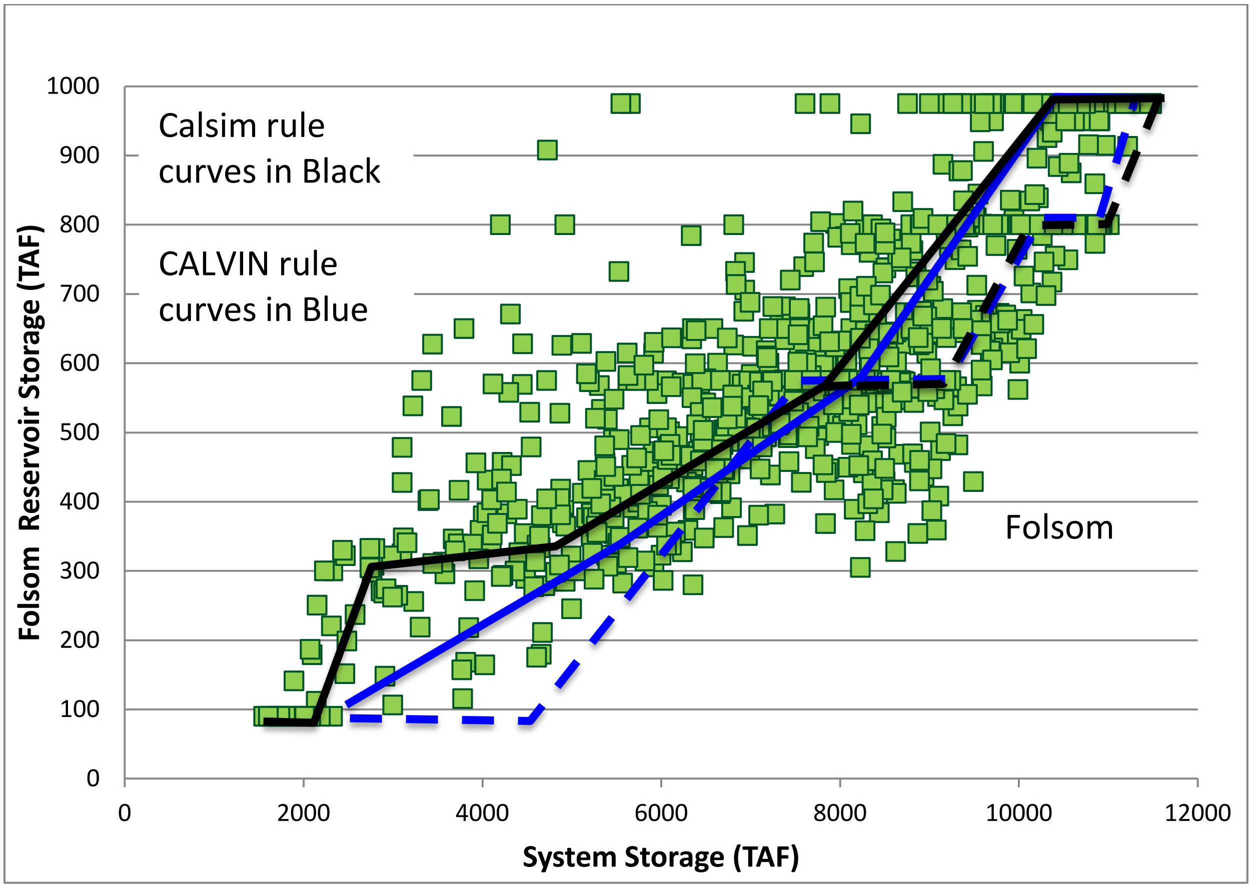


Table 4-11: Monthly Storage Allocation Rules for Shasta-Trinity-Oroville-Folsom in CALVIN

	(Shasta/Trinity/Oroville) + Folsom CALVIN				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	Systems Storage rule (numbers in TAF)	Shasta/Trinity/Oroville release/refill proportion	Folsom release/refill proportion
January	2286	8789	<3450	1.00	0.00
			between 3450 and 7850	0.89	0.11
			>7850	1.00	0.00
February	4205	9013	<8400	0.90	0.10
			>8400	1.00	0.00
March	5238	9345	<8400	0.93	0.07
			>8400	1.00	0.00
April	7348	9893	<9150	0.92	0.08
			>9150	1.00	0.00
May	7774	10700	always	0.90	0.10
June	6626	11062	<8250	1.00	0.00
			>8250	0.84	0.16
July	6845	11141	<7800	0.96	0.04
			between 7800 and 10600	0.82	0.18
			>10600	1.00	0.00
August	4031	10848	<6900	0.97	0.03
			between 6900 and 10300	0.84	0.16
			>10300	0.99	0.01
September	2943	9889	<7550	0.93	0.07
			between 7550 and 9550	0.86	0.14
			>9550	1.00	0.00
October	2382	8965	always	0.92	0.08
November	1771	8924	always	0.93	0.07
December	1607	8609	<4100	0.99	0.01
			between 4100 and 7700	0.89	0.11
			>7700	1.00	0.00

Table 4-12: Monthly Storage Allocation Rules for Shasta-Trinity-Oroville-Folsom in CalSim

	(Shasta/Trinity/Oroville) + Folsom CalSim				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	Systems Storage rule (numbers in TAF)	Shasta/Trinity/Oroville release/refill proportion	Folsom release/refill proportion
January	2074	8680	<8050	0.93	0.07
			>8050	1.00	0.00
February	3771	8804	<7700	0.92	0.08
			>7700	0.99	0.01
March	2867	9991	<7850	0.94	0.06
			>7850	1.00	0.00
April	4608	10168	<8700	0.90	0.10
			>8700	1.00	0.00
May	3975	11013	<9050	0.90	0.10
			>9050	1.00	0.00
June	3814	11485	<10000	0.89	0.11
			>10000	1.00	0.00
July	2911	11460	<4450	0.81	0.19
			between 4450 and 7150	0.97	0.03
			between 7150 and 10250	0.85	0.15
			>10250	1.00	0.00
August	2142	10908	<4000	0.85	0.15
			between 4000 and 6600	0.97	0.03
			between 6600 and 10200	0.87	0.13
			>10200	0.97	0.03
September	2328	10188	<5100	0.98	0.02
			between 5100 and 8900	0.89	0.11
			>8900	1.00	0.00
October	2096	9376	<5600	0.95	0.05
			between 5600 and 7300	0.89	0.11
			>7300	0.98	0.02
November	2234	8983	<5050	0.97	0.03
			>5050	0.91	0.09
December	2152	8527	<4600	0.98	0.02
			between 4600 and 7150	0.91	0.09
			>7150	1.00	0.00

4.3.4. Oroville - New Bullards Bar System

Figure 4-18 below shows the overall storage allocation plot for the Oroville-New Bullards Bar system in CALVIN. Like the previous system, New Bullards Bar storage allocation has different operations for refill and drawdown. Here, the dashed line is the refill curve and the solid line is the drawdown curve. Unfortunately, Figure 4-18 gives little detail on storage allocation for New Bullards Bar since it is small compared to Oroville, so Figure 4-19 is the same plot with only New Bullards Bar's storage allocation.

Following the solid line from right to left, drawdown operations suggest that New Bullards Bar should provide the first 400 TAF of drawdown while Oroville remains at capacity. As was mentioned above, Oroville has high depletion penalties at the beginning of the summer, so the model tries to keep Oroville full during that period. When system storage falls to about 4.1 MAF, New Bullards Bar has already emptied half of its usable storage, so to make the rest of its storage last longer, the model starts draining Oroville faster than New Bullards Bar. However, by the time system storage falls to 3 MAF, New Bullards Bar cannot release any more storage and Oroville must account for any further drawdown.

Following the dashed line from left to right, during the refill season most early refill goes to Oroville so that it can regain lost drought storage. When system storage reaches about 2.4 MAF, New Bullards Bar begins to fill faster as the Spring arrives. Like Folsom, New Bullards Bar has the same staircase pattern for refill operations. The goal of the model is to fill New Bullards Bar to capacity each month, if it is able, and then stop refilling until the following month. In general, New Bullards Bar should be filled to 600 TAF by March, to 685 TAF by April, to 825 TAF by May, and finally to the overall capacity of 930 TAF by June.

Table 4-13 summarizes monthly storage allocation rules for New Bullards Bar vs. Oroville in CALVIN. At the beginning of the drawdown season, in June and July, if system storage is near maximum then most drawdown will come from New Bullards Bar. However, after the first 150 to 300 TAF of drawdown, the model shifts to drain more water from Oroville, preserving New Bullards Bar storage for later months. August through November have similar operations, except that as system storage declines, the model must rely on Oroville more since New Bullards Bar is almost empty. In December through April, between 84 and 90 % of the refill goes to Oroville, partly because it is much larger than New Bullard Bar and partly because it has more valuable storage. Finally, in May, refill to New Bullards Bar will increase to account for about 40% of the total refill.

Figure 4-18: CALVIN Storage Allocation between Oroville and New Bullards Bar in all Months

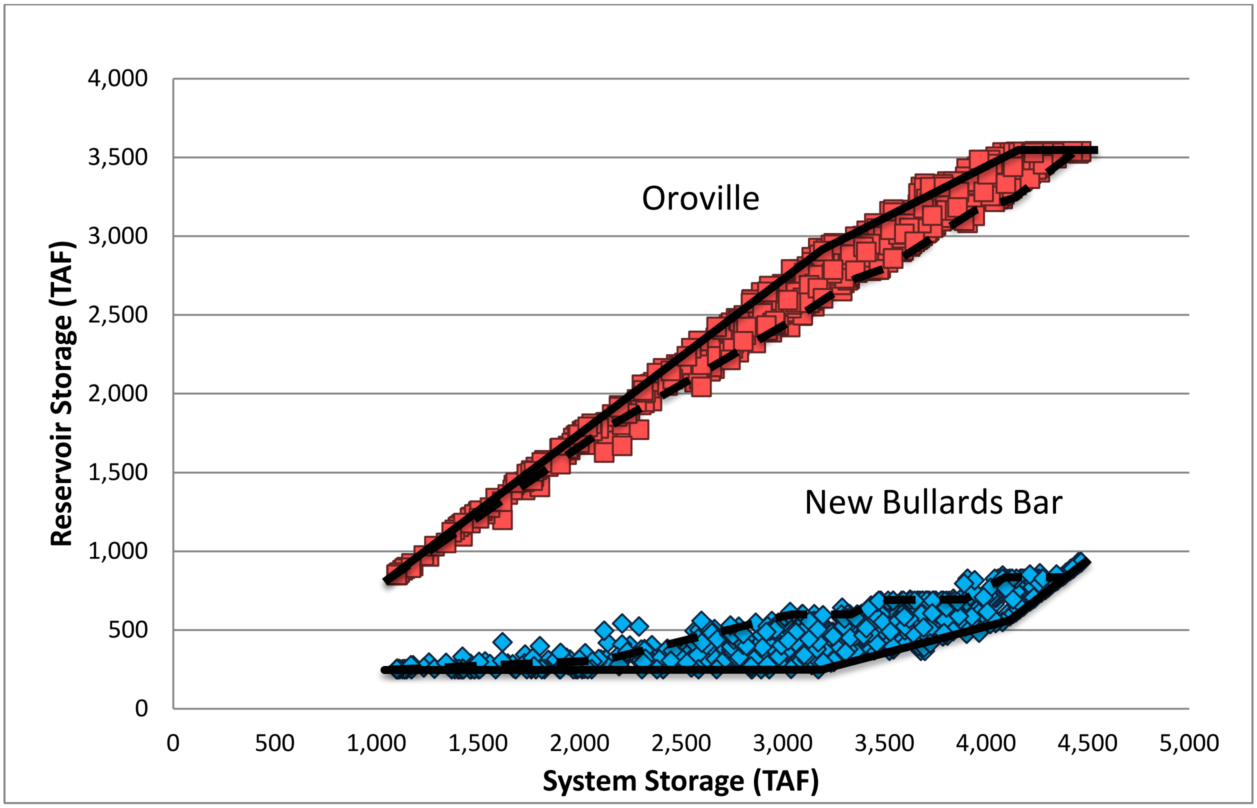


Figure 4-19: CALVIN Storage Allocation for New Bullards Bar in all Months

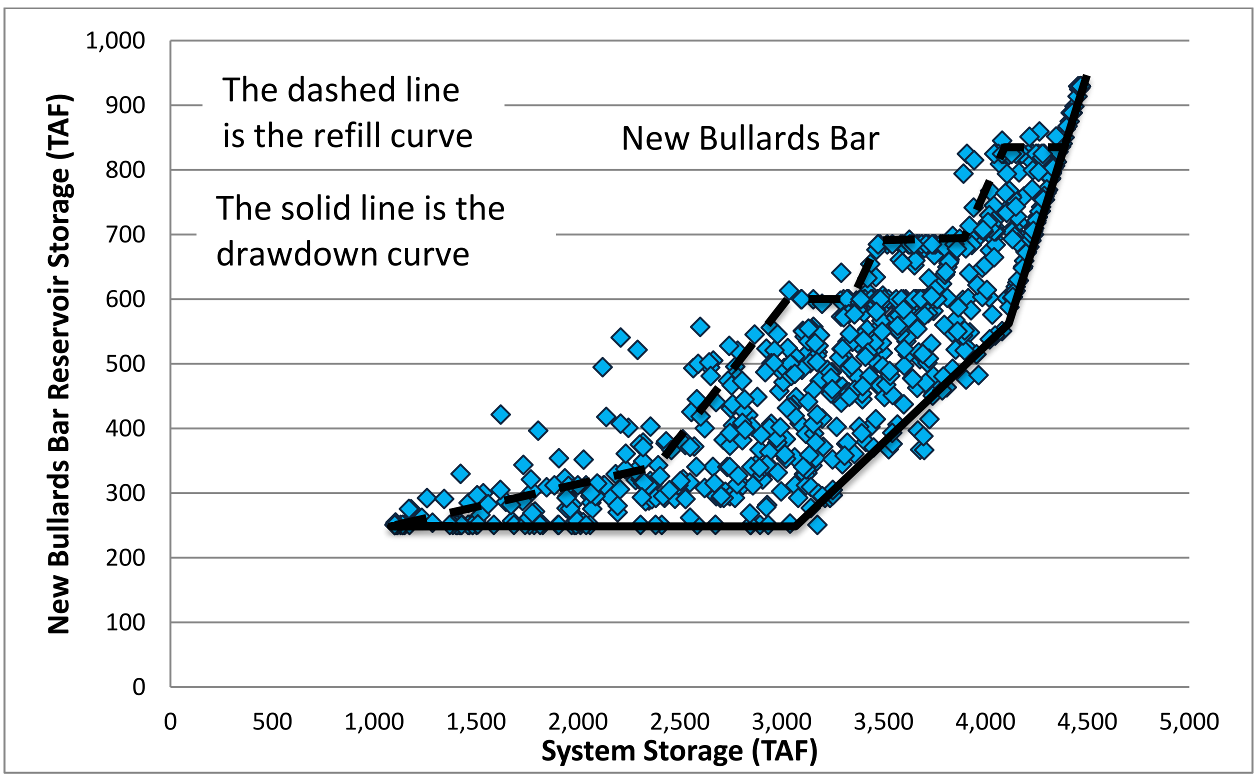


Table 4-13: Monthly Storage Allocation Rules between Oroville and New Bullards Bar in CALVIN

	Oroville + New Bullards Bar CALVIN				
	System Storage Boundaries (TAF)		Balance Rules		
	Min	Max	Systems Storage rule (numbers in TAF)	Oroville release proportion	NBB release proportion
January	1141	3754	Always	0.87	0.13
February	1429	3763	Always	0.85	0.15
March	1814	3763	Always	0.84	0.16
April	2664	3848	Always	0.84	0.16
May	3624	4288	Always	0.59	0.41
June	3672	4468	<4300	0.58	0.42
			>4300	0.04	0.96
July	3248	4426	< 4150	0.72	0.28
			> 4150	0.04	0.96
August	2233	4357	<2850	0.89	0.11
			Between 2850 and 4150	0.75	0.25
			>4150	0.11	0.89
September	1410	4292	<2450	0.96	0.04
			Between 2450 and 4050	0.83	0.17
			> 4050	0.15	0.85
October	1108	4051	<2750	0.95	0.05
			Between 2750 and 3850	0.80	0.20
			>3850	0.26	0.74
November	1100	3822	<2150	0.97	0.03
			Between 2150 and 3550	0.87	0.13
			>3550	0.26	0.74
December	1101	3801	Always	0.88	0.12

4.3.5. Sacramento Valley Surface Water storage vs. Groundwater storage

In this section storage allocation between the major Sacramento surface water reservoirs and Sacramento groundwater is examined. The pervious storage allocation rules were designed to operate each reservoir over a single year, with well-defined periods of drawdown and refill. Each year most of California reservoirs draw down in summer when demands are high and inflow is low, and refill in winter when more water is available. For groundwater, drawdown and refill are not tied to any one season; rather, aquifers refill in wet years and drawdown in dry years, with smaller seasonal storage fluctuations. Therefore, aquifer storage fluctuates more slowly than surface water storage. Refilling aquifers is a long process, because it requires waiting for water to percolate through the soil. We could speed it up through artificial recharge, but that takes water supplies away from other demands and it costs money. Drawdown, on the other hand, is easier to control through pumping and can occur over a relatively short period if surface water supplies are scarce, demands are high, and pumping capacity is ample. However, it is too expensive to rely on groundwater all the time and overuse has environmental consequences. In general, surface water is preferred over groundwater as it is easier to access, can be environmentally safer, and is less costly.

Figure 4-20 shows the storage allocation for major surface water reservoirs (Shasta, Trinity, Oroville, New Bullards Bar, and Folsom) in the Sacramento region, while Figure 4-21 shows the storage allocation for groundwater. To develop these rules, groundwater storage was corrected for total overdraft over the 72 year modeling period by adding the average monthly overdraft back into the aquifer each month. Unlike in previous cases, there are no storage allocation curves to define yearly operations. Instead, most yearly drawdown and refill is allocated to surface water reservoirs, as would be expected. Figure 4-20 has several lines that could represent the yearly operations for surface water storage. During drawdown, surface water storage will move left along the lines as the system drains, and then it will move to the right as the system refills. During non-drought years the slope of these lines averages out to about 0.87, which means that each year 87% of the drawdown and refill goes to surface water reservoirs. Over longer periods of time groundwater levels can change, but surface water operations probably won't be affected too much, which is why all the lines in Figure 4-20 have similar slopes. During droughts, the operations are less obvious, but it usually means there will be more drawdown of groundwater storage.

Figure 4-20: CALVIN Storage Allocation for Surface Water in the Sacramento Valley

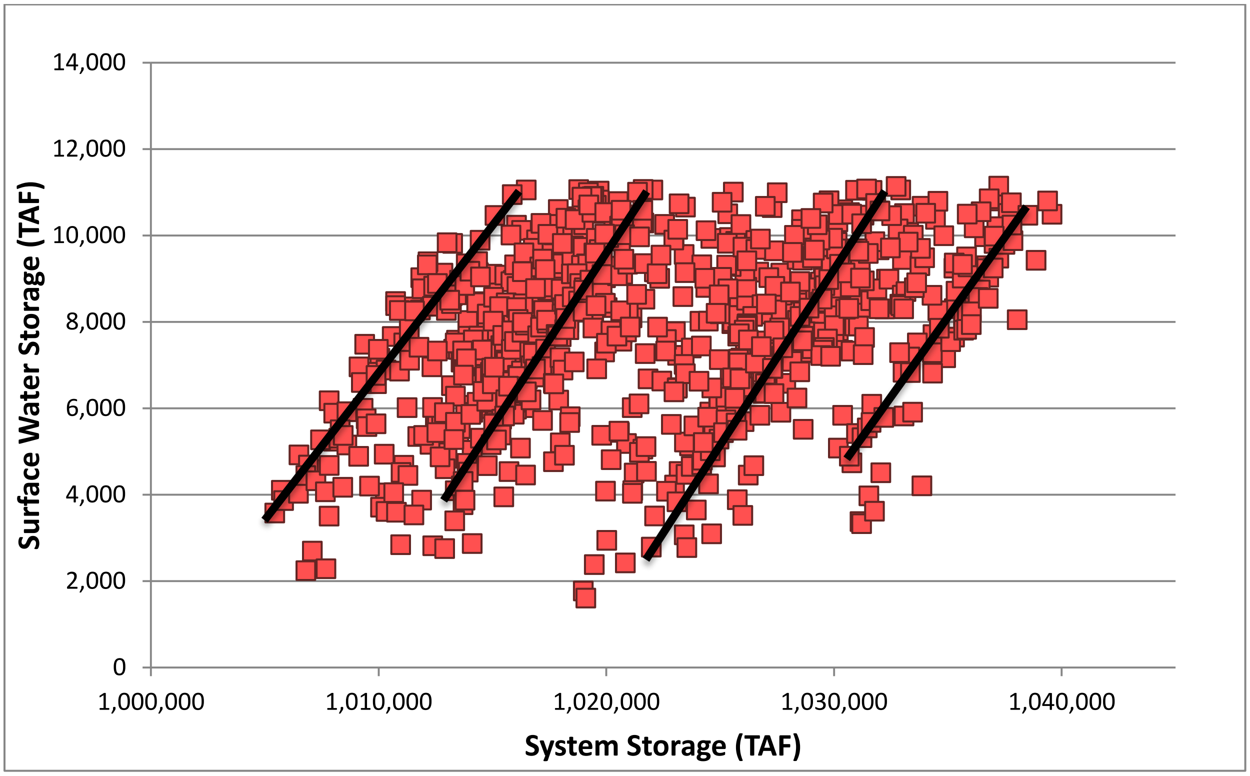
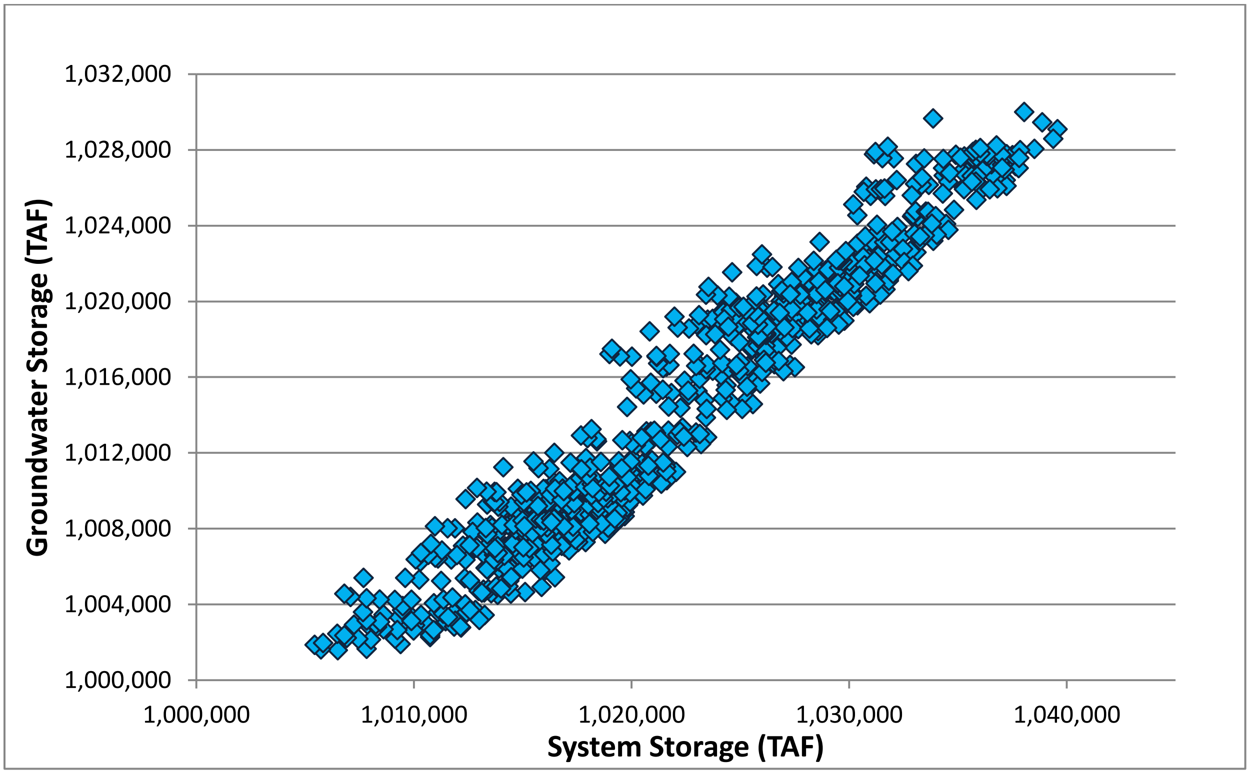


Figure 4-21: CALVIN Storage Allocation for Groundwater in the Sacramento Valley

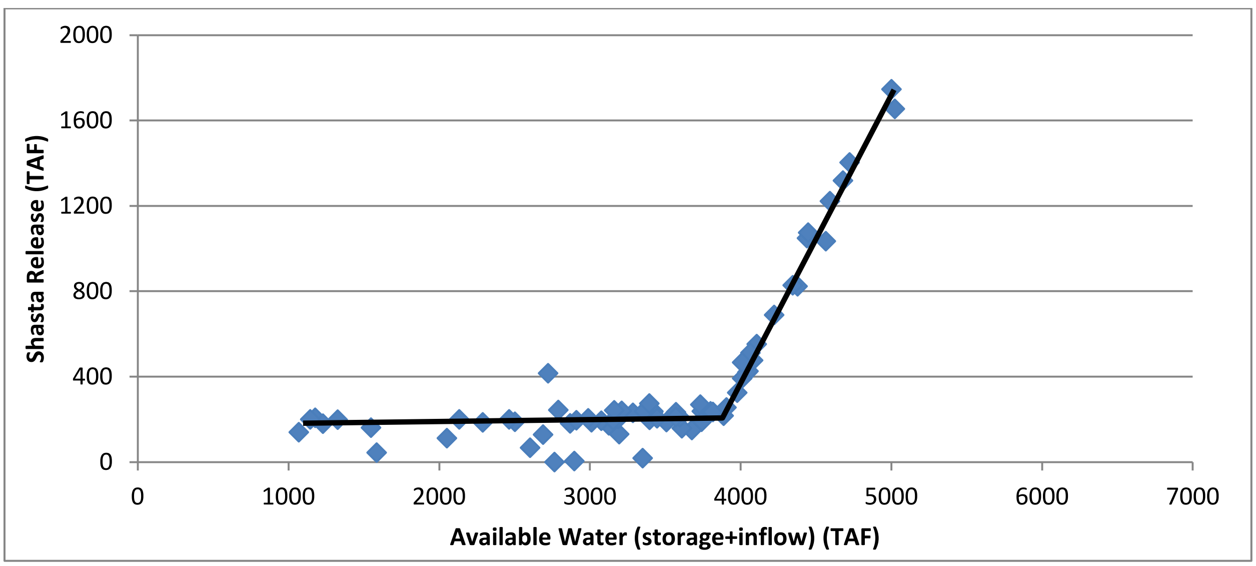


4.4. Reservoir Release Rules

This section presents the reservoir release rules for each individual reservoir inferred from CALVIN and CalSim results. These release rules are defined to operate a single reservoir for a single month based on some variable related to the system. The most common release rules in this study were based on available water (storage + inflow), inflow over the past year, and total regional storage. Since there are many figures for these rules, most are presented in Appendix C, with only a few in this chapter to serve as examples.

Release rules are often more difficult to create than storage allocation rules. Rules will rarely reproduce model results perfectly, instead the rules are inferred to approximate the observed patterns. Some patterns are easy to identify. Figure 4-22 shows Shasta release for January based on CALVIN results plotted vs. the available water (storage + inflow) of the reservoir in January. There is an obvious target of 200 TAF regardless of the available water, but when available water is too large, even after the target is released, the reservoir's capacity will be exceeded and it must release any extra water.

Figure 4-22: Shasta Reservoir Release Rule for January Inferred from CALVIN Results



Other times the rule may be more difficult to derive or involves more uncertainty. Figure 4-23 shows the Oroville release rule for October derived from CALVIN. The chosen release rule here sets two targets: one around 100 TAF when the available water < 2000 TAF and another at about 400 TAF when the available water > 2000 TAF, but there is substantial variation that this rule does not account for. For another example, Figure 4-24 gives Shasta release for June in CALVIN. When available water is low the reservoir release should increase as available water increases, until AW reaches about 3700 TAF then the release should plateau at a target of 900 TAF. Finally, at higher levels of available water, the modeled releases tend to fall to around 500 TAF. There are two reasons for this: 1) wetter years may already have enough water in the system, so additional reservoir releases are not needed, and 2) reservoir releases may be kept low to reduce flooding from inflows downstream. In addition, since CALVIN can see a drought before it arrives, the model may reduce release to preserve storage for the next year.

Figure 4-23: Oroville Reservoir Release Rule for October Inferred from CALVIN

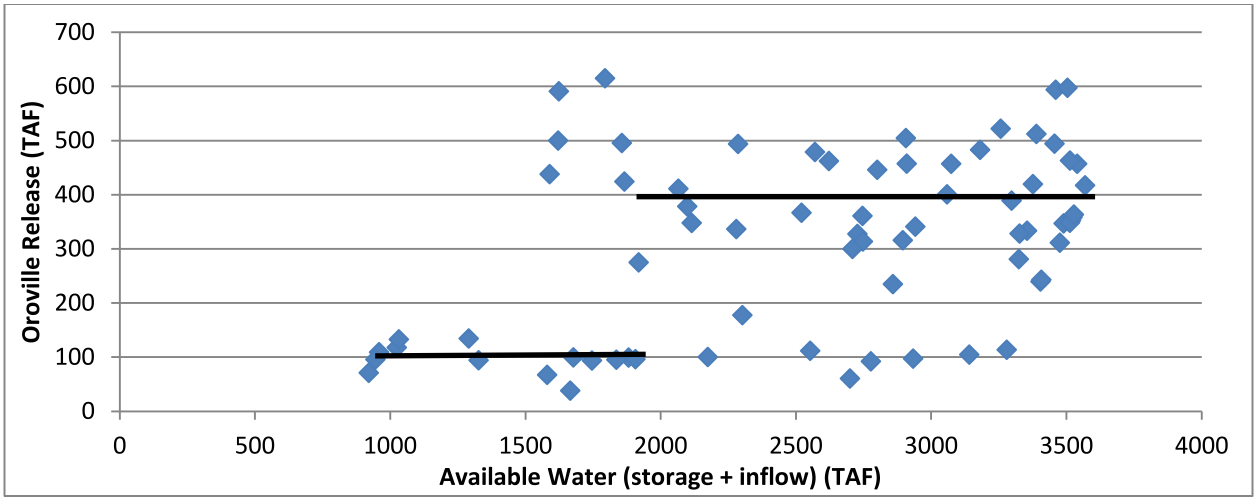
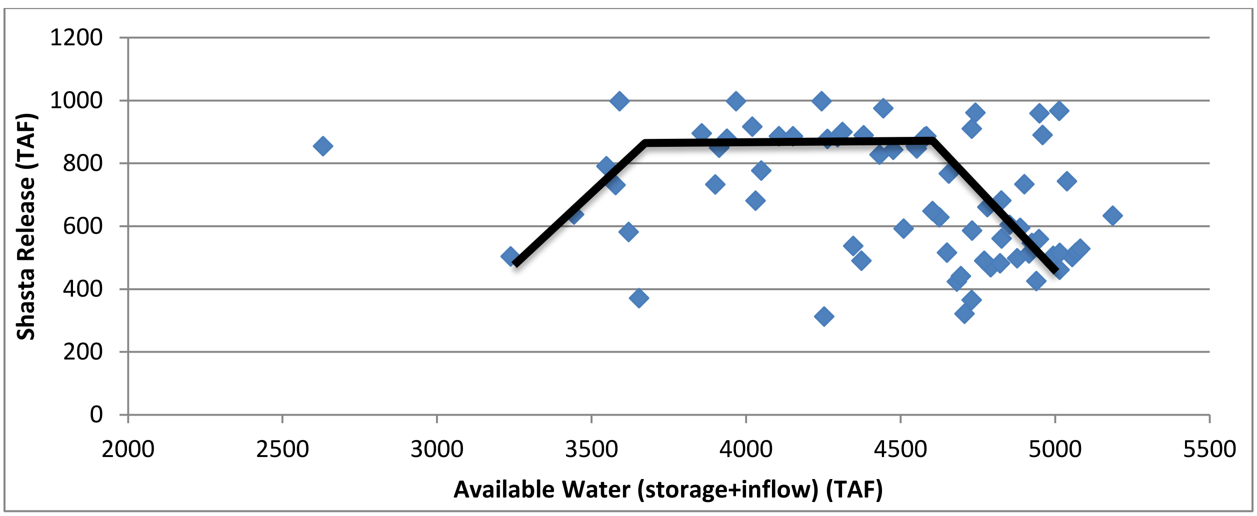
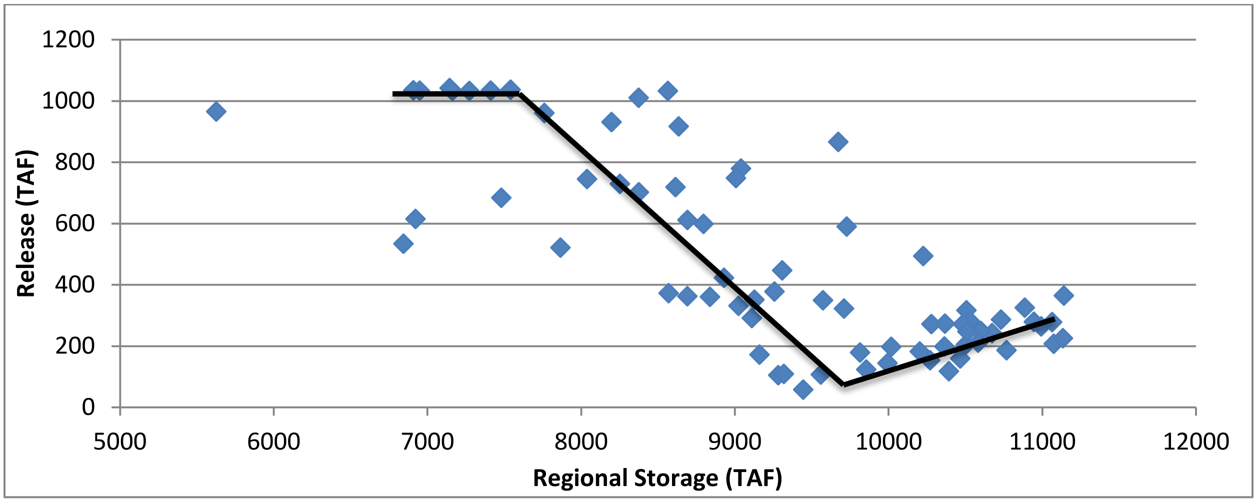


Figure 4-24: Shasta Reservoir Release Rule for June derived from CALVIN



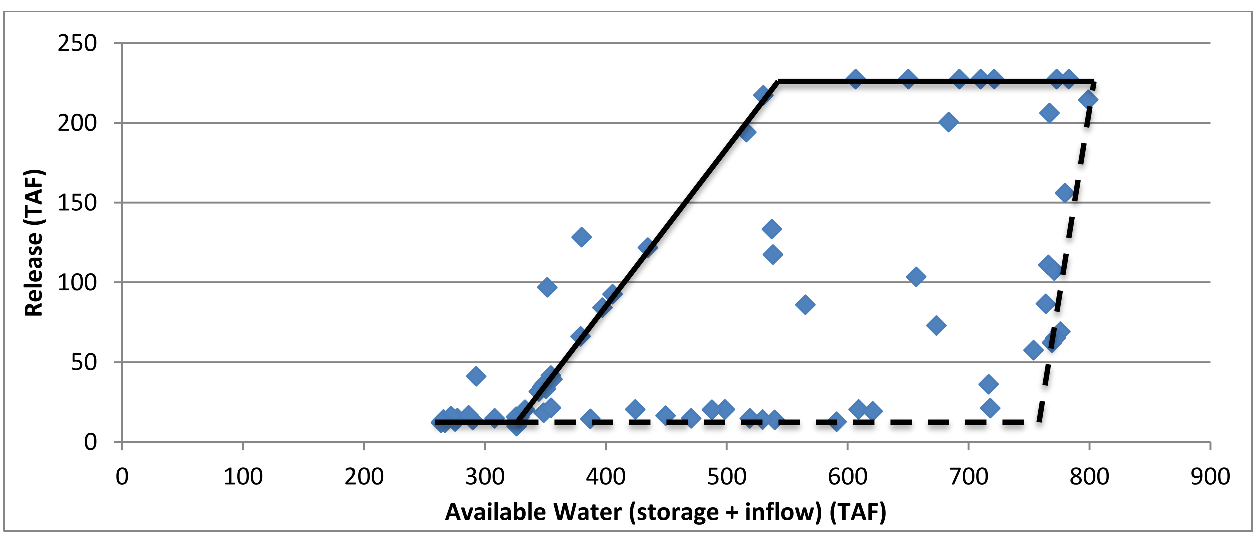
Release rules are sometimes driven by the state of the larger system around that reservoir. Figure 4-25 shows Oroville releases in July derived from CALVIN, this time plotted against the regional storage (including Folsom, Oroville, New Bullards Bar, Shasta, and Trinity storages). When regional storage is below 8 MAF the model relies on Oroville to release about 1 MAF of water. Oroville has a high value for storage in July, so the only time the model will make such large releases should be if the other reservoirs in the system are running low. As system storage increases from 8000 to 9800 TAF Oroville's release falls to about 100 TAF because there is enough water elsewhere to meet the demands. Finally, when the system storage exceeds 9800 TAF, release increases because there is a relative abundance of water at Oroville.

Figure 4-25: Oroville Reservoir Release Rule for July derived from CALVIN



Another interesting case is the release rule for NBB in September from CALVIN results shown in Figure 4-26. In this case, when available water is below 325 TAF there is low release target of about 15 TAF/month. However, above 325 TAF of available water, releases can follow two paths. The path chosen depends on available water for the coming year, which we cannot know in advance, so it is not useful for rule development. If available water over the next year is high, then NBB will need to make room for incoming flows by following the solid black line, increasing releases based on how much water it currently has until it reaches an upper release value of 225 TAF/month when the current available water is about 525 TAF or more. If little available water is coming over the next year, then the optimum release pattern would be to stick with the low target of 15 TAF/month, regardless of current available water, unless the available water exceeds the reservoir capacity. With this low target, the reservoir saves as much water as possible for the following dry year.

Figure 4-26: New Bullards Bar Reservoir Release Rule for September Inferred from CALVIN



These are a few examples of release rules inferred from CALVIN results; in total there are 60 release rules. These rules are presented graphically and summarized in the tables of Appendix C. However, in this form it is difficult to directly compare release rules between CALVIN and CalSim. The best way to compare these release rules is to examine how the system would perform under each rule set, given the same inputs. To achieve this, a simple excel simulation was made to model storage in the five reservoirs based on the rules derived from CALVIN. From here on the derived results are the results that would occur using the developed release rules described in Appendix C and the direct results are the actual results taken from the CALVIN and CalSim models.

4.4.1. Shasta Reservoir

Figure 4-27 compares average monthly releases from Shasta produced by simulation of the derived rule sets and the direct model results themselves. For the derived and direct CALVIN results, both begin the drawdown season averaging large releases, around 700 TAF in May through August. Releases then gradually decrease from August to November until they fall to about 250 TAF/month. During this period, both the simulated rules and direct CALVIN results behave similarly, except in October when direct CALVIN releases are about 100 TAF larger. However, from December to May, the derived and modeled CALVIN results behave a bit differently. Direct CALVIN releases remain around 250 TAF until February and then rapidly increase over the next three months to 650 TAF, as spring runoff enters the reservoir. However, the derived results have releases increase slowly to about 400 TAF from December to March and then remain at 400 TAF in April before jumping to 700 TAF in May.

In comparison with CALVIN results, CalSim releases only reach 700 TAF in July and then quickly fall over the next few months until October when they reach a minimum of 300 TAF. From October to February the average release increases to about 480 TAF. At this point releases are much larger than they were in CALVIN, as CalSim opens up extra storage for spring runoff. Average releases then fall to 400 TAF in April, which matches the results of the simulated release rules. However, for the rest of the spring and early summer, releases slowly increase to the maximum in July rather than ramp up quickly in May, as CALVIN does.

Figures 4-28A and 4-28B show the storage time series comparison between the simulated results and the direct CALVIN and CalSim results for Shasta reservoir. In the direct results, CALVIN storage levels usually fluctuate by about 2.5 MAF in most years, while CalSim has a yearly storage change of only 1.5 MAF. During droughts, the storage in CalSim that usually goes unused will be quickly drained and the reservoir will be forced to operate at lower overall storage levels. CALVIN, however, foresees when droughts will occur and how long they will last, which allows it to better allocate its storage over the length of the drought. Rather than drain storage completely, CALVIN saves water by reducing yearly drawdown until the final year of a drought, when the model knows there will be more water available in the near future. However, in the results derived from the CALVIN release rules, hydrologic foresight is no longer an issue. The release rules cannot predict how long a drought will last and end up behaving much more like CalSim, draining most of the storage rather than preserving it. In non-drought periods the derived CALVIN storage level tends to vary more during the year, usually ending with about 1 MAF less storage than CalSim at the end of the drawdown season.

Figure 4-27: Average Monthly Shasta Release Comparison for the Derived Rules and Direct Model Results

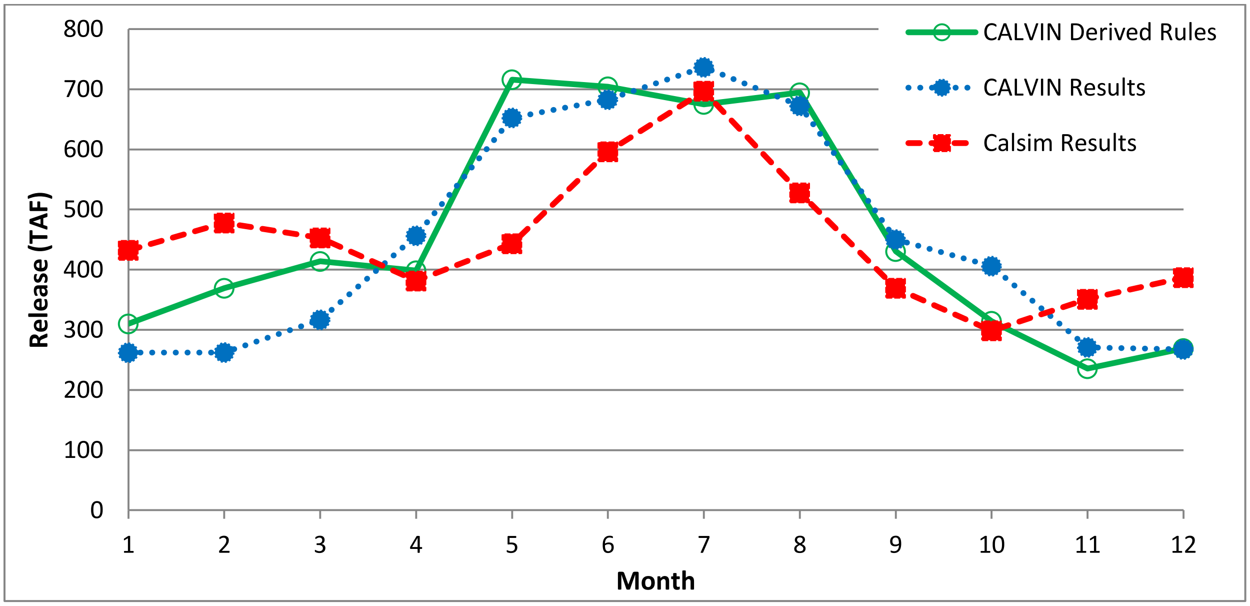


Figure 4-28A: Shasta Storage Time Series Comparison from Derived Rules and Direct Model Results, Part (A) 1921 to 1957

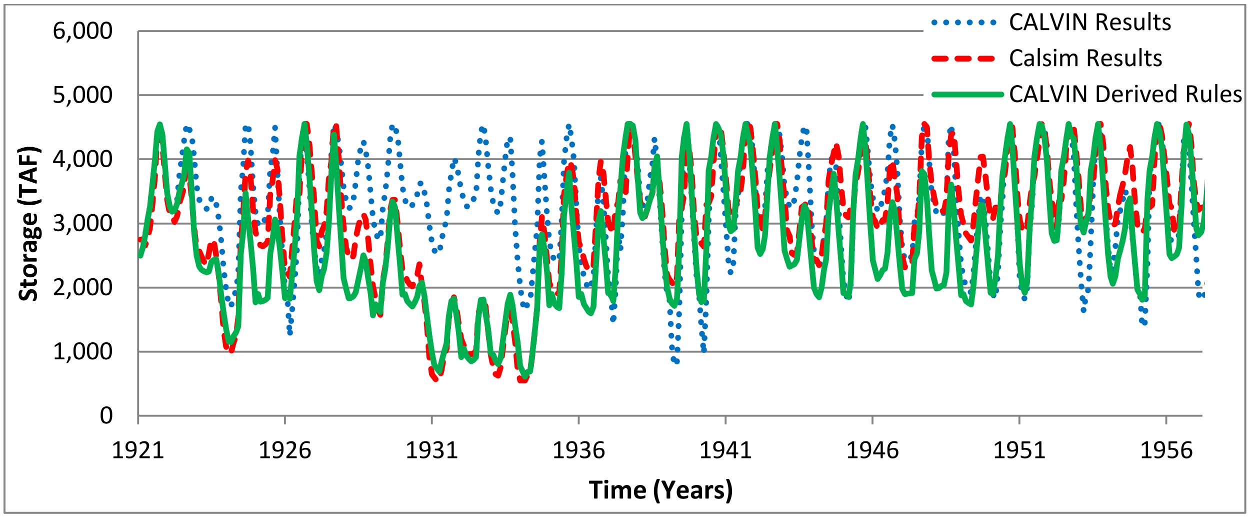
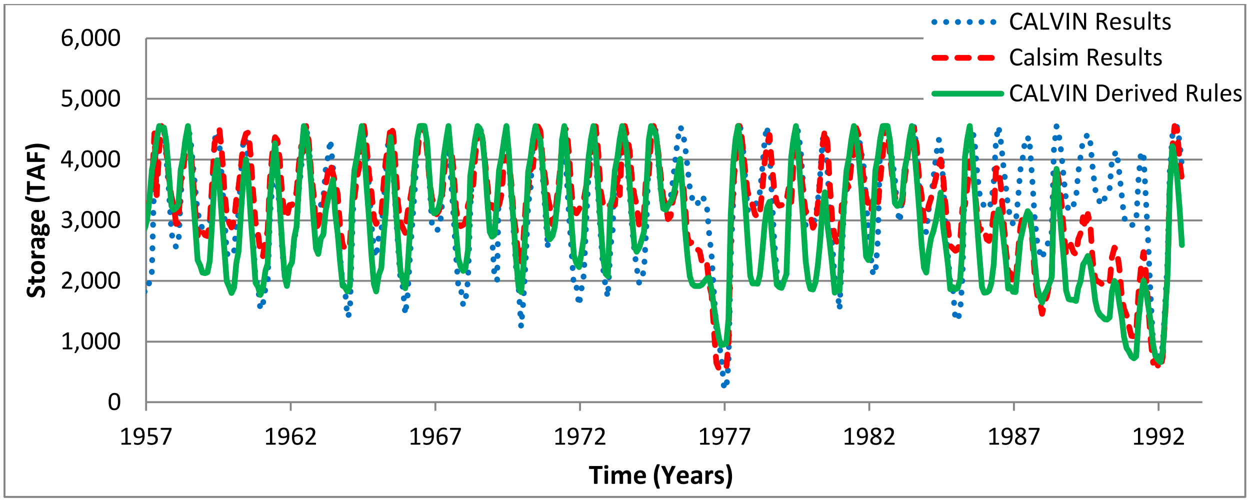


Figure 4-28B: Shasta Storage Time Series Comparison from Derived Rules and Direct Model Results, Part (B) 1957 to 1993



4.4.2. Trinity Reservoir

Figure 4-29 shows the average monthly releases from Trinity produced by the derived rules and by the models. For the derived and modeled CALVIN, both begin the summer averaging relatively large releases, around 250 TAF in May. The modeled results then show the average release gradually decrease from June to November, until it falls to about 50 TAF/month. During this period, the derived results behave similarly, but, in general, releases are a little larger than the modeled results and in October there is a large drop off in the average release, from 125 to 40 TAF/month. In the winter, both sets of results keep discharge low, this time with the modeled version making slightly larger releases than the derived version. Then in February and March the modeled release falls to about 30 TAF/month to match the derived results. Finally, in April and then in May the releases rapidly increase, ending around 250 TAF/month in both versions.

Like in CALVIN, the CalSim results start the summer with a large average release, around 235 TAF/month. In June the discharge falls to 150 TAF/month, a bit lower than in the CALVIN cases, and then remains close to that level through September. In October and November the average release decreases again to about 50 TAF/month matching the modeled CALVIN results. For the rest of the winter and into the spring CalSim results continue to discharge at a relatively low level until May when the release skyrockets, like in CALVIN, to the peak release of 235 TAF/month.

Figures 4-30A and 4-30B present the storage time series comparison of the derived rules and the direct model results of both CALVIN and CalSim for Trinity reservoir. All results show that Trinity storage is sensitive to the water availability, but CALVIN storage results tend to be more variable than in CalSim. Overall, storage levels in CALVIN are usually much lower than in CalSim, rarely surpassing 2 MAF and often falling below 1 MAF at the end of the drawdown cycle. CalSim, on the other hand, only falls below 1 MAF during the longest or most extreme droughts. During droughts, however, the direct model results match up better, as both versions quickly drain Trinity storage to less than 1 MAF. The derived CALVIN results are similar to the direct model results, although the storage level falls a little faster during droughts. In addition, the derived results have less drawdown during non-drought years, usually keeping storage above 1 MAF. Comparing the derived rules with the CalSim results, CALVIN storage is still well below CalSim, even during droughts. In addition, the CALVIN release rules start draining water sooner than CalSim when droughts arrive.

Figure 4-29: Average Monthly Trinity Release Comparison for the Derived Rules and Direct Model Results

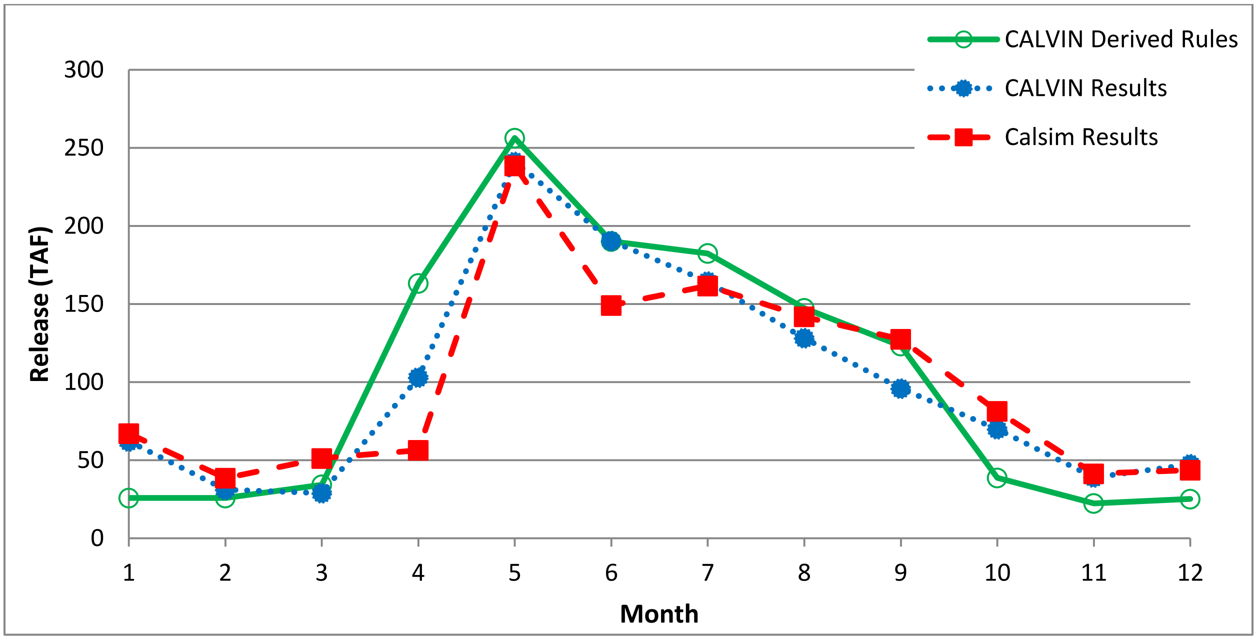


Figure 4-30A: Trinity Storage Time Series Comparison of Derived Rules and Direct Model Results, (Part (A) 1921 to 1957)

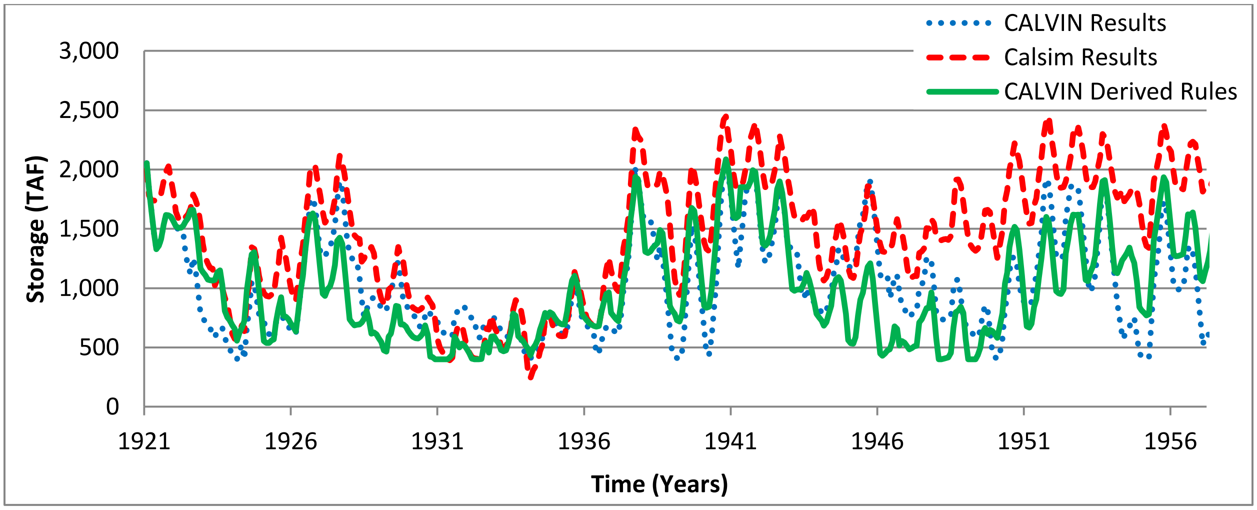
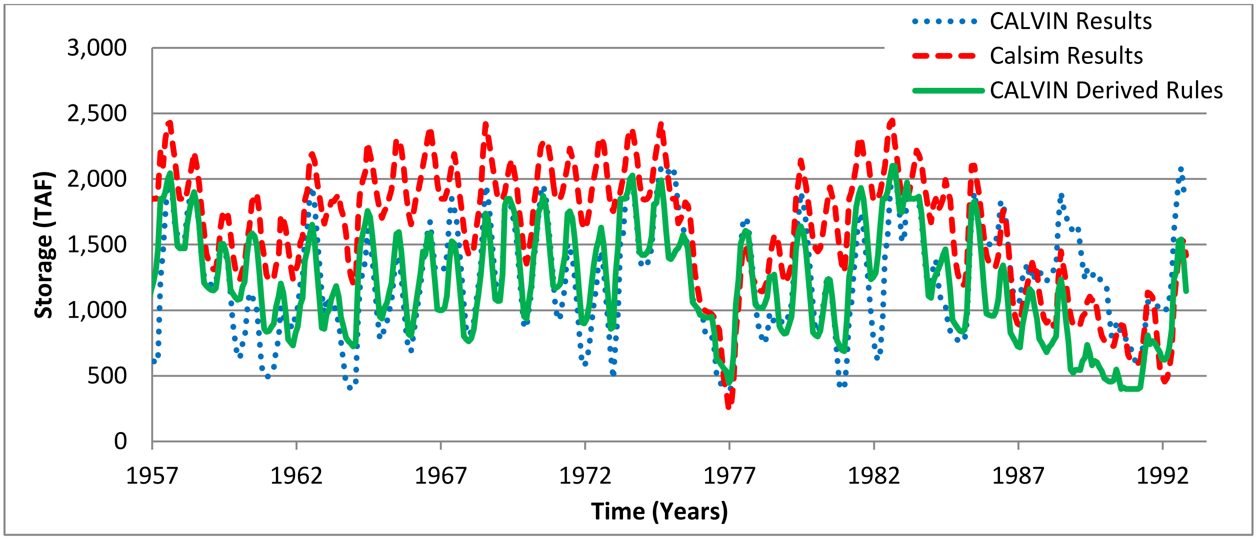


Figure 4-30B: Trinity Storage Time Series Comparison of Derived Rules and Direct Model Results, (Part (B) 1957 to 1993)



4.4.3. Oroville Reservoir

Figure 4-31 shows the average monthly releases from Oroville produced by the CALVIN derived rule set and by the models themselves. In January through March, the average monthly release from both the derived and modeled CALVIN results are very close, as the discharge rises from 225 to 325 TAF/month. In April, both versions still show similar behavior as the release drops to 200 TAF/month to save storage before the summer. However, from this point the derived and modeled CALVIN results diverge. From April to July, both versions discharge more as water demands increase, but the modeled CALVIN results peak at an average discharge of 475 TAF/month, while the derived version reaches 600 TAF/month. In the derived CALVIN results, August discharge remains at 600 TAF/month, but then quickly falls over the next three months until it bottoms out in November at about 100 TAF/month. At the same time, since less water was released early in the summer, the modeled version can release more water in later months of the year. In August and September the direct modeled results continue discharging around 450 TAF/month. From September to November the direct CALVIN discharge starts to decline, but still remains higher than in the derived results, with November release around 260 TAF/month. Finally, in December, both versions end with a release of about 190 TAF/month.

In comparison with the CalSim results, the CALVIN results match up well for the first three months of the year. Like in CALVIN, CalSim reduces discharge for April, but only to 300 TAF/month, which is 100 TAF/month higher than in either CALVIN version. May and June see discharge increase a little, to about 350 TAF/month, but in July the release jumps to 625 TAF/month. For the remainder of the year discharge gradually falls and bottoms out at 150 TAF by November. Finally, in December CalSim increases discharge again to about 190 TAF/month, which match the release rate in both versions of CALVIN.

Figures 4-32A and 4-32B compare Oroville reservoir storage produced by the release rule simulation with the modeled CALVIN and CalSim results over the 72 year modeling period. In the direct CALVIN model, Oroville typically has high storage because of its large depletion penalties during the summer. Even during droughts the reservoir is usually refilled to capacity by the end of the refill season. Reservoir storage is rarely emptied, only falling below 1 MAF at the end of significant droughts. In the CalSim results, storage in non-drought years does not reach capacity as often as in the direct CALVIN model results. In addition, yearly drawdown is greater in CalSim since the model doesn't need to save water to fill the reservoir to capacity as often. During droughts, CalSim quickly drains Oroville and until the drought ends the reservoir rarely refills past 1.5 MAF. Derived CALVIN operations are similar to CalSim operations during droughts, but they tend to empty Oroville more often.

Figure 4-31: Average Monthly Oroville Release Comparison for Derived Rules and Direct Model Results

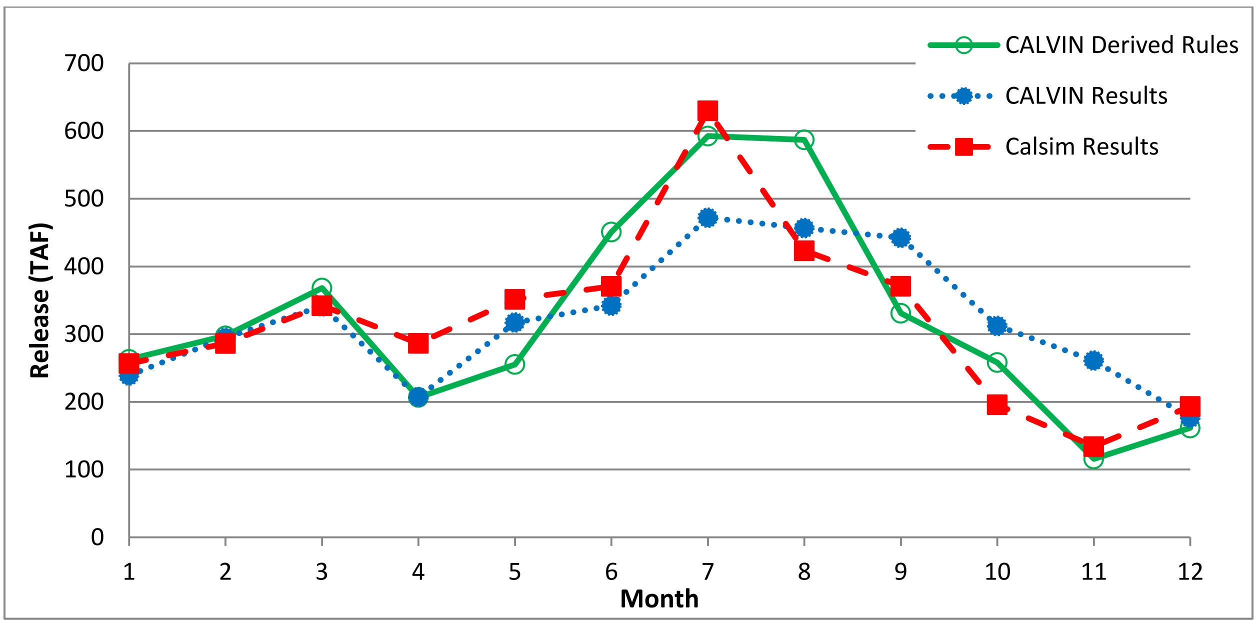


Figure 4-32A: Oroville Storage Time Series Comparison of Derived Rules and Direct Model Results, (Part (A) 1921 to 1957)

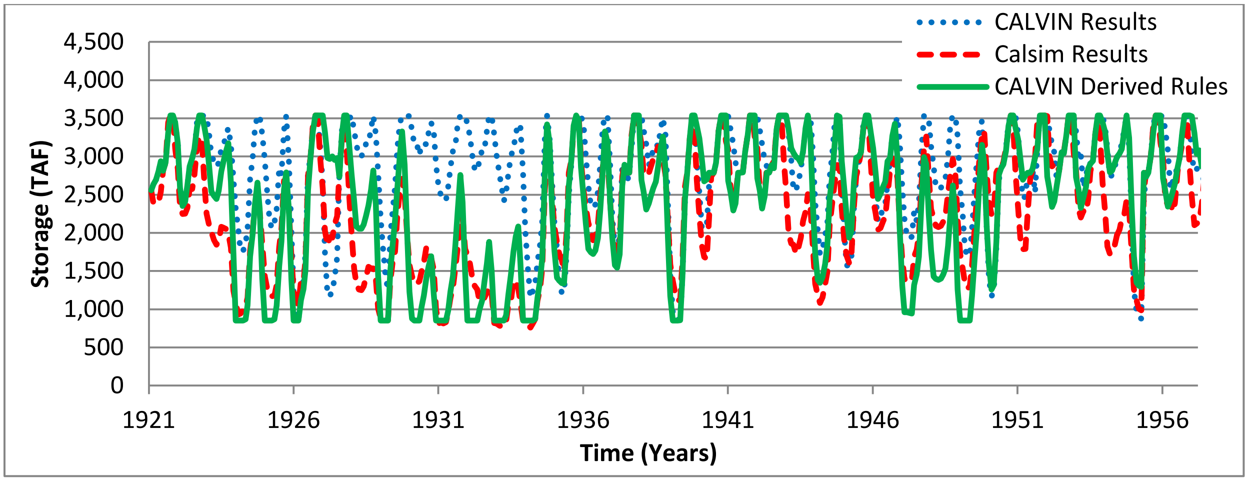
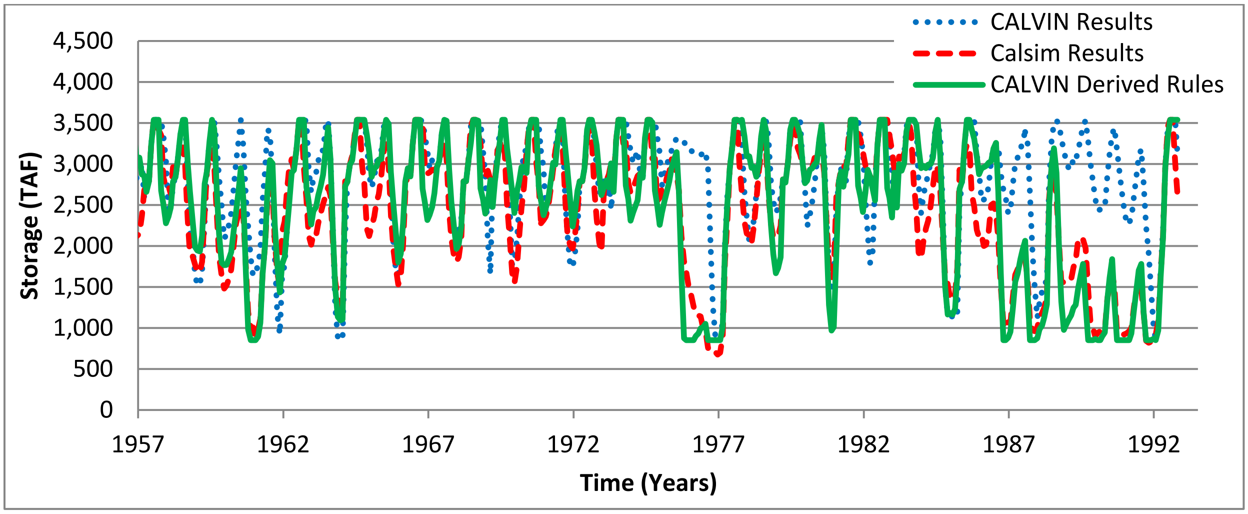


Figure 4-32B: Oroville Storage Time Series Comparison of Derived Rules and Direct Model Results, Part (B) 1957 to 1993



4.4.4. Folsom Reservoir

Figure 4-33 shows the average monthly releases from Folsom produced by the CALVIN derived rule set and by the models themselves. For Folsom all sets of results are very similar, with only minor differences in most months. In January and February all versions favor releasing slightly more than 250 TAF/month. Moving forward, the release rate then decreases to slightly below 250 TAF/month, from March through May, and then increases to about 250 TAF/month for June and July. From August to October average discharge decreases until it bottoms out at about 100 TAF/month in CalSim and at about 150 TAF/month in both CALVIN cases. Finally, in November and December the discharge rises once again peaking at 250 TAF/month in January.

Figures 4-34A and 4-34B present the storage time series comparison of the release rule simulation results and the direct CALVIN and CalSim results for Folsom reservoir, In the direct CALVIN results Folsom usually drains a large portion of its total storage during non-drought year , many times bringing it from full to empty. During droughts, CALVIN reduces its drawdown to keep storage from falling below 300 TAF. In the direct CalSim results, drawdown in non-drought years is a usually lower than in CALVIN and the storage doesn't often fall below 300 TAF. Even during droughts CalSim rarely drains the reservoir completely, instead it tries to keep storage between 200 and 600 TAF. In the derived CALVIN results Folsom storage drastically falls during droughts. During some drought years, Folsom is drained entirely and is unable to refill any storage for several years afterwards until the drought has passed. Otherwise, during non-drought years results of the release rule simulation match up well with the direct CALVIN results.

Figure 4-33: Average Monthly Folsom Release Comparison for Derived Rules and Direct Model Results

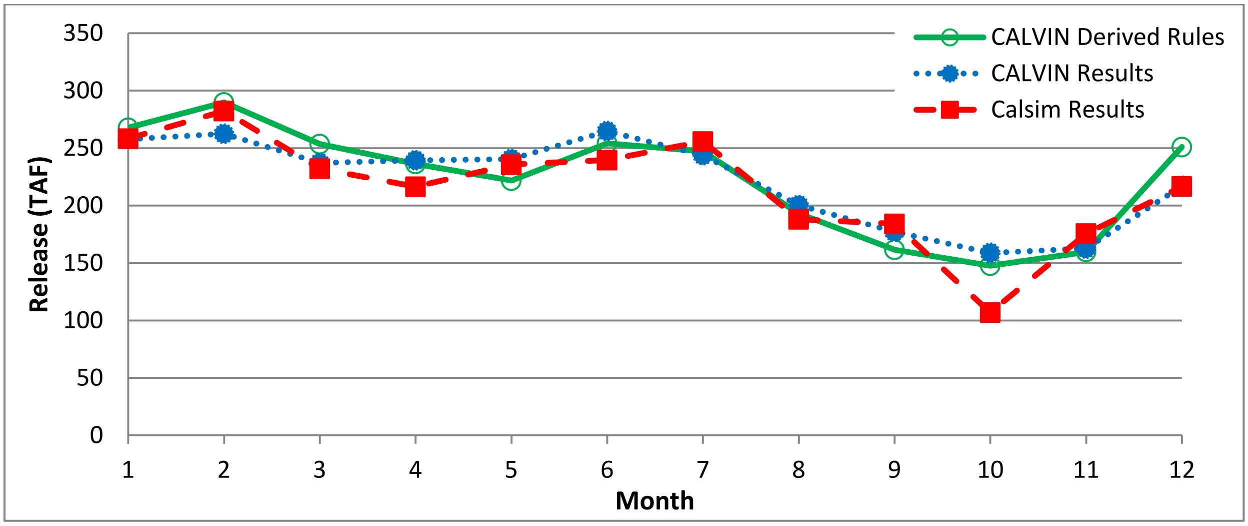


Figure 4-34A: Folsom Storage Time Series Comparison for Derived Rules and Direct Model Results (Part (A) 1921 to 1957)

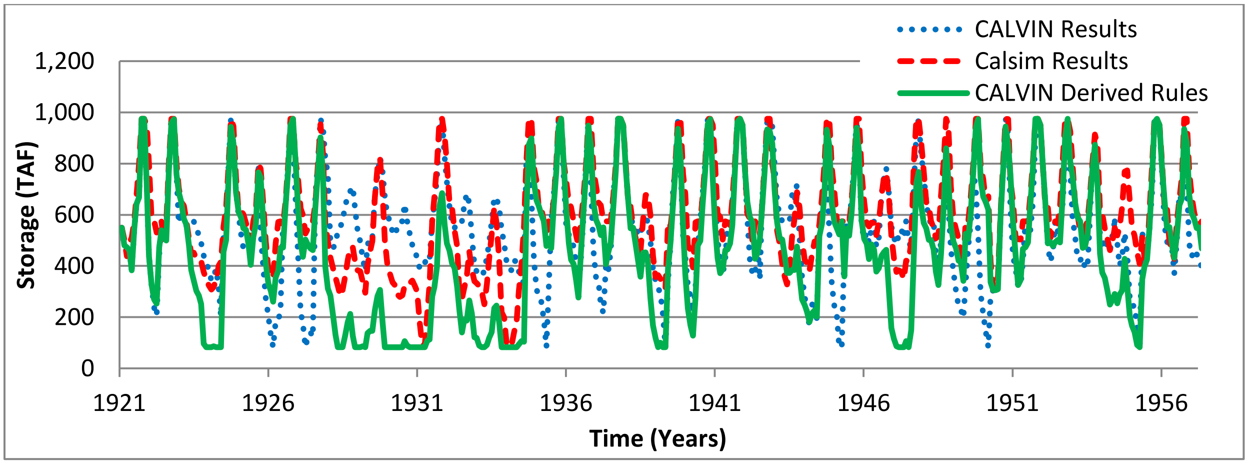
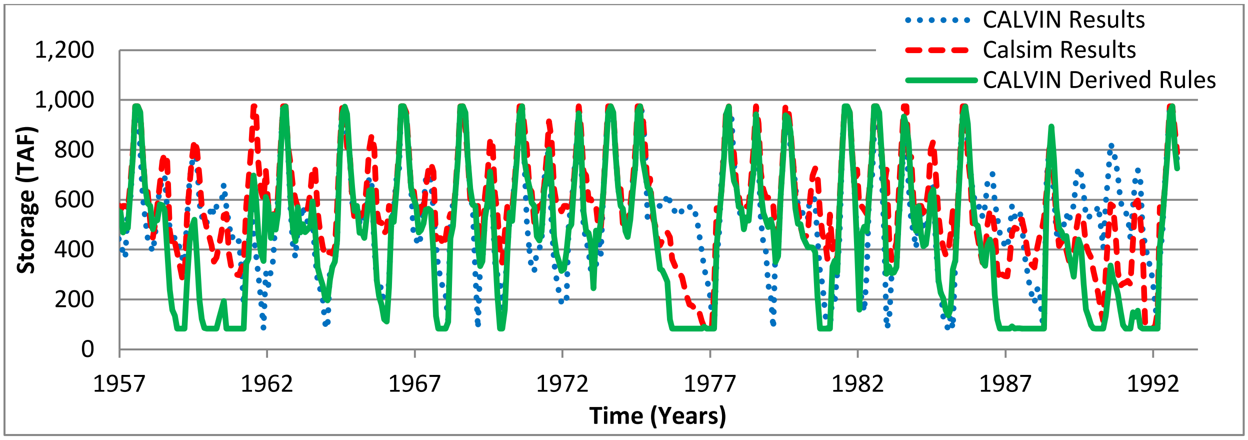


Figure 4-34B: Folsom Storage Time Series Comparison for Derived Rules and Direct Model Results (Part (B) 1957 to 1993)



4.4.5. New Bullards Bar Reservoir

Figure 4-35 shows the average monthly releases from New Bullards Bar produced by the CALVIN model and its derived release rules. There are no CalSim results for New Bullards bar. From January through April, both the derived and direct results discharge about 80 TAF/month on average. In May both versions increase the release rate, but the derived version peaks at 200 TAF/month, while the direct version only reaches 150 TAF/month. Continuing into June the direct version continues to increase discharge until it climbs to about 200 TAF/month, matching the derived results. In the second half of the year, both CALVIN versions gradually decrease average release rate; in the direct CALVIN results discharge decreases a little slower, dropping to 175 TAF in July, while in the derived results it falls to 125 TAF/month. However, in August, the release rates are nearly the same, about 100 TAF/month, and by November they have decreased further, to 50 TAF/month. Finally, in December, discharge increases until it reaches 80 TAF/month in January.

Figures 4-36A and 4-36B present the storage time series comparison between the derived and direct CALVIN results for storage at New Bullards Bar reservoir. In the direct results storage levels commonly fluctuate by about 700 TAF. In most non-drought years the reservoir is filled to capacity, about 930 TAF, and then emptied to its dead pool, about 251 TAF. Even during droughts the reservoir refills a significant portion of its storage. However, during dry periods, CALVIN decreases drawdown to preserve available storage for the length of the drought. The derived CALVIN results sometimes match up well with the modeled results, but they can also be very different. The derived results are a little more sensitive to water availability, the drier it is the greater the drawdown will be. In some of the wetter years drawdown may stop when storage falls to about 600 TAF, while in the driest years drawdown usually empties the reservoir.

Figure 4-35: Average Monthly New Bullards Bar Release Comparison for Derived Rules and Direct Model Results

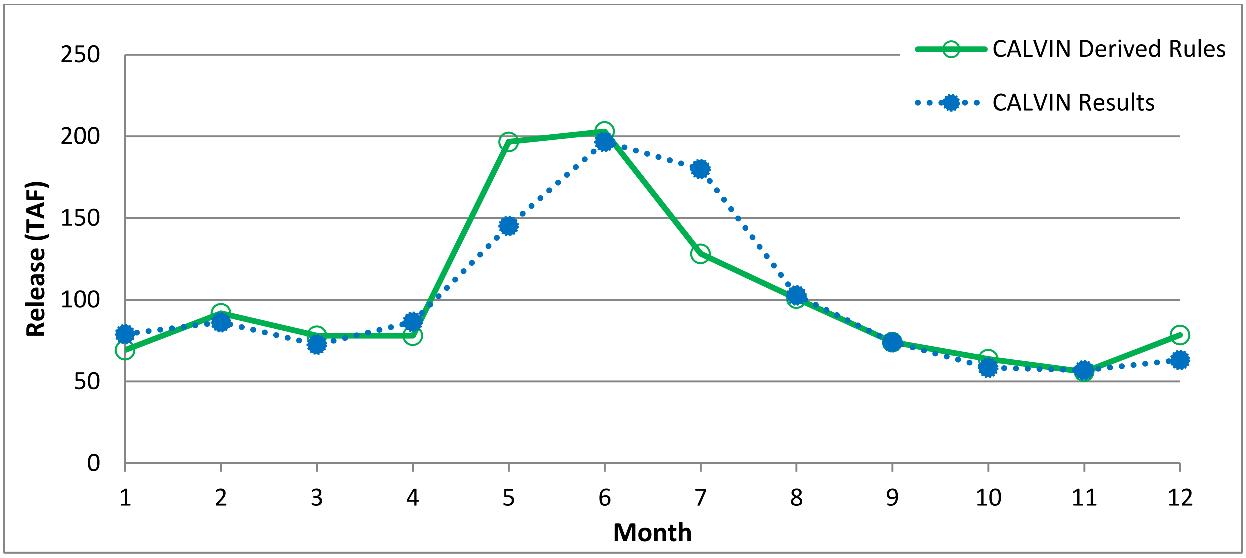


Figure 4-36A: New Bullards Bar Storage Time Series Comparison for Derived Rules and Direct Model Results (Part (A) 1921 to 1957)

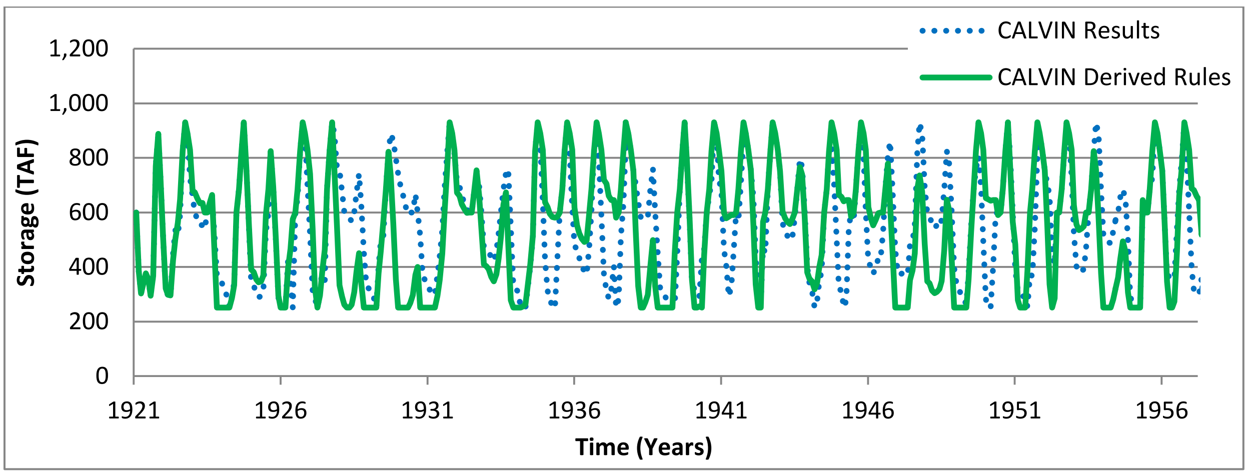
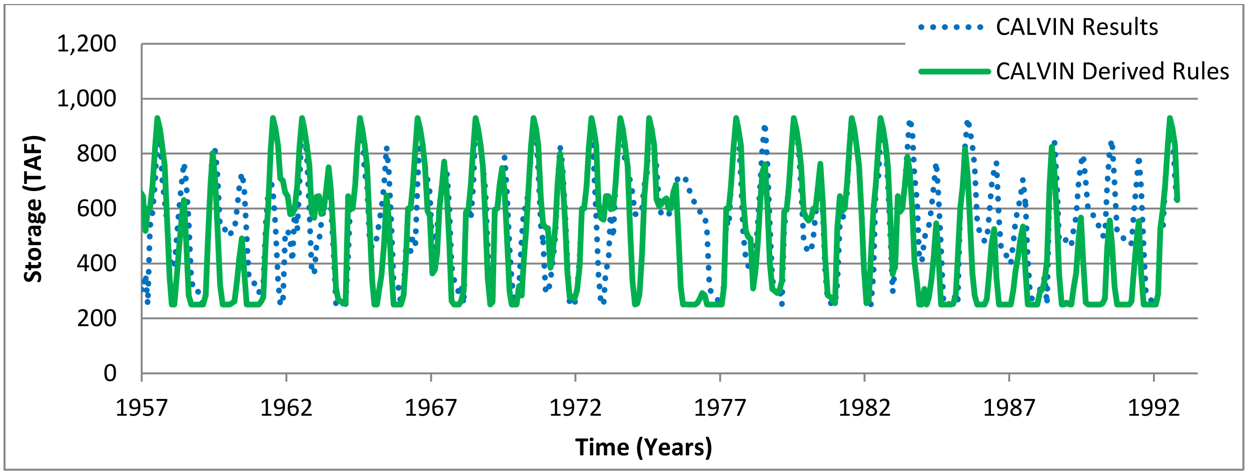


Figure 4-36B: New Bullards Bar Storage Time Series Comparison for Derived Rules and Direct Model Results (Part (B) 1957 to 1993)



4.5. Concluding Remarks

Storage allocation rules are most useful for dividing refill and drawdown between different reservoirs. However, for the best storage allocation rules the reservoirs being compared should have similar storage levels or else one reservoir may dominate system storage, reducing detail on the other one. Some of the important insights revealed through the storage allocation plots are:

- Optimal Shasta and Trinity storage allocation depends largely on total inflow over the previous year.
- CalSim begins releasing from Shasta sooner than is optimal according to CALVIN.
- Optimal storage allocation among Shasta, Trinity, Oroville, and Folsom differ for the refill and drawdown seasons.
- CalSim refill operations may be economically optimal between Shasta, Trinity, and Oroville, but drawdown operations are not (Oroville releases to soon).
- Folsom operations in CalSim are very similar to those in CALVIN when system storage is high, so it may already be operating well in terms of economics.

The reservoir release rules are simple to use, but more difficult to infer since there could be many different relationships between release and system variables. The rules derived here were based on one or two variables, but some rules may depend on several variables. With so many possibilities, considerable exploration, refinement, and testing are needed to improve the rules (Lund and Ferreira 1996). Some important insights revealed through the release rule development and simulation are:

- Shasta and Trinity usually have greater annual drawdown in CALVIN than CalSim
- Drought storage based on the derived CALVIN release rules is less than in the modeled results for all reservoirs
- the derived CALVIN results usually empty Oroville and Folsom during droughts, unlike in the modeled results or in the CalSim results.

The reason drought storage falls when using the derived release rules is because when using them it behaves like a simulation model, so there is no hydrologic foresight. Without hydrologic foresight the model cannot predict the when droughts will arrive and how long they will last. In a way some of the optimality from CALVIN is unavoidably lost with less hydrologic foresight.

Simulation modeling using historical hydrology is not immune from the effects of hydrologic foresight, especially for extreme events. Most operating rules used in simulation models will have been established to perform well for a repeat of the historical hydrology – and so are implicitly designed with foresight into the historical hydrology. But future droughts (or floods) each can show a new hydrologic pattern for which operating rules, necessarily calibrated on past conditions, might not perform so well. This is an unavoidable dilemma.

Assuming that CALVIN operations are the best possible operations to maximize economic benefit, the release rules based on CALVIN should behave better than, or as well as, CalSim operations. If these derived rules are truly more optimal than CalSim operations, then reservoir storage based on these rules should be closer to CALVIN reservoir storage than the CalSim reservoir storage is. Table 4-14 presents the percentage of months where reservoir storage from the release rule simulation was closer to CALVIN reservoir storage than the CalSim reservoir storage was and Table 4-15 presents the same thing for each month. Overall, using the optimized release rules operates Trinity better than CalSim in 77% of months, Oroville better in about 60 % of months, and the other two reservoirs better about 50% of months. In general, the release rules operate the system better as years become wetter and water is more abundant. Folsom operations are especially sensitive to water availability, operating better than CalSim only 16 % of months in really dry years, compared to about 50% of months in all other years types. This might be improved with more refinements to the operating rules.

Table 4-14: How well do Derived Release Rules Operate the System compared to CalSim, for each Past Year Type

	% of Months where Release Rule Simulation is more optimal than CalSim			
PYT	**Shasta**	**Trinity**	**Oroville**	**Folsom**
1	44%	60%	49%	16%
2	41%	66%	55%	46%
3	45%	80%	64%	60%
4	59%	86%	74%	58%
5	58%	94%	61%	68%
Overall	50%	77%	61%	50%

Table 4-15: How well do Derived Release Rules Operate the System compared to CalSim, by Month

	% of Months where Release Rule Simulation is more optimal than CalSim			
Month	**Shasta**	**Trinity**	**Oroville**	**Folsom**
1	49%	79%	54%	57%
2	38%	76%	53%	53%
3	43%	74%	57%	40%
4	54%	75%	65%	36%
5	56%	79%	78%	35%
6	33%	79%	94%	36%
7	43%	83%	88%	63%
8	54%	78%	68%	56%
9	58%	76%	38%	56%
10	60%	76%	44%	54%
11	58%	76%	44%	65%
12	56%	75%	50%	56%

In the future it would be interesting to examine the economic implications of these reservoir operations. The best way to do this would be to constrain reservoir storage in CALVIN to match the reservoir storage that results from using the derived rules. After running the CALVIN model with these constraints we could use the economic postprocessors to identify how urban and agricultural deliveries change and how much it would cost to run the system. Additionally, we could determine the economic value of the CalSim operations in the same way.

Chapter Five: Overall Conclusions

In the latest updates of the CALVIN optimization model, groundwater representation has greatly improved, with more accurate aquifer storage capacities, pumping rates, inflows, and recharge. In addition, new agricultural demands have been applied based on the SWAP model. Finally, new constraints on required Delta outflow and Banks pumping plant capacity were acquired from the CalSim II model. With these updates, the new CALVIN base case results have also improved. The improvements include: no more Central Valley calibration flows, more accurate groundwater overdraft, and more accurate agricultural scarcity. The model now better, but still imperfectly, represents hydrologic, operational, and economic aspects of California's statewide water supply system.

The most significant improvement to the model was the elimination of 2.2 MAF of calibration flows in the Central Valley. The old CALVIN base case overestimated the amount of groundwater available, so to avoid infeasibilities with groundwater storage, more groundwater had to be pumped than was required. This additional water had to be removed from the system through calibration links. With the updates, groundwater estimates have improved and groundwater storage capacities have increased, reducing the likelihood of groundwater storage infeasibilities. As a result, groundwater pumping in the new base case has significantly decreased, reducing operating costs for the Central Valley by about 300 $M/year.

In the old base case, with so much extra groundwater, agricultural scarcity was unrealistically low in regions like the Tulare, where water shortages are a common problem. Agricultural water scarcity in the Central Valley before the updates totaled only 37 TAF, split between CVPM 3 and 12. After the updates, the scarcity in CVPM 3 disappeared, while scarcity increased throughout the San Joaquin and Tulare. Overall, average annual scarcity increased almost 10 times to 360 TAF/yr. When overdraft is limited, average annual scarcity increases again to 645 TAF/yr (with much greater compensating Delta exports). Even the Sacramento basin, the wettest region of the Central Valley, sees significant increases in scarcity for several CVPM regions as more water is pumped south through the Delta. In addition, scarcity in CVPM 18 of the Tulare region increased by almost 100 TAF, to over 200 TAF total. In response to the increased scarcity, the willingness to pay for additional water also has increased in all regions.

With the updates, Delta pumping operations also see significant changes. Though the total amount of Delta pumping has fallen by 40 TAF/yr, the timing of exports has become more critical. In the new base case, more water is pumped during the winter and spring when it is available to be stored in preparation for summer demands. In conjunction, the new base case has an increase in the importance of San Luis Reservoir, the predominant storage facility along the California Aqueduct. Imports to Southern California also shift, with more water is imported during the Spring to be stored in Diamond Valley Reservoir and Castaic Lake before the summer. In the No Overdraft case, Delta exports are even more important with limited groundwater supplies, causing total Delta exports to increase by about 900 TAF/yr, primarily from Tracy.

As an application of the updated CALVIN, base case results were used to develop a preliminary set of economically optimized operating rules for major reservoirs in the Sacramento Valley. These reservoirs included Shasta, Trinity, Oroville, New Bullards Bar, and Folsom. The rules developed include storage allocation rules and release rules. Storage allocation rules are used to balance storage among multiple reservoirs in a system, establish drawdown and refill priority, and set storage targets. Release rules define reservoir release based one or more state variables related to the reservoir, such as storage or inflow, or to the system at large, such as system storage. In addition, these optimized rules were compared to operations from the CalSim II simulation model to see how they compare to realistic operating rules. Such comparisons could reveal areas where the system could be operated better, not just in CalSim, but in reality.

Storage allocation rules were first developed between Shasta and Trinity, before adding Oroville and then Folsom to the system. Operations between Shasta and Trinity are very sensitive to water availability; during drier years draining Trinity first and preserving Shasta storage is preferable, while in wet years Shasta starts releasing much sooner. CalSim operations are similar to those in CALVIN, but Shasta tends to release water sooner than would be optimal in both wet and dry years. When Oroville and then Folsom are added to the system, operations differ in the refill and drawdown season. CalSim storage allocation between Shasta, Trinity, and Oroville is similar to CALVIN during the refill season, but in the drawdown season Oroville begins draining too soon. With Folsom, CalSim operations match CALVIN operations at high system storage, but as system storage decreases CalSim tries to keep Folsom storage above 300 TAF, while CALVIN empties the reservoir.

Release rules were defined for all five reservoirs for each month. The most common rules depend on available water (storage + inflow), inflow over the past year, and total system storage. To compare these rules with CalSim operations a simple excel simulation model (called CALSIMP) was created using the derived rules to operate the system over 72 years with CALVIN inflows. Assuming CALVIN results are optimal, the operations suggested by the derived rules were more optimal than the CalSim operations only about 50 % of the time for Shasta, Oroville, and Folsom, but they were more optimal 75 % of the time for Trinity. In general, the rules did better as years became wetter.

In the future it would be valuable to extend the analysis done here for the Sacramento Valley to the rest of the Central Valley. The reservoir of interest would be Pardee, Camanche, New Melones, Hetch Hetchy, Eleanor, New Don Pedro, San Luis, Millerton, Pine Flat, and Isabella. San Luis may be the best opportunity to improve the system's operation since CALVIN and CalSim operate it very differently. In addition, it would be useful to estimate the economic benefits of an inferred optimal rule set over current CalSim operations. In the future it is hoped that such rule development will be adapted to the CalSim framework to allow better integration and exploration of component operation across the entire system.

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Appendix A

Table A-1: Ag Demand, Delivery, Scarcity for Individual Demand Areas

	Demands (TAF)			Delivery (TAF)			Scarcity (TAF)		
Ag Demand Area	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
CVPM 1	126.3	138.8	138.8	126.3	137.6	118.4	0.0	1.2	20.4
CVPM 2	496.7	473.4	473.4	496.7	473.4	473.4	0.0	0.0	0.0
CVPM 3	2196.3	1315.4	1315.4	2181.3	1315.4	1315.4	15.0	0.0	0.0
CVPM 4	956.1	884.0	884.0	956.1	884.0	881.5	0.0	0.0	2.5
CVPM 5	1312.5	1485.4	1485.4	1312.5	1485.4	1485.4	0.0	0.0	0.0
CVPM 6	619.0	731.6	731.6	619.0	728.6	701.9	0.0	2.9	29.7
CVPM 7	428.9	413.1	413.1	428.9	413.1	413.1	0.0	0.0	0.0
CVPM 8	801.8	736.9	736.9	801.8	736.9	677.6	0.0	0.0	59.2
CVPM 9	926.2	1207.5	1207.5	926.2	1207.5	1175.9	0.0	0.0	31.6
CVPM 10	919.0	1402.9	1402.9	919.0	1352.2	1347.3	0.0	50.8	55.7
CVPM 11	855.4	777.0	777.0	855.4	777.0	771.4	0.0	0.0	5.6
CVPM 12	771.8	760.4	760.4	749.8	739.1	734.8	22.0	21.4	25.6
CVPM 13	1506.1	1679.4	1679.4	1506.1	1602.6	1594.5	0.0	76.8	84.9
CVPM 14	1357.7	1129.0	1129.0	1357.7	1129.0	1129.0	0.0	0.0	0.0
CVPM 15	1701.2	1828.0	1828.0	1701.2	1828.0	1828.0	0.0	0.0	0.0
CVPM 16	344.8	367.8	367.8	344.8	365.2	356.6	0.0	2.6	11.2
CVPM 17	797.2	738.6	738.6	797.2	705.0	701.7	0.0	33.6	36.9
CVPM 18	1759.5	2119.4	2119.4	1759.5	2013.4	1916.3	0.0	106.0	203.0
CVPM 19	886.7	841.8	841.8	886.7	841.8	841.8	0.0	0.0	0.0
CVPM 20	828.8	640.2	640.2	828.8	614.1	608.8	0.0	26.1	31.4
CVPM 21	1195.4	999.3	999.3	1195.4	961.2	952.4	0.0	38.1	47.0
Ventura	174.5	174.5	174.5	174.5	174.5	174.5	0.1	0.1	0.1
Antelope Val	79.6	79.6	79.6	0.0	0.0	0.0	79.6	79.6	79.6
Coachella	333.3	333.3	333.3	306.8	306.8	306.8	26.5	26.5	26.5
Imperial	2672.7	2672.7	2672.7	1856.1	1856.1	1856.1	816.6	816.6	816.6
Palo Verde	784.4	784.4	784.4	764.9	764.9	764.9	19.5	19.5	19.5
San Diego	172.1	172.1	172.1	172.1	172.1	172.1	0.0	0.0	0.0
E&W MWD	92.1	92.1	92.1	64.9	64.9	64.9	27.2	27.2	27.2
Totals									
Sacramento	7863.8	7386.1	7386.1	7848.8	7382.0	7242.7	15.0	4.1	143.5
SJ/ South Bay	4052.3	4619.8	4619.8	4030.3	4470.8	4448.0	22.0	149.0	171.8
Tulare	8871.2	8664.1	8664.1	8871.2	8457.7	8334.6	0.0	206.5	329.6
Southern Cal	4308.6	4308.6	4308.6	3339.3	3339.3	3339.3	969.4	969.4	969.4
Central Valley	20787	20670.1	20670.1	20750.3	20310.5	20025.3	37.0	359.6	644.8
Statewide	25096	24978.7	24978.7	24089.6	23649.8	23364.5	1006	1329	1614.2

Table A-2: Urban Demands, Deliveries, and Scarcities for Individual Demands Areas

	Demands (TAF)			Delivery (TAF)			Scarcity (TAF)		
Urban Demand Area	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
Napa	175.7	175.7	175.7	175.4	175.4	175.4	0.3	0.3	0.3
Contra Costa	113.8	113.8	113.8	113.8	113.8	113.8	0.0	0.0	0.0
East Bay MUD	260.4	260.4	260.4	260.4	260.4	260.4	0.0	0.0	0.0
Stockton	117.7	117.7	117.7	117.7	117.7	117.7	0.0	0.0	0.0
Redding	89.7	89.7	89.7	89.7	89.7	89.7	0.0	0.0	0.0
Galt	82.7	82.7	82.7	82.9	82.7	82.7	0.0	0.0	0.0
Sacramento	677.2	677.2	677.2	677.2	677.2	677.2	0.0	0.0	0.0
Yuba	91.4	91.4	91.4	91.4	91.4	91.4	0.0	0.0	0.0
SFPU	219.2	219.2	219.2	219.2	219.2	219.2	0.0	0.0	0.0
Modesto	235.8	235.8	235.8	235.8	235.8	235.8	0.0	0.0	0.0
Merced	224.2	224.2	224.2	224.4	224.2	224.2	0.0	0.0	0.0
Turlock	177.3	177.3	177.3	177.3	177.3	177.3	0.0	0.0	0.0
Santa Clara	714.9	714.9	714.9	714.9	714.9	714.9	0.0	0.0	0.0
Fresno	336.7	336.7	336.7	336.7	336.7	336.7	0.0	0.0	0.0
Bakersfield	256.6	256.6	256.6	256.6	256.6	256.6	0.0	0.0	0.0
Sanger	144.4	144.4	144.4	144.4	144.4	144.4	0.0	0.0	0.0
Visalia	207.1	207.1	207.1	207.1	207.1	207.1	0.0	0.0	0.0
Delano	137.1	137.1	137.1	137.3	137.2	137.1	0.0	0.0	0.0
SB-SLO	201.8	201.8	201.8	196.6	196.6	196.6	5.1	5.1	5.1
San Bernardino	547.0	547.0	547.0	500.2	500.1	498.9	46.8	46.9	48.1
SDWD	836.7	836.7	836.7	836.7	836.7	836.7	0.0	0.0	0.0
Coachella	321.2	321.2	321.2	321.2	321.2	321.2	0.0	0.0	0.0
E&W MWD	886.0	886.0	886.0	830.1	830.4	829.4	55.9	55.6	56.5
Mojave	220.7	220.7	220.7	211.4	211.2	211.2	9.2	9.5	9.5
Ventura	153.4	153.4	153.4	133.0	133.0	133.0	20.4	20.4	20.4
El Centro	70.2	70.2	70.2	70.2	70.2	70.2	0.0	0.0	0.0
Castaic Lake	159.5	159.5	159.5	159.4	159.3	159.3	0.1	0.1	0.2
CMWD	3279.7	3279.7	3279.7	3279.7	3279.7	3279.7	0.0	0.0	0.0
Blyth	15.6	15.6	15.6	15.3	15.3	15.3	0.3	0.3	0.3
Antelope Val	349.7	349.7	349.7	292.0	292.0	292.0	57.7	57.7	57.7
Totals									
Sacramento	1608.6	1608.6	1608.6	1608.6	1608.4	1608.4	0.3	0.3	0.3
SJ/ South Bay	1571.4	1571.4	1571.4	1571.6	1571.4	1571.4	0.0	0.0	0.0
Tulare	1082.0	1082.0	1082.0	1082.2	1082.1	1082.0	0.0	0.0	0.0
Southern Cal	7041.4	7041.4	7041.4	6845.7	6845.7	6843.5	195.7	195.7	197.9
Central Valley	4262.0	4262.0	4262.0	4262.4	4261.9	4261.8	0.3	0.3	0.3
Statewide	11303	11303	11303	11108.1	11107.6	11105.3	195.9	196.0	198.2

Table A-3: Average Maximum Willingness to Pay for Ag Water in each Demand Area

	Willingness to Pay ($/AF)		
Ag Demand Area	Old Calvin	New Calvin	No Overdraft
CVPM 1	0.0	10.0	88.1
CVPM 2	0.0	0.0	0.0
CVPM 3	15.0	0.0	0.0
CVPM 4	0.0	0.2	5.7
CVPM 5	0.0	0.0	0.0
CVPM 6	0.0	13.3	16.8
CVPM 7	0.0	0.0	0.0
CVPM 8	0.0	0.0	57.6
CVPM 9	0.0	0.0	7.8
CVPM 10	0.0	20.5	23.2
CVPM 11	0.0	0.0	5.1
CVPM 12	16.1	13.7	18.6
CVPM 13	0.0	29.4	65.1
CVPM 14	0.0	0.0	0.0
CVPM 15	0.0	0.0	0.0
CVPM 16	0.0	30.1	35.4
CVPM 17	0.0	37.9	43.9
CVPM 18	0.0	44.7	90.6
CVPM 19	0.0	0.0	0.0
CVPM 20	0.0	56.2	69.7
CVPM 21	0.0	55.2	68.4
Ventura	122.7	122.7	122.7
Antelope Valley	147.3	147.3	147.3
Coachella	153.4	153.4	153.4
Imperial	140.5	140.5	140.5
Palo Verde	56.7	56.7	56.7
San Diego	0.0	0.0	0.0
E&W MWD	582.8	582.8	582.8

Table A-4: Average Maximum Willingness to Pay for Urban Water in each Demand Area

	Willingness to Pay ($/AF)		
Urban Demand Area	Old Calvin	New Calvin	No Overdraft
Napa	104.1	104.1	104.1
Contra Costa WD	0.0	0.0	0.0
East Bay MUD	0.0	0.0	0.0
Stockton	0.0	0.0	0.0
Redding	8416.7	8416.7	8416.7
Galt	0.0	0.0	0.0
Sacramento	0.0	0.0	0.0
Yuba	10166.7	10166.7	10166.7
SFPU	0.0	0.0	0.0
Modesto	0.0	0.0	0.0
Merced	0.0	0.0	0.0
Turlock	0.0	0.0	0.0
Santa Clara Valley	0.0	0.0	0.0
Fresno	0.0	0.0	0.0
Bakersfield	0.0	0.0	0.0
Sanger	0.0	0.0	0.0
Visalia	0.0	0.0	0.0
Delano	0.0	0.0	0.0
SB-SLO	1623.5	1623.5	1623.5
San Bernardino Valley	839.9	839.9	839.9
SDWD	0.0	0.0	0.0
Coachella	0.0	0.0	0.0
E&W MWD	1028.2	1028.2	1028.2
Mojave	1062.1	1062.1	1062.1
Ventura	1284.8	1284.8	1284.8
El Centro	0.0	0.0	0.0
Castaic Lake WA	82.4	88.4	123.1
C MWD	0.0	0.0	0.0
Blyth	430.9	430.9	430.9
Antelope Valley	1086.3	1086.3	1086.3

Figure A-1: Box Plot of the Average Maximum WTP for Additional Agricultural Water in the Sacramento Region

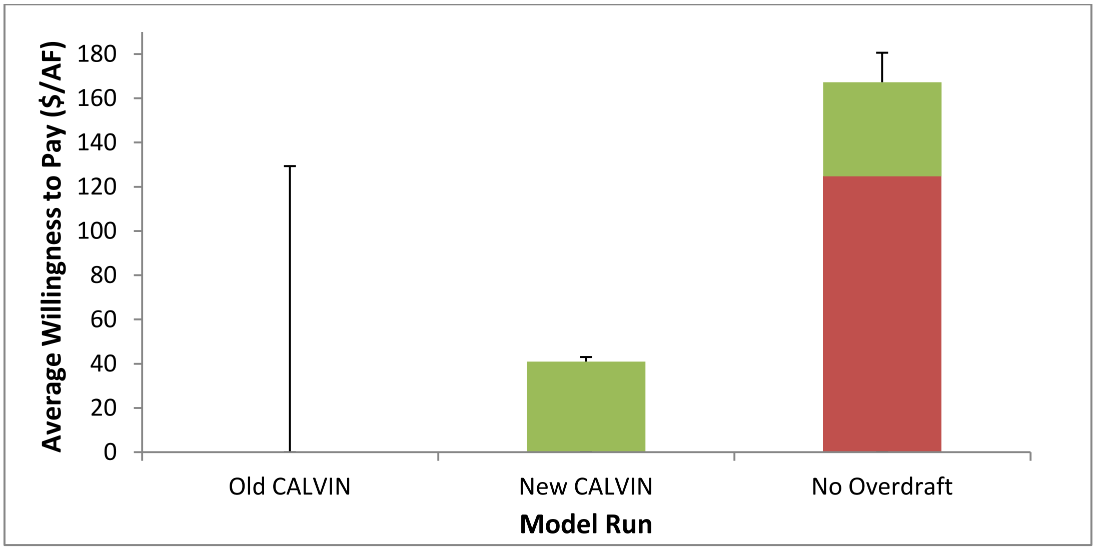


Figure A-2: Box Plot of the Average Maximum WTP for Additional Agricultural Water in the San Joaquin Region

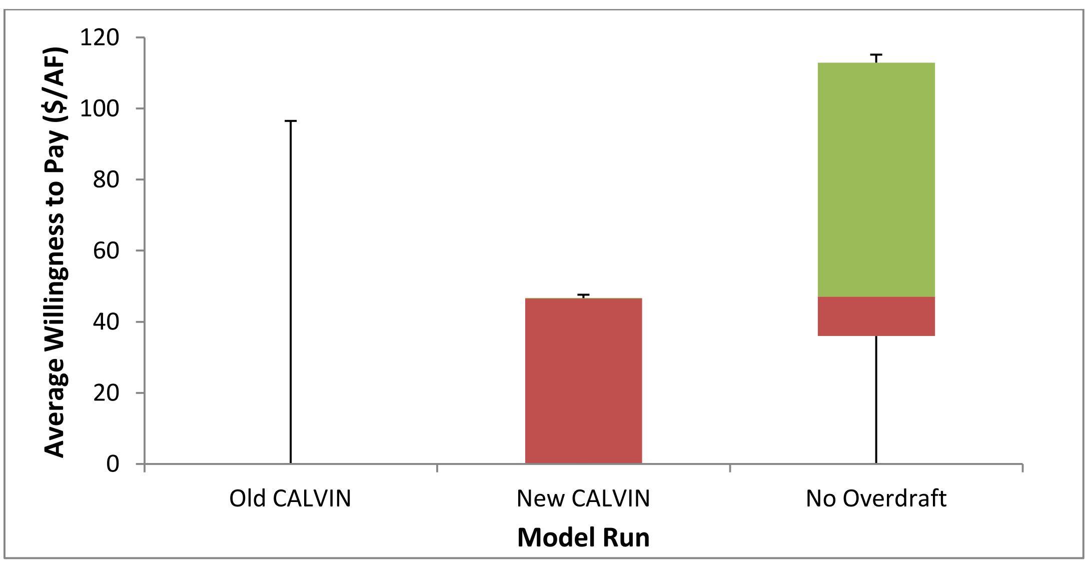


Figure A-3: Box Plot of the Average Maximum WTP for Additional Agricultural Water in the Tulare Region

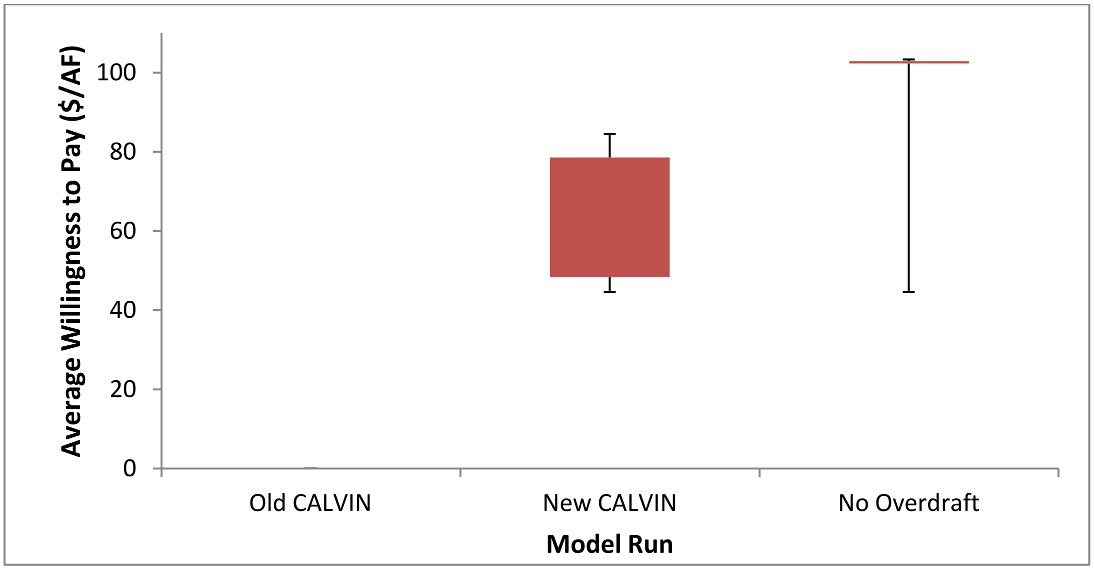


Table A-5: Supply Breakdown of Annual Avg. Ag Deliveries for each Demand Area

	Ground Water Use (TAF)			Surface Water Use (TAF)			Other Sources (TAF)		
Ag Demand Area	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
CVPM 1	40.6	51.5	56.3	90.5	86.1	62.1	0.0	0.0	0.0
CVPM 2	409.9	145.0	145.0	86.2	328.4	328.4	0.0	0.0	0.0
CVPM 3	462.6	108.8	95.8	1749.7	1140.5	1153.6	103.8	203.5	203.5
CVPM 4	274.3	12.0	8.6	634.0	871.1	872.0	118.1	0.9	0.9
CVPM 5	391.1	227.2	218.1	1018.9	1163.6	1172.5	81.1	135.0	135.0
CVPM 6	393.6	173.7	175.3	333.4	554.3	525.9	232.6	0.7	0.7
CVPM 7	44.4	150.8	120.8	398.9	240.4	270.4	35.5	21.9	21.9
CVPM 8	626.0	472.1	388.6	135.0	258.2	283.0	76.1	6.6	6.0
CVPM 9	30.6	79.4	81.3	810.6	1113.9	1080.7	84.1	14.3	13.9
CVPM 10	298.7	305.3	260.6	964.3	1034.8	1074.7	63.2	12.1	12.0
CVPM 11	0.0	65.6	56.2	1063.0	673.0	677.1	42.5	38.4	38.1
CVPM 12	142.5	106.7	82.0	554.2	606.0	626.6	69.7	26.4	26.2
CVPM 13	849.0	611.6	501.2	765.8	989.4	1091.7	161.5	1.6	1.6
CVPM 14	599.0	599.1	504.2	757.8	515.4	610.3	0.0	14.5	14.5
CVPM 15	1259.7	920.1	937.0	359.5	907.9	891.0	81.0	0.0	0.0
CVPM 16	234.2	47.4	14.7	272.4	290.1	314.9	50.7	27.7	27.0
CVPM 17	301.2	213.4	198.4	485.0	491.6	503.3	78.6	0.0	0.0
CVPM 18	812.4	814.1	779.7	951.1	1204.8	1142.2	0.0	0.0	0.0
CVPM 19	297.6	607.6	419.6	803.9	234.2	422.2	0.0	0.0	0.0
CVPM 20	210.9	210.9	44.8	585.7	401.3	562.2	55.8	1.8	1.8
CVPM 21	602.2	177.4	304.1	821.6	776.4	637.3	0.0	11.4	11.3
Coachella	0.0	0.0	0.0	306.4	306.8	306.8	0.0	0.0	0.0
Imperial	0.0	0.0	0.0	1853.4	1856.1	1856.1	0.0	0.0	0.0
Palo Verde	0.0	0.0	0.0	763.9	764.9	764.9	0.0	0.0	0.0
Ventura	0.0	0.0	0.0	174.2	174.5	174.5	0.0	0.0	0.0
Antelope Val	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E&W MWD	0.0	0.0	0.0	64.8	64.9	64.9	0.0	0.0	0.0
San Diego	185.2	186.0	186.0	441.3	444.9	442.4	0.0	0.0	0.0

Table A-6: Supply Breakdown of Annual Avg. Urban Deliveries for each Demand Area

	Ground Water Use (TAF)			Surface Water Use (TAF)			Other Sources (TAF)		
Urban Demand Area	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft	Old Calvin	New Calvin	No Overdraft
Napa	1.2	1.2	1.2	174.0	174.2	174.2	0.0	0.0	0.0
Contra Costa	0.0	0.0	0.0	106.5	105.7	105.0	7.1	8.1	8.8
East Bay MUD	0.0	0.0	0.0	270.4	270.7	270.7	0.0	0.0	0.0
Stockton	13.3	0.0	0.0	104.3	117.7	117.7	0.0	0.0	0.0
Redding	37.2	37.2	37.2	52.4	52.4	52.4	0.0	0.0	0.0
Galt	82.8	82.7	82.7	0.0	0.0	0.0	0.0	0.0	0.0
Sacramento	483.9	223.6	147.7	192.3	453.6	529.5	0.0	0.0	0.0
Yuba	0.0	0.0	0.0	91.3	91.4	91.4	0.0	0.0	0.0
SFPU	0.0	0.0	0.0	218.9	219.2	219.2	0.0	0.0	0.0
Modesto	209.1	235.8	235.8	26.4	0.0	0.0	0.0	0.0	0.0
Merced	224.1	224.2	224.2	0.0	0.0	0.0	0.0	0.0	0.0
Turlock	167.4	177.3	177.3	9.6	0.0	0.0	0.0	0.0	0.0
Santa Clara Val	399.7	400.3	400.3	298.7	299.0	299.0	15.6	15.6	15.6
Fresno	150.5	93.1	134.1	185.7	243.6	202.6	0.0	0.0	0.0
Bakersfield	113.1	113.3	113.3	143.1	143.3	143.3	0.0	0.0	0.0
Sanger	144.2	144.4	144.4	0.0	0.0	0.0	0.0	0.0	0.0
Visalia	206.8	207.1	207.1	0.0	0.0	0.0	0.0	0.0	0.0
Delano	137.1	137.2	137.1	0.0	0.0	0.0	0.0	0.0	0.0
SB-SLO	0.0	0.0	0.0	134.3	134.4	134.4	62.1	62.2	62.2
San Bernardino	227.9	228.2	228.1	273.7	274.1	273.0	35.6	35.7	35.7
SDWD	0.0	0.0	0.0	823.9	825.2	825.2	11.6	11.5	11.5
Coachella	295.2	295.6	295.6	25.5	25.6	25.6	0.0	0.0	0.0
E&W MWD	0.0	0.0	0.0	802.0	802.9	802.0	27.0	27.5	27.5
Mojave	186.2	186.2	186.2	0.0	0.0	0.0	24.9	25.0	25.0
Ventura	228.8	229.2	229.2	68.9	69.0	69.0	9.4	9.4	9.4
El Centro	0.0	0.0	0.0	70.1	70.1	70.1	0.0	0.0	0.0
Castaic Lake	0.0	0.0	0.0	159.1	159.3	159.3	0.0	0.0	0.0
C MWD	1185.7	1187.1	1187.1	2093.9	2097.0	2097.0	0.0	0.0	0.0
Blyth	0.0	0.0	0.0	15.3	15.3	15.3	0.0	0.0	0.0
Antelope Val	64.3	64.6	64.6	162.4	162.4	149.4	64.9	65.0	77.9

Appendix B

Shasta-Trinity Storage Allocation

Figure B-1: Storage Allocation Between Shasta and Trinity for January in CALVIN

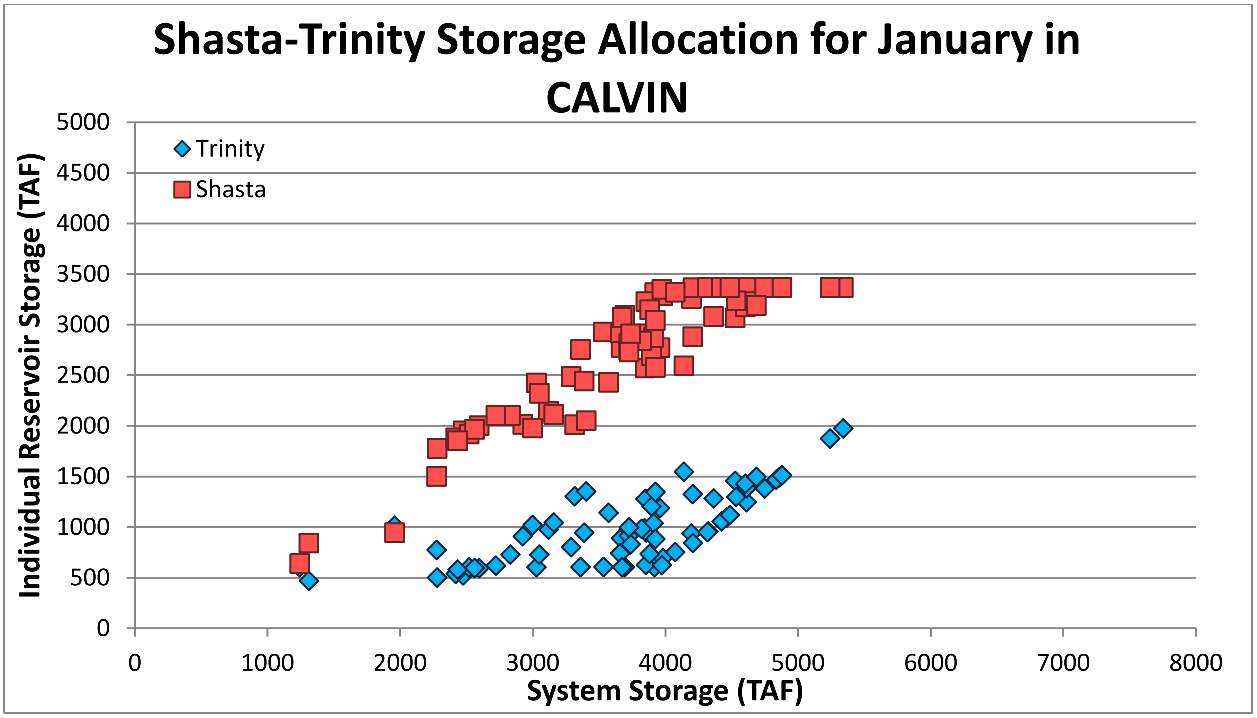


Figure B-2: Storage Allocation Between Shasta and Trinity for February in CALVIN

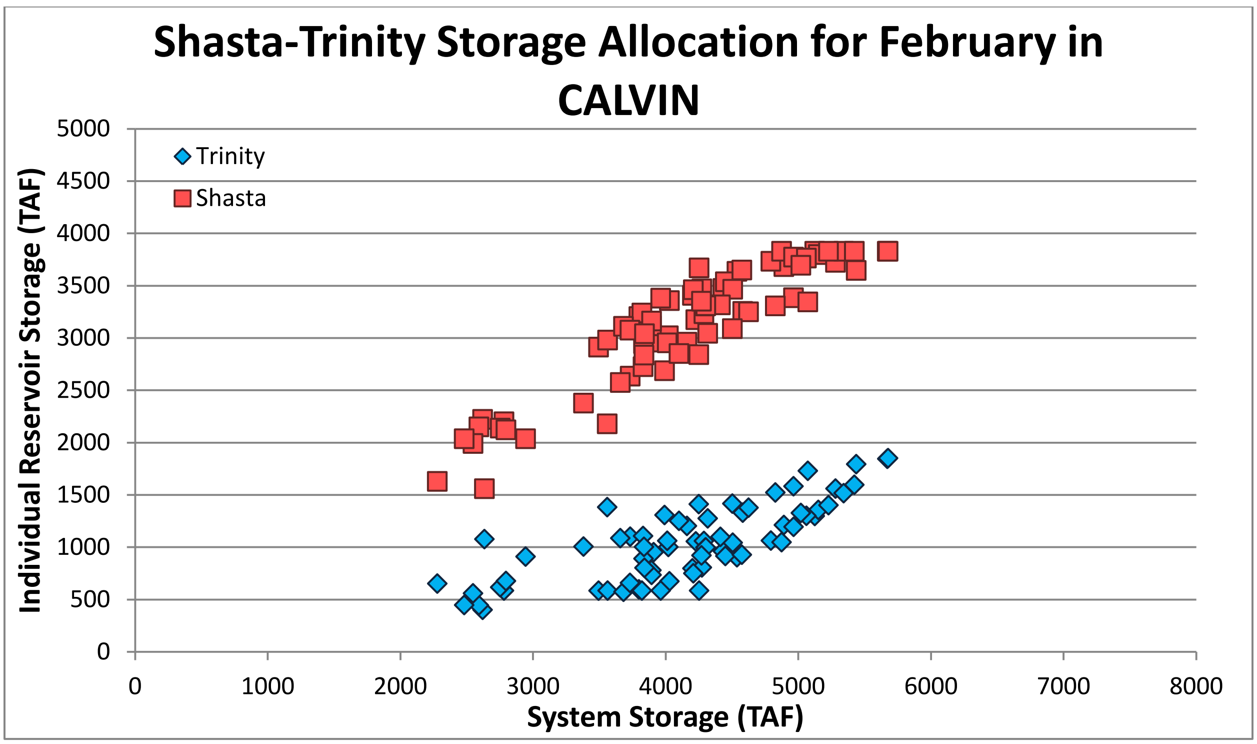


Figure B-3: Storage Allocation Between Shasta and Trinity for March in CALVIN

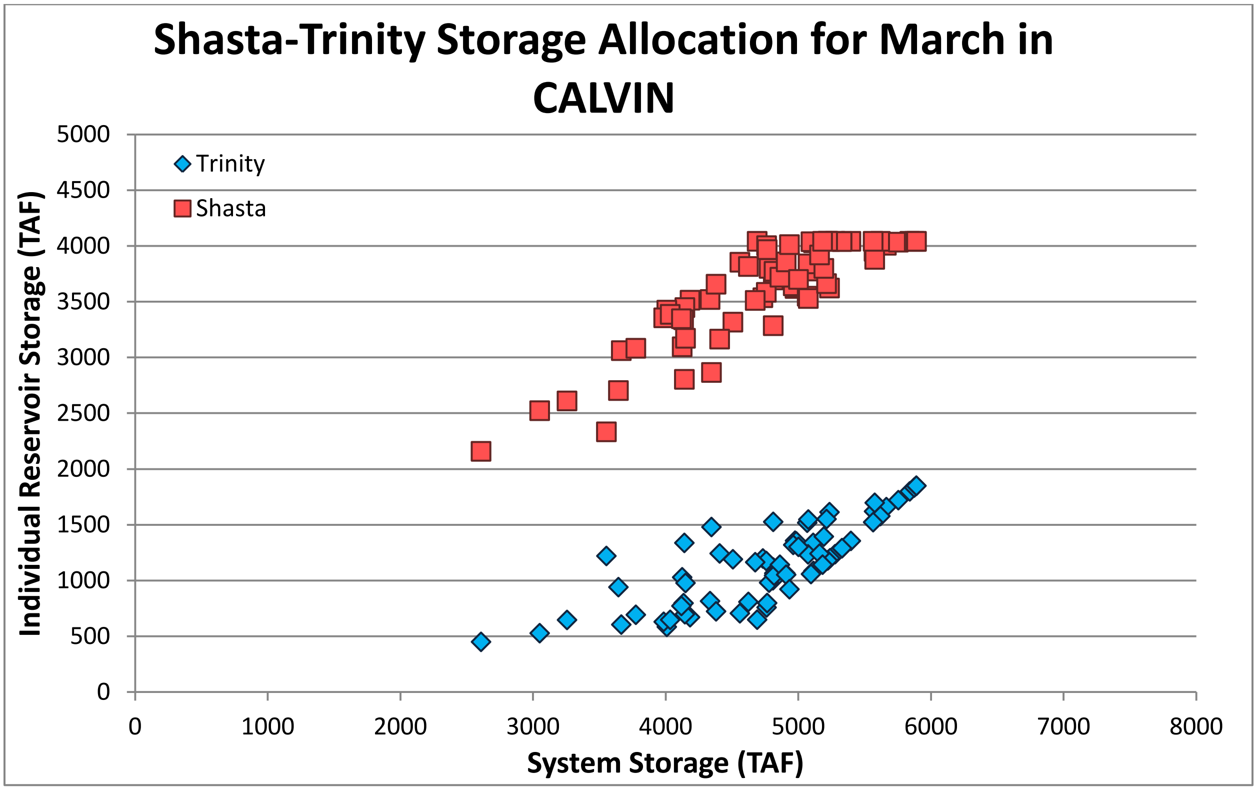


Figure B-4: Storage Allocation Between Shasta and Trinity for April in CALVIN

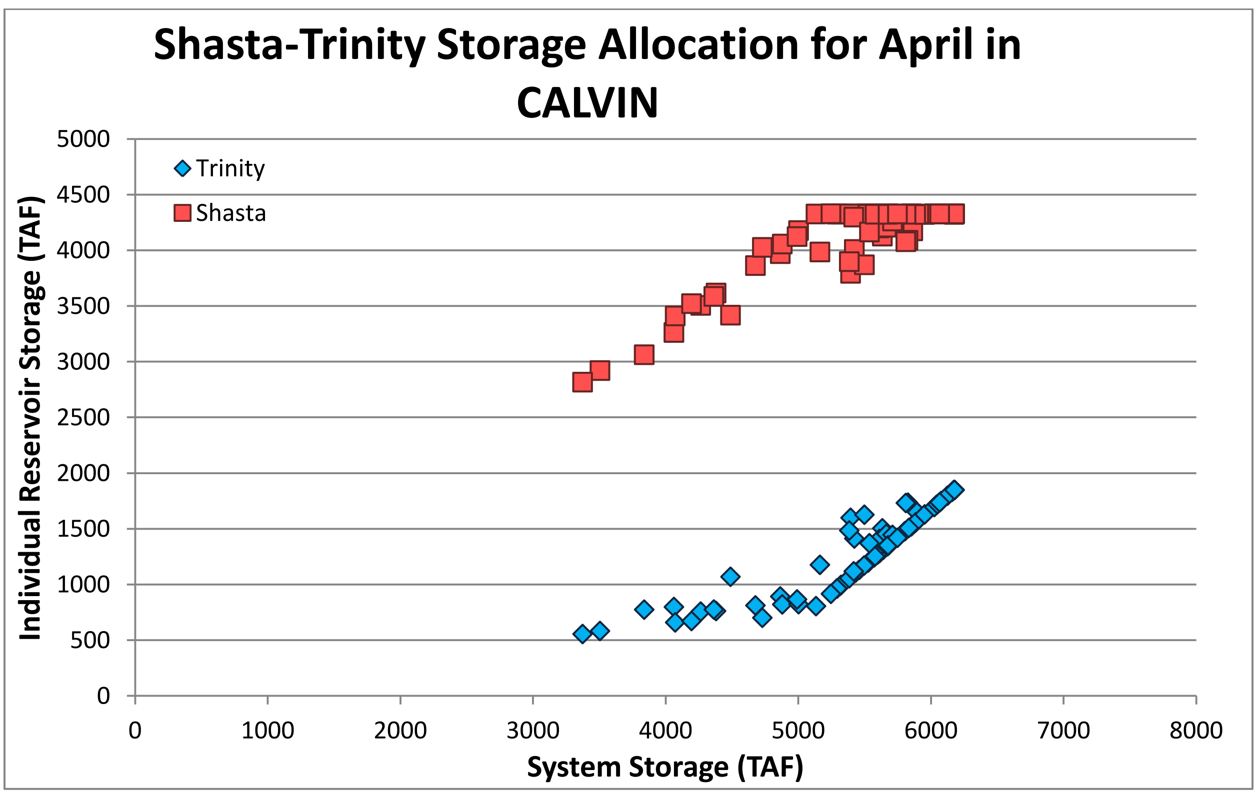


Figure B-5: Storage Allocation Between Shasta and Trinity for May in CALVIN

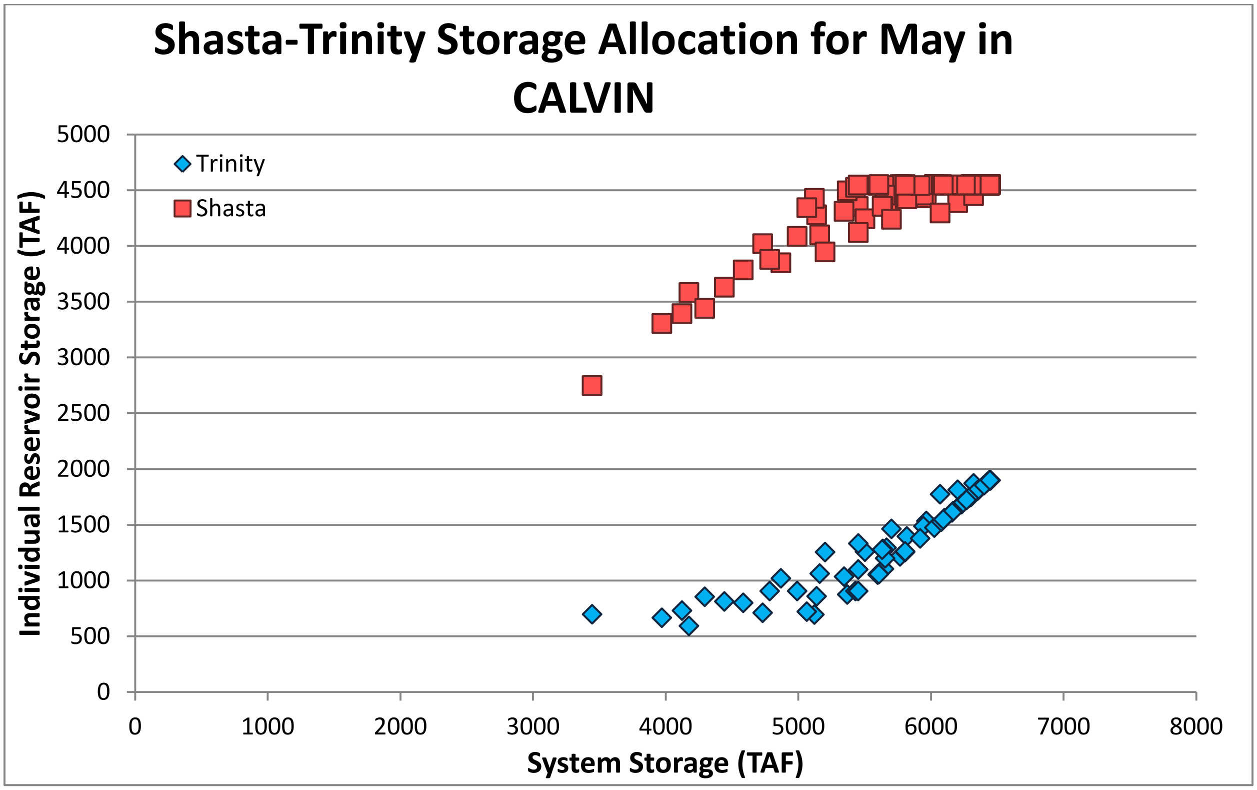


Figure B-6: Storage Allocation Between Shasta and Trinity for June in CALVIN

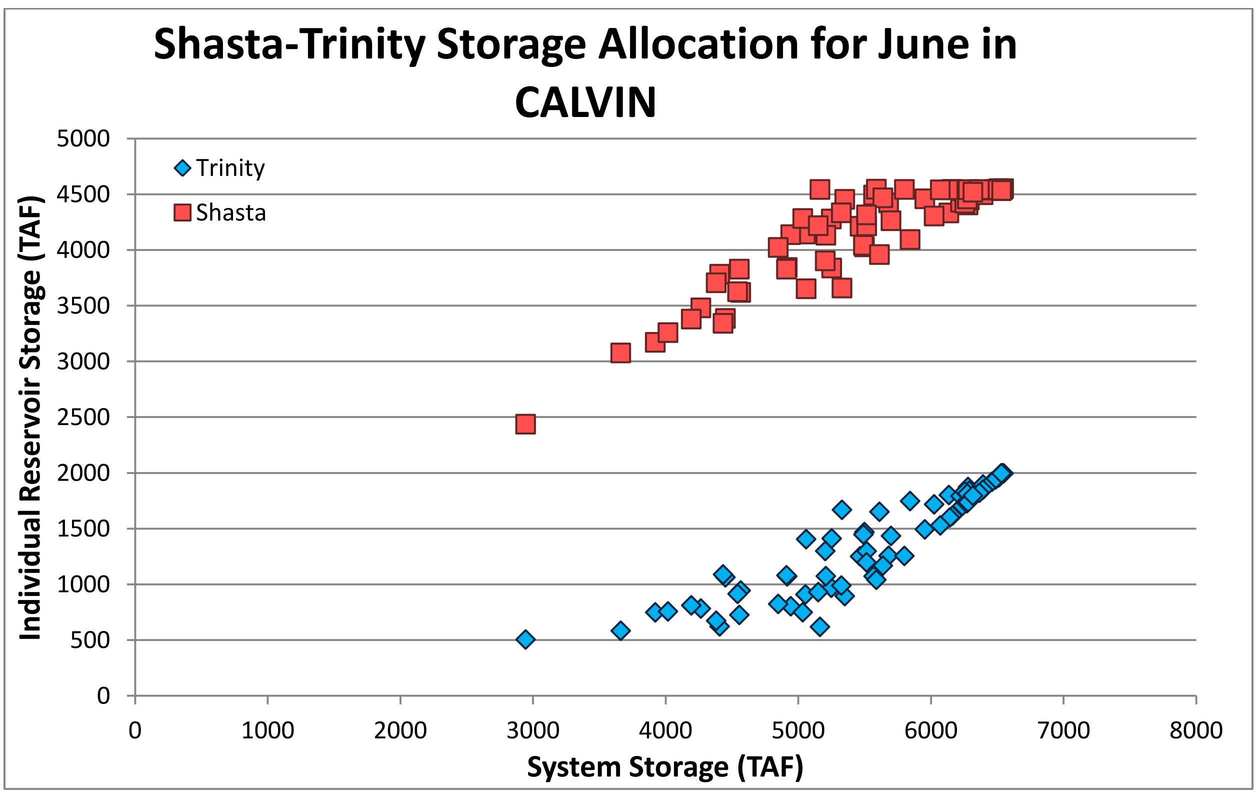


Figure B-7: Storage Allocation Between Shasta and Trinity for July in CALVIN

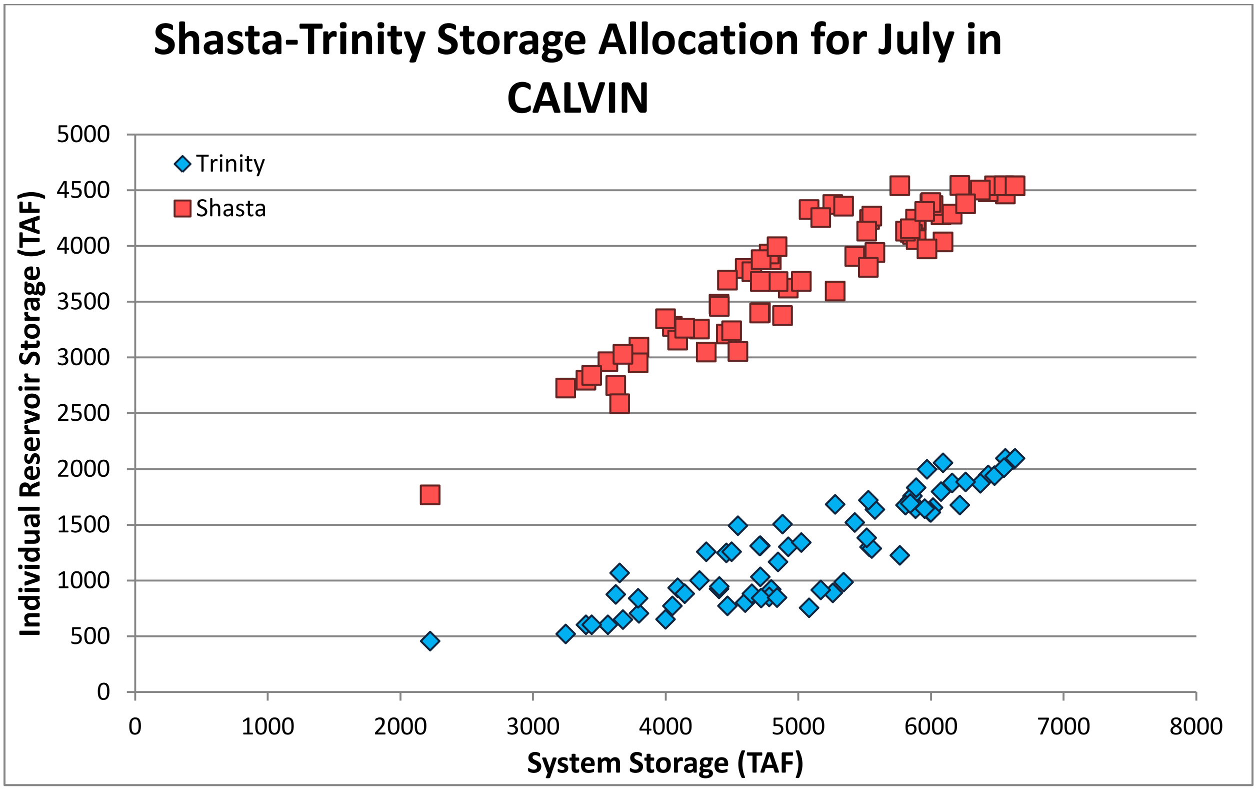


Figure B-8: Storage Allocation Between Shasta and Trinity for August in CALVIN

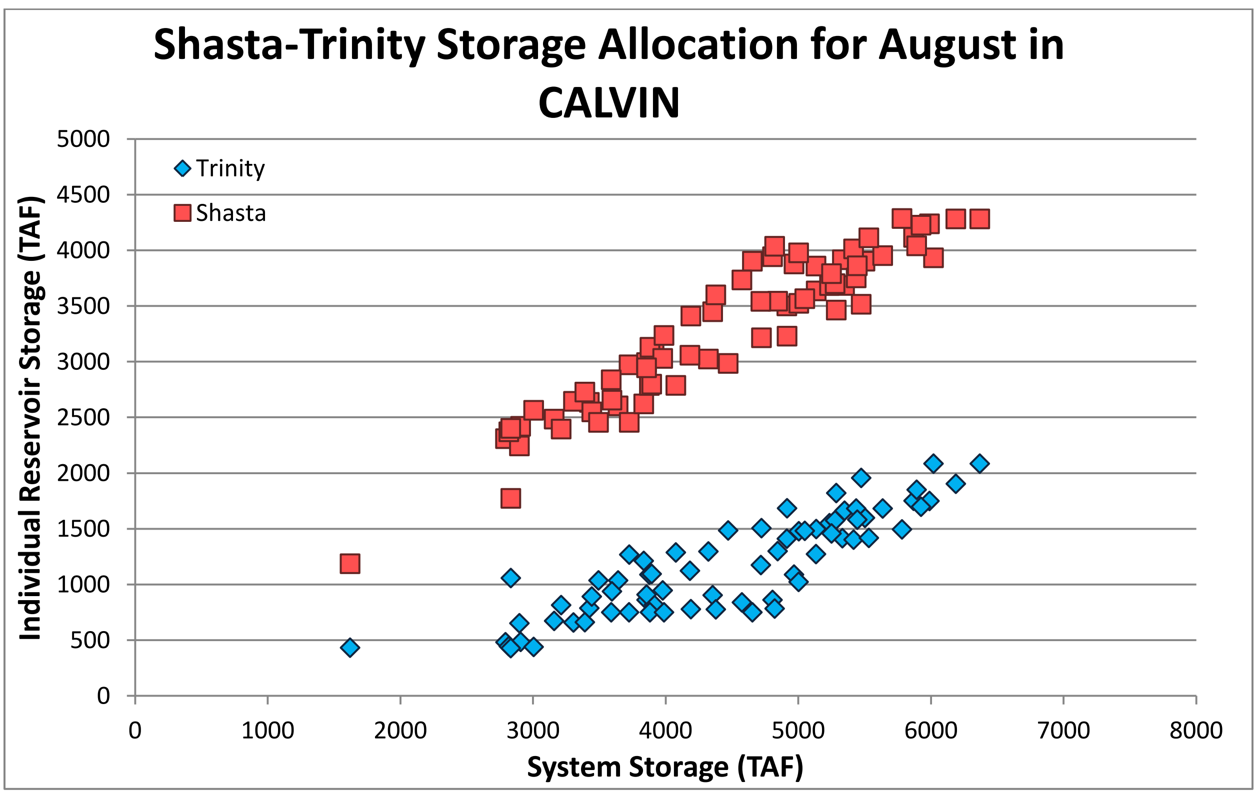


Figure B-9: Storage Allocation Between Shasta and Trinity for September in CALVIN

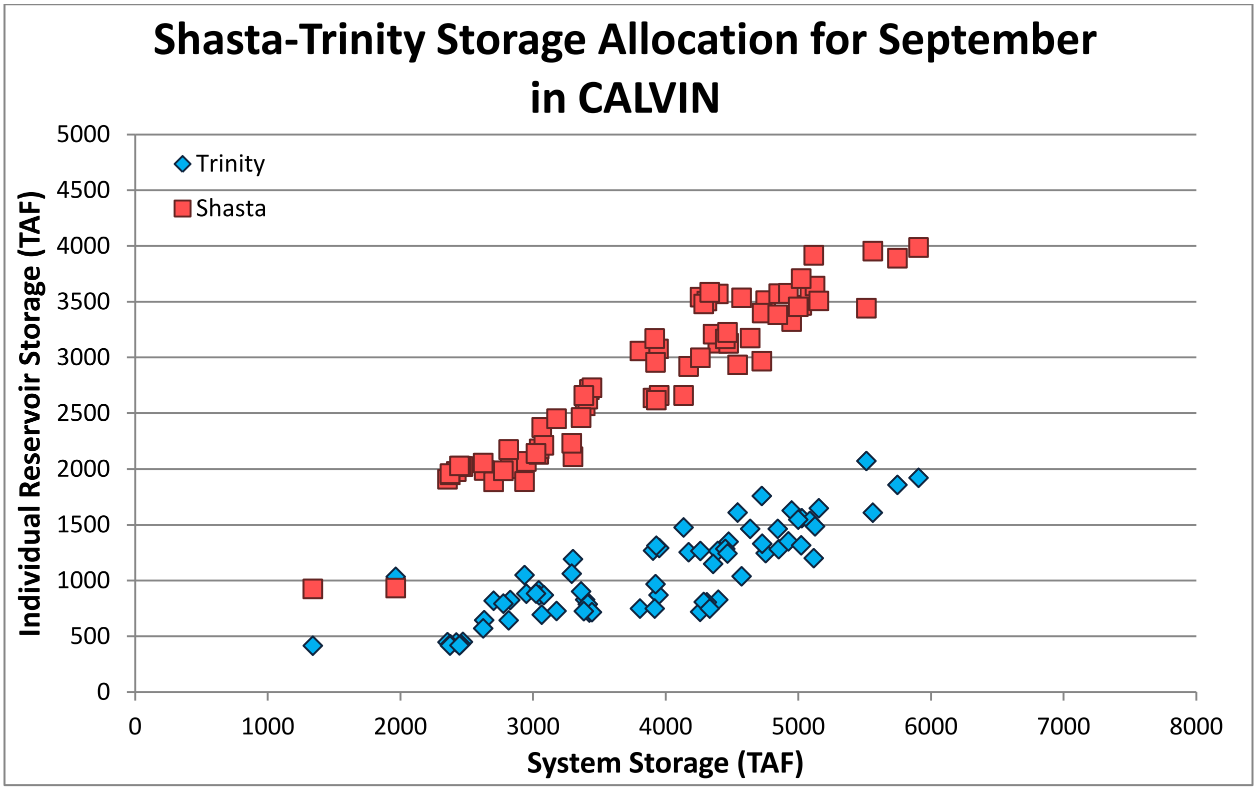


Figure B-10: Storage Allocation Between Shasta and Trinity for October in CALVIN

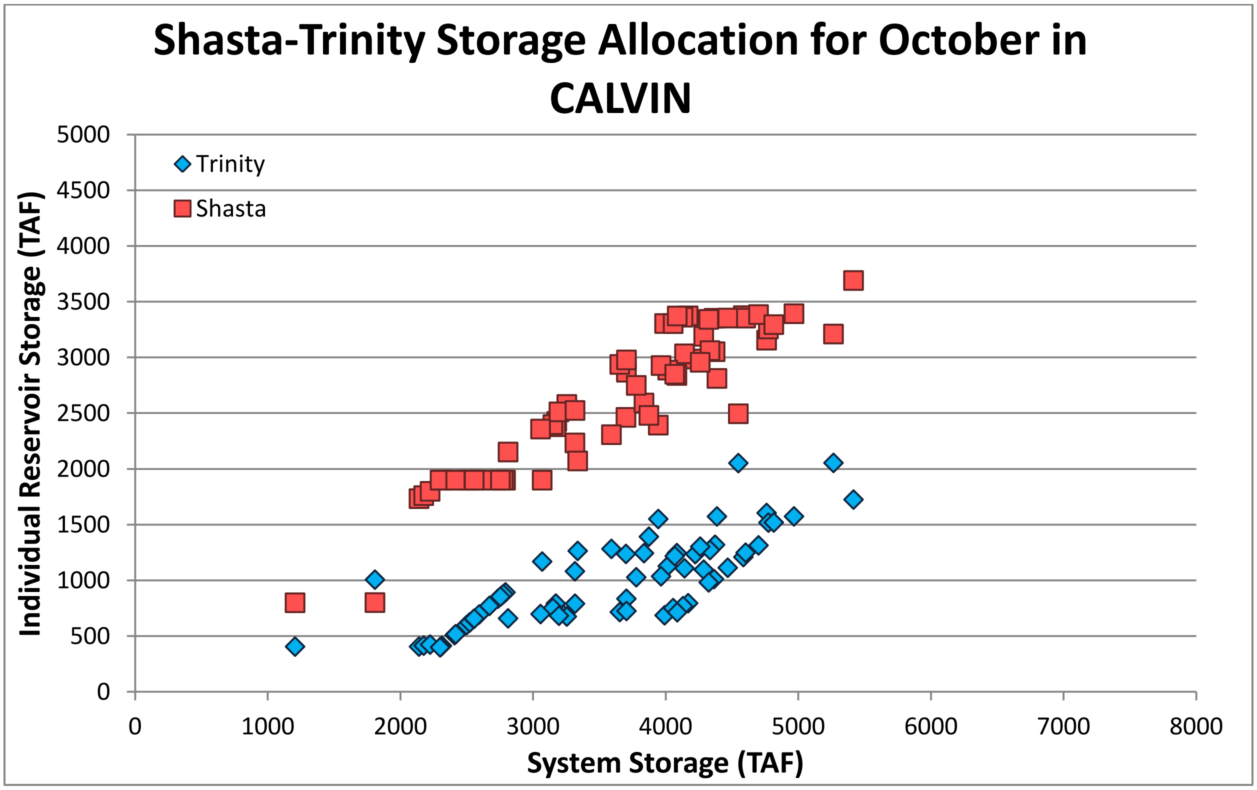


Figure B-11: Storage Allocation Between Shasta and Trinity for November in CALVIN

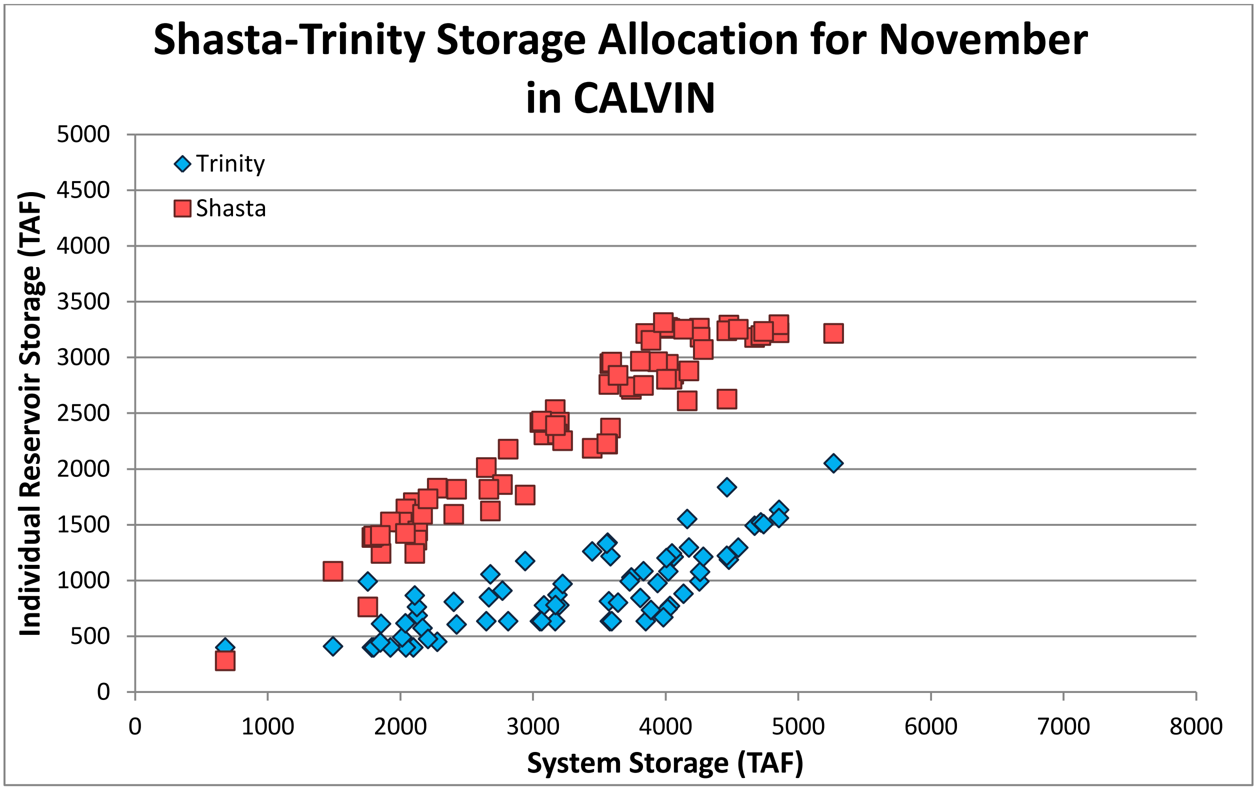


Figure B-12: Storage Allocation Between Shasta and Trinity for December in CALVIN

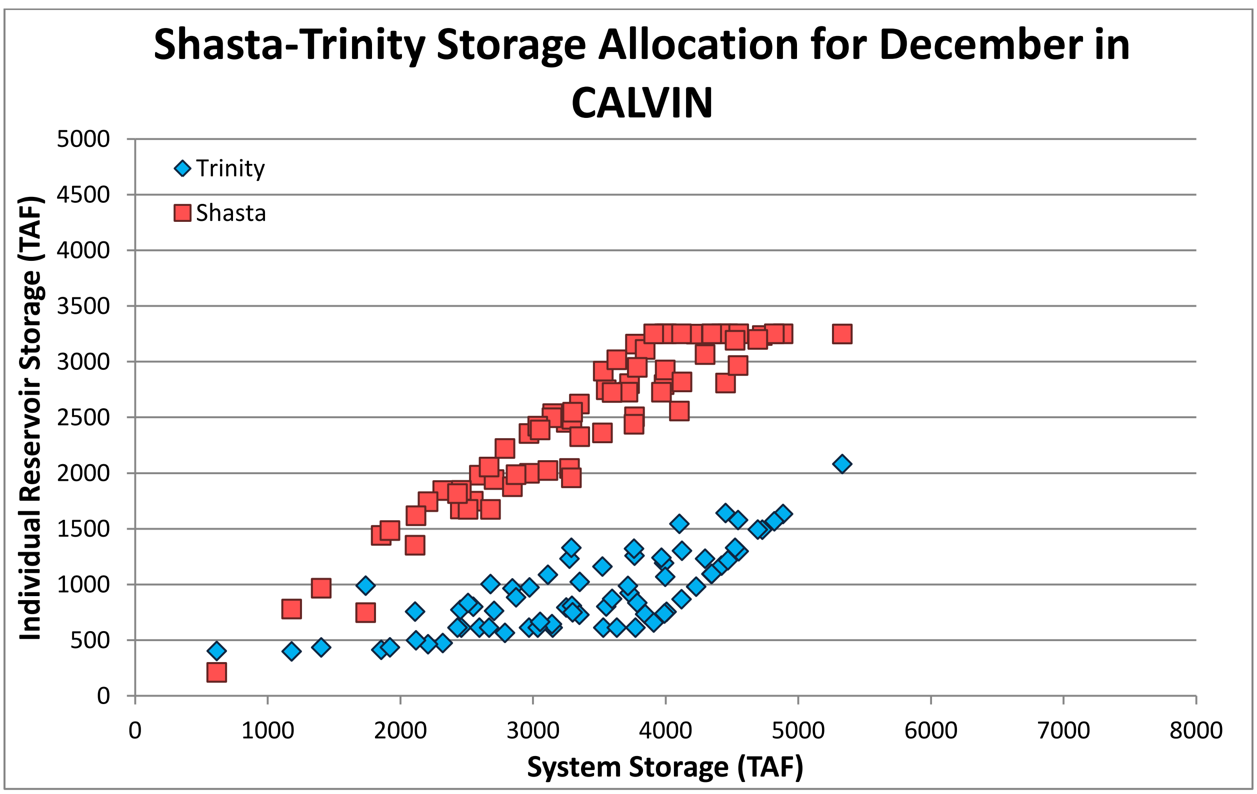


Figure B-13: Storage Allocation Between Shasta and Trinity for January in CalSim

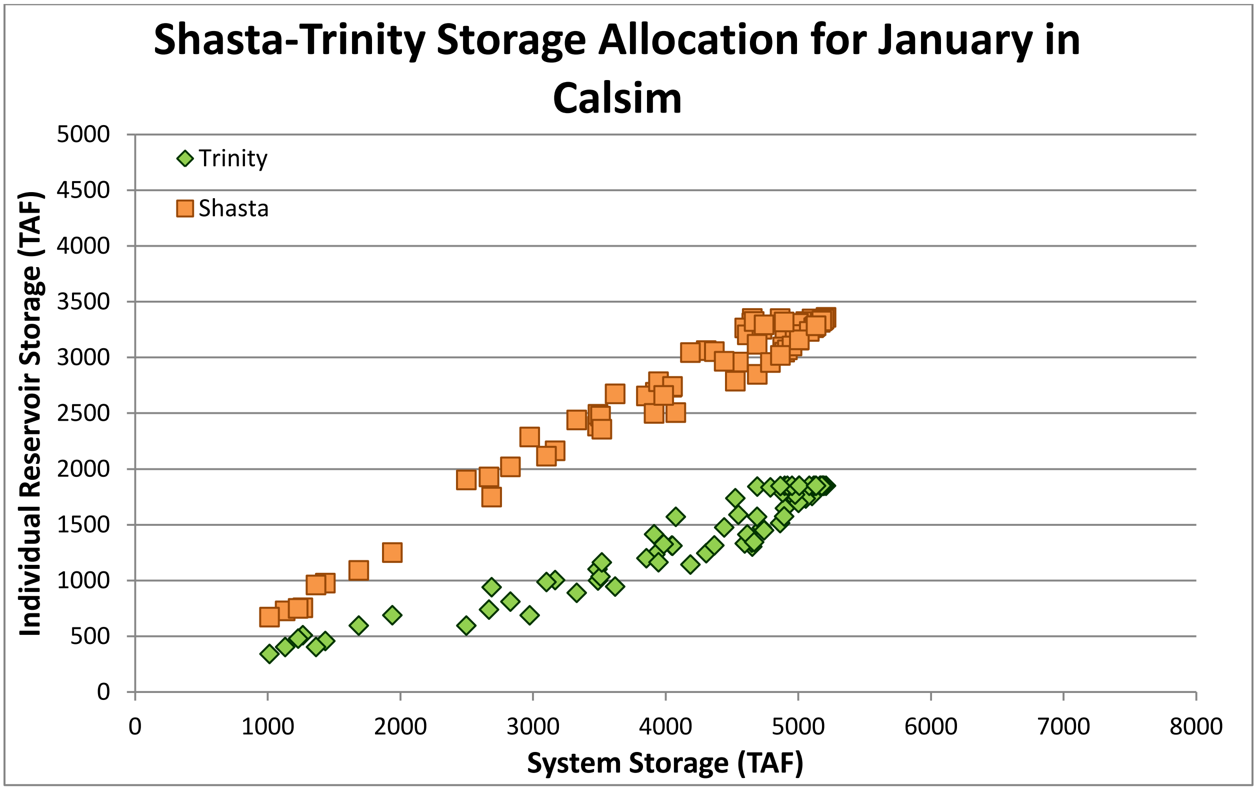


Figure B-14: Storage Allocation Between Shasta and Trinity for February in CalSim

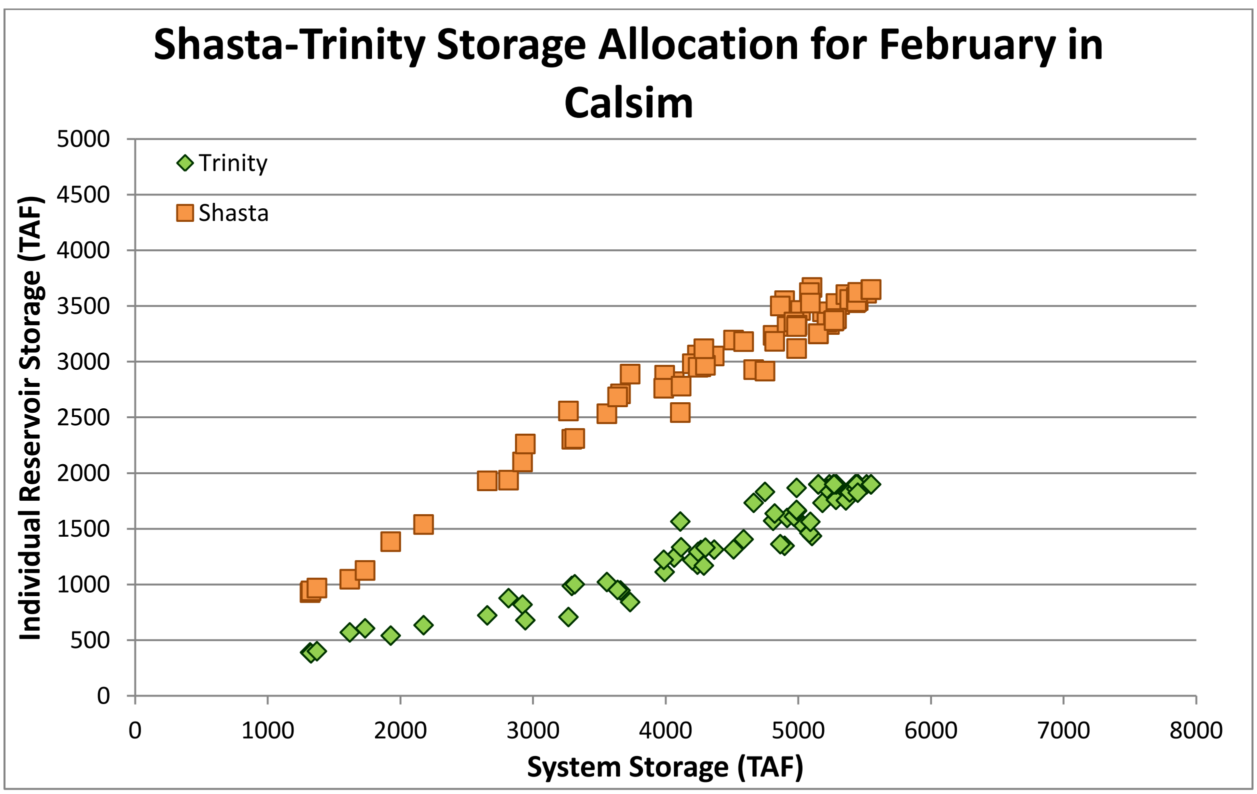


Figure B-15: Storage Allocation Between Shasta and Trinity for March in CalSim

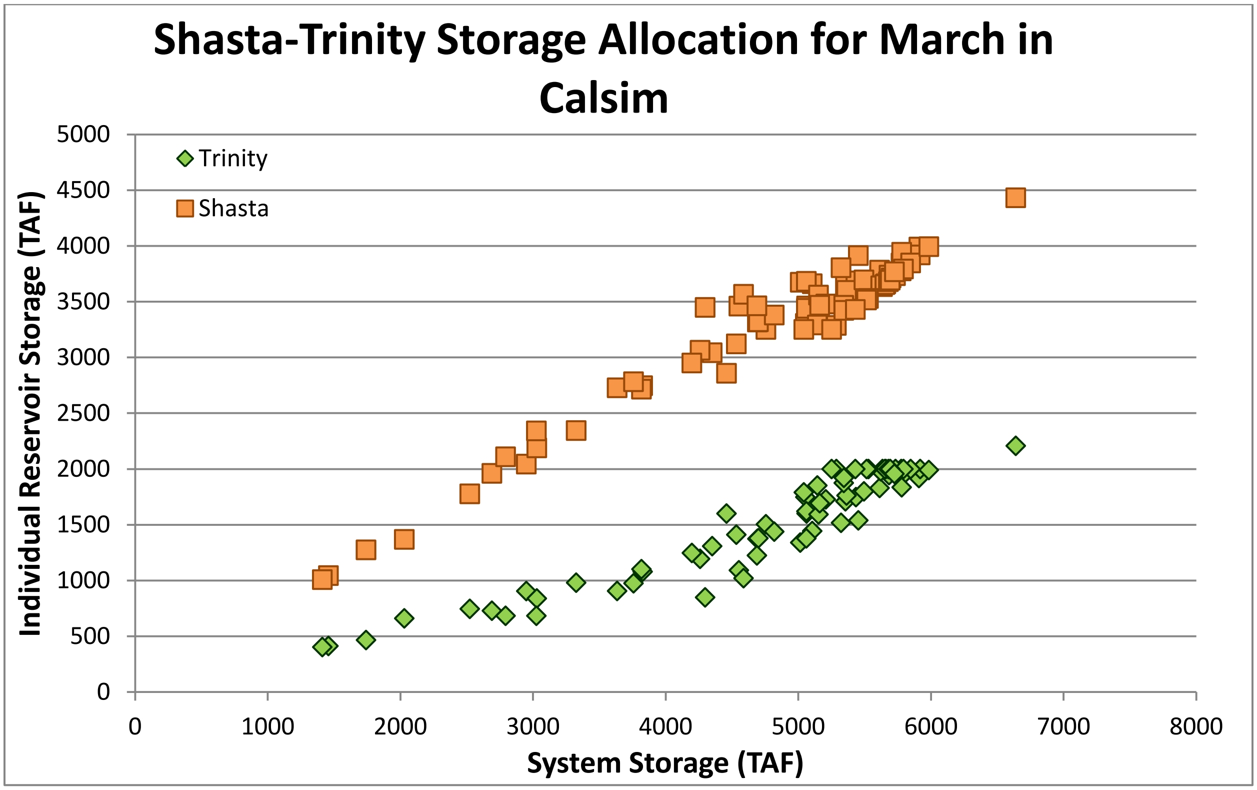


Figure B-16: Storage Allocation Between Shasta and Trinity for April in CalSim

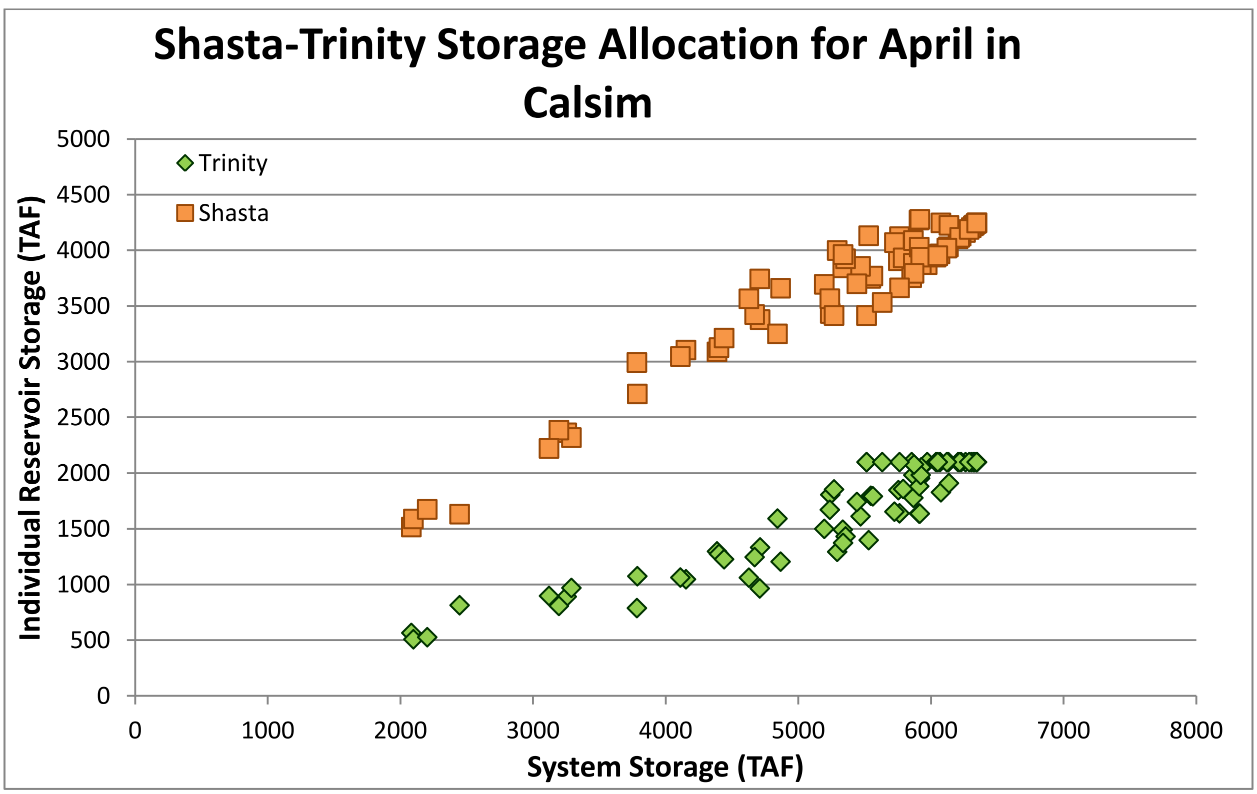


Figure B-17: Storage Allocation Between Shasta and Trinity for May in CalSim

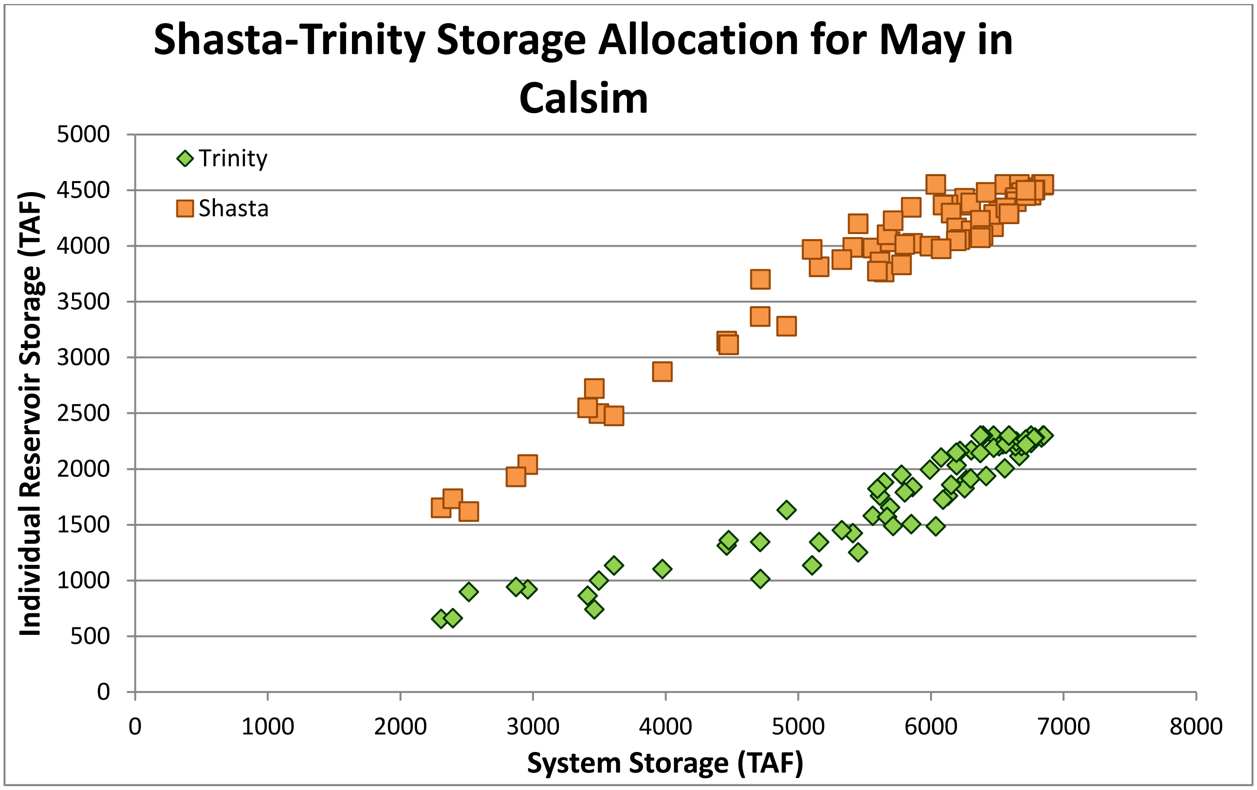


Figure B-18: Storage Allocation Between Shasta and Trinity for June in CalSim

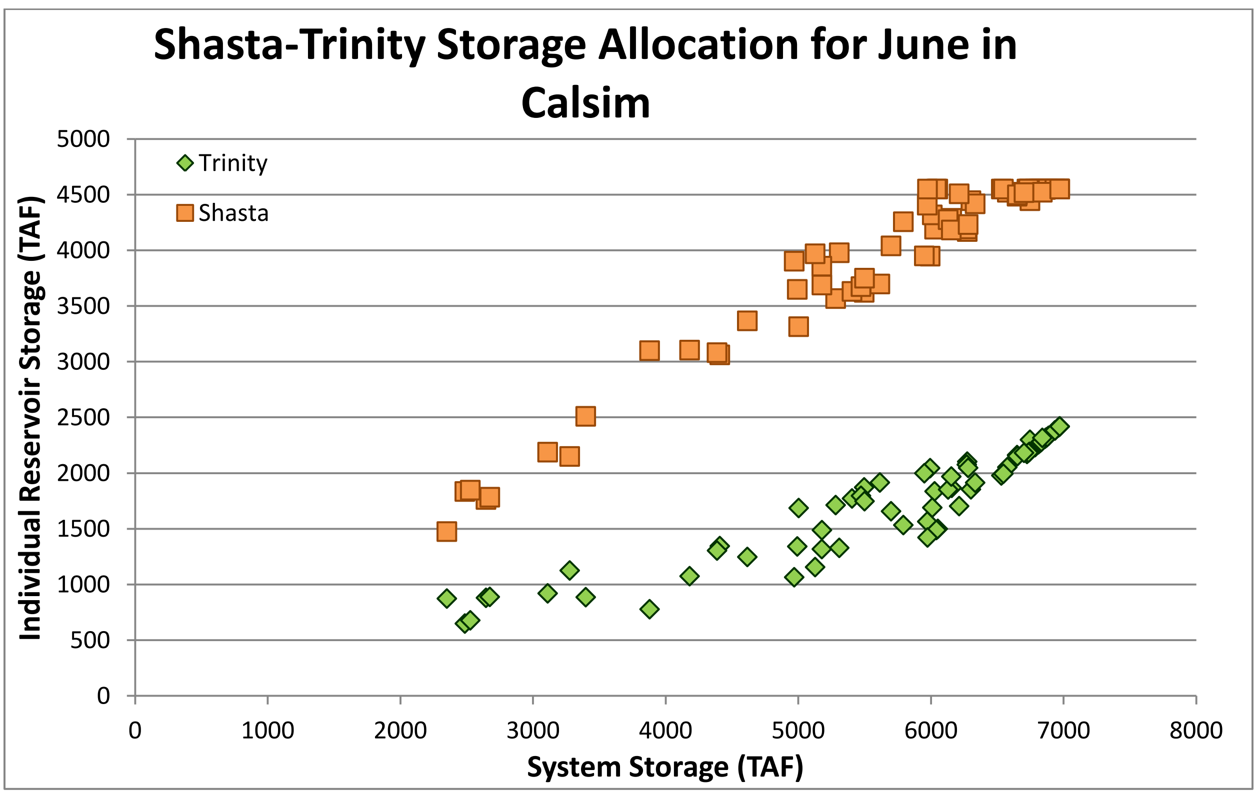


Figure B-19: Storage Allocation Between Shasta and Trinity for July in CalSim

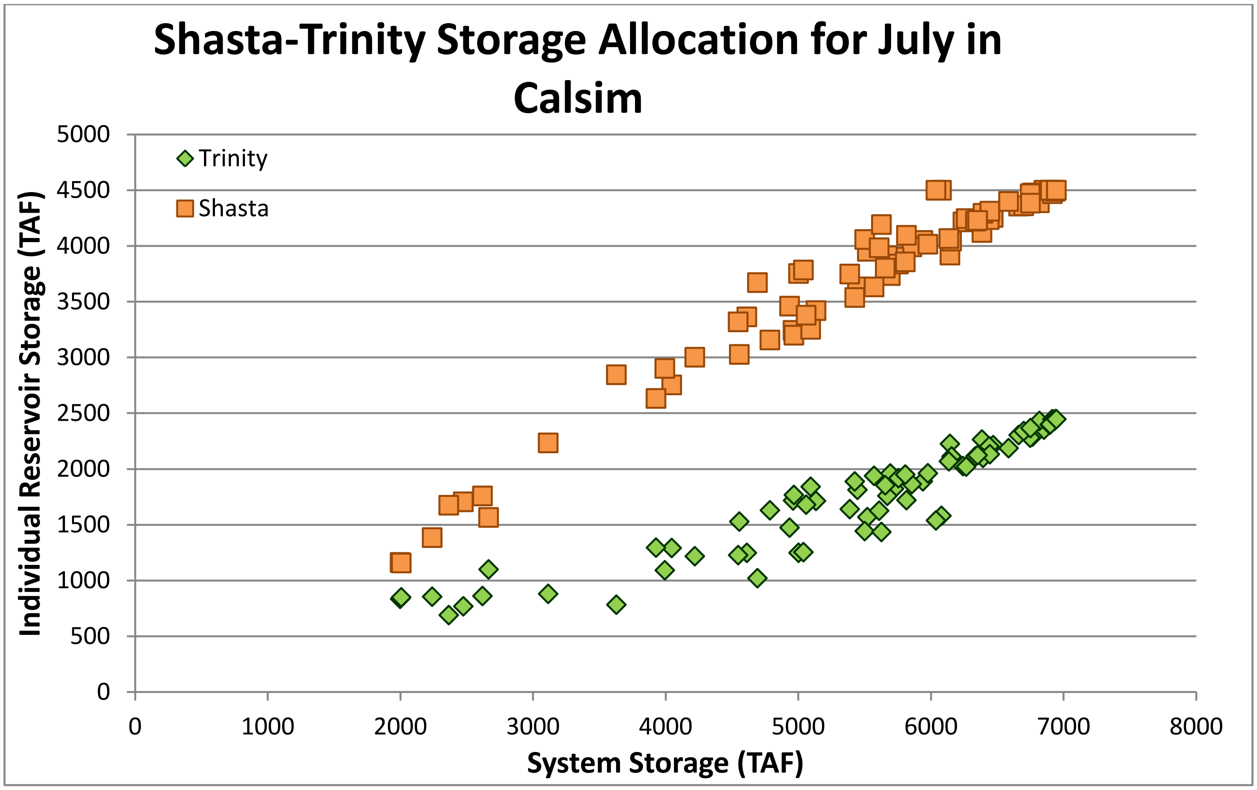


Figure B-20: Storage Allocation Between Shasta and Trinity for August in CalSim

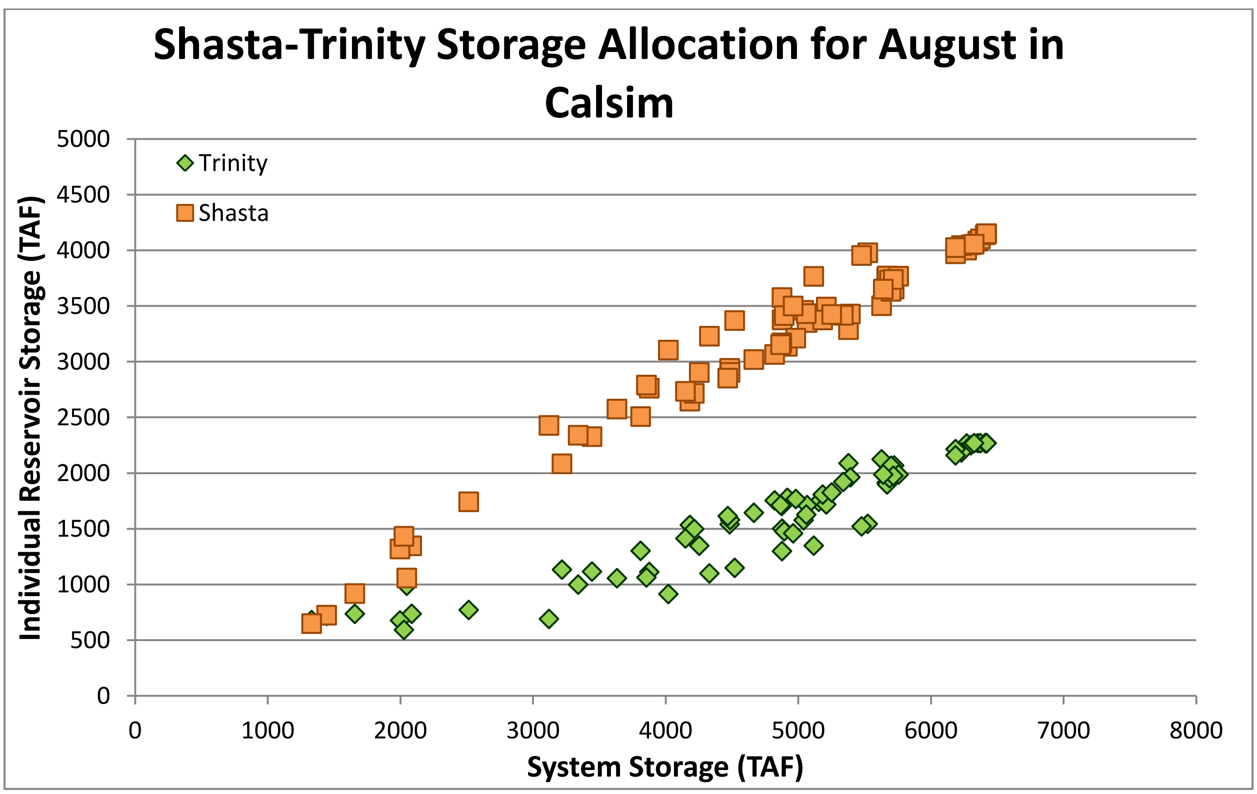


Figure B-21: Storage Allocation Between Shasta and Trinity for September in CalSim

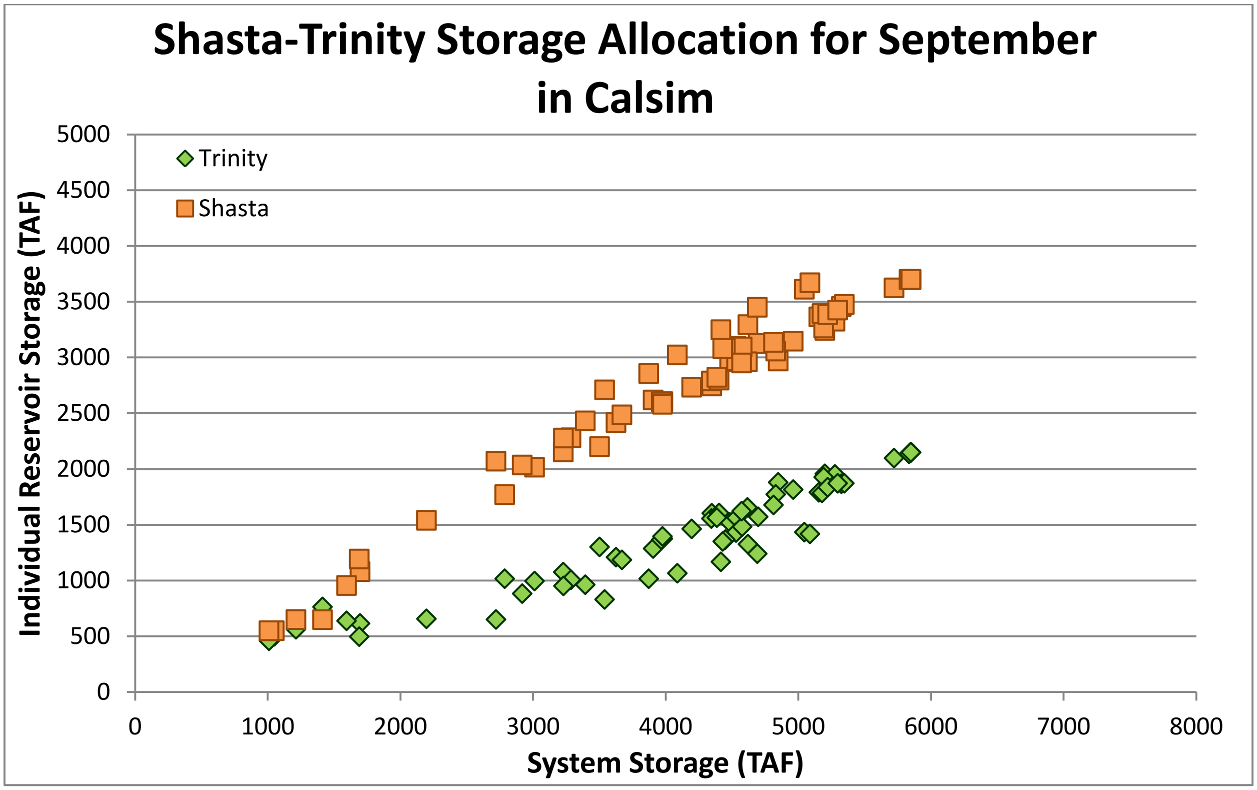


Figure B-22: Storage Allocation Between Shasta and Trinity for October in CalSim

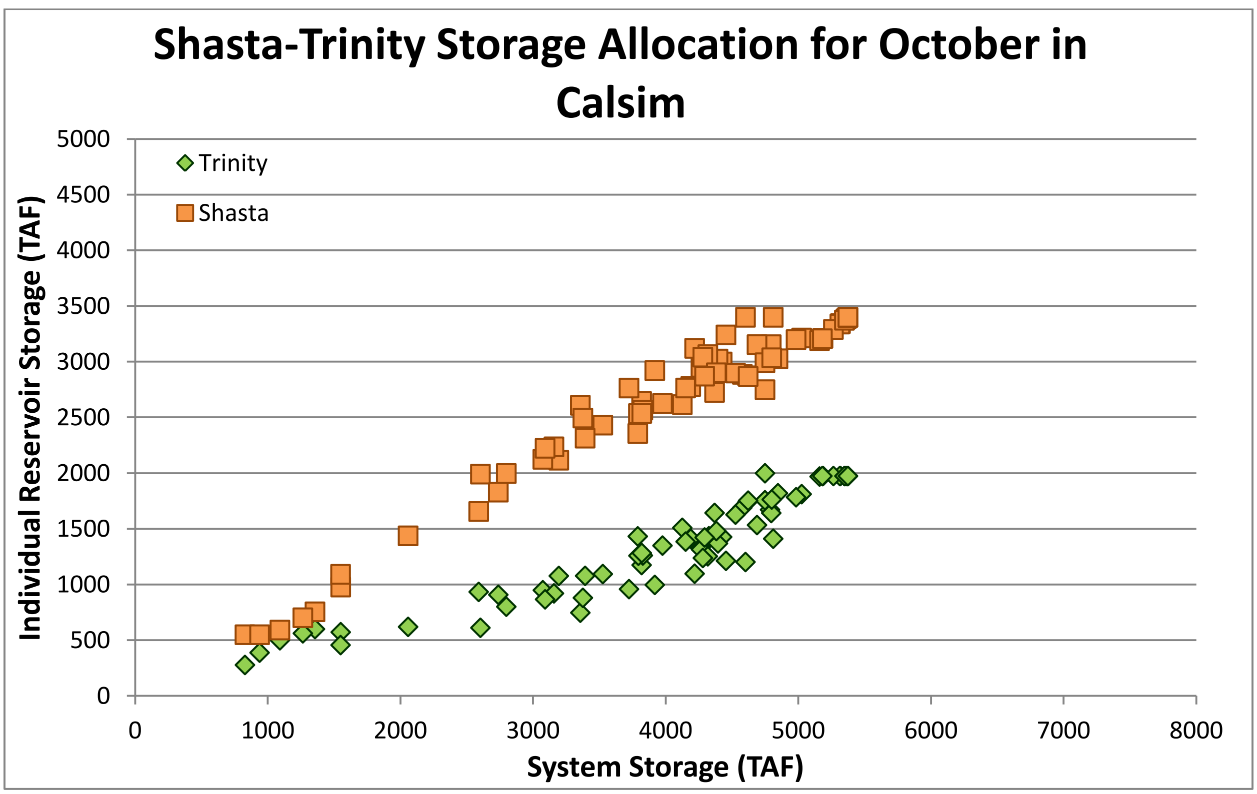


Figure B-23: Storage Allocation Between Shasta and Trinity for November in CalSim

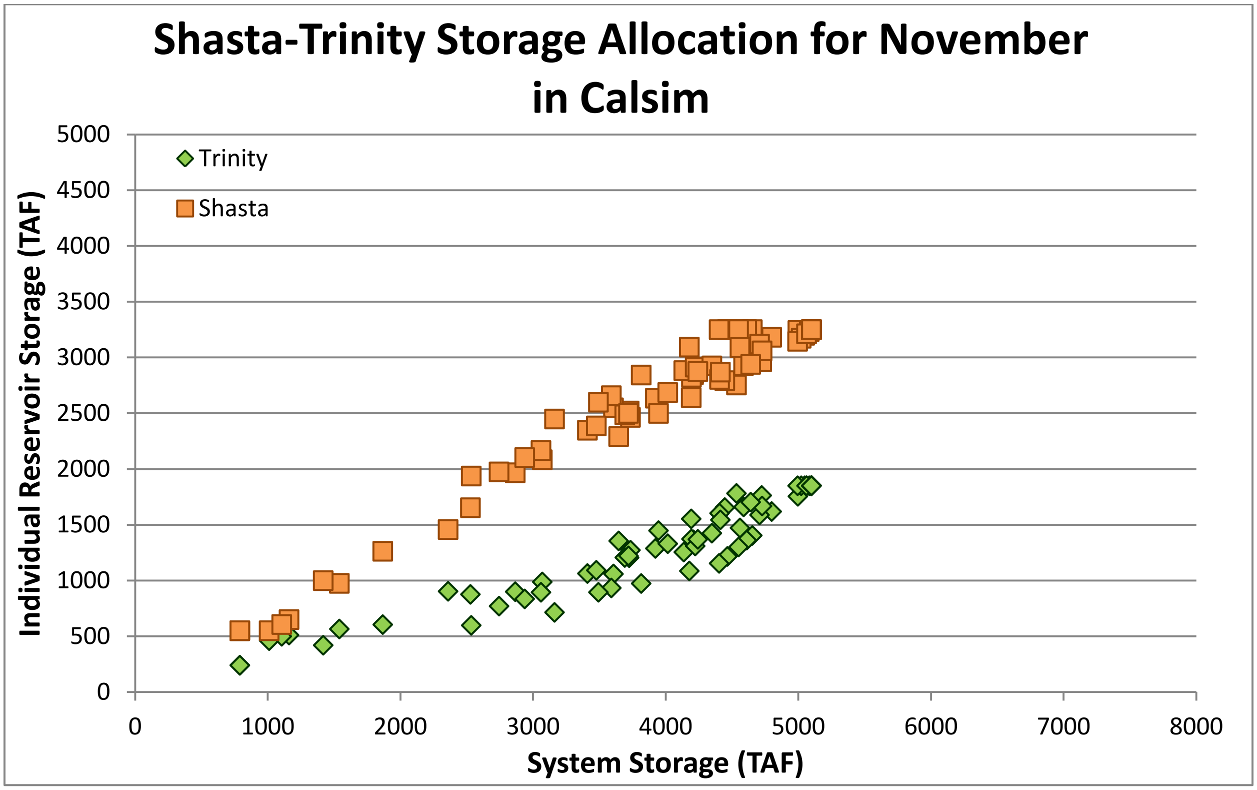
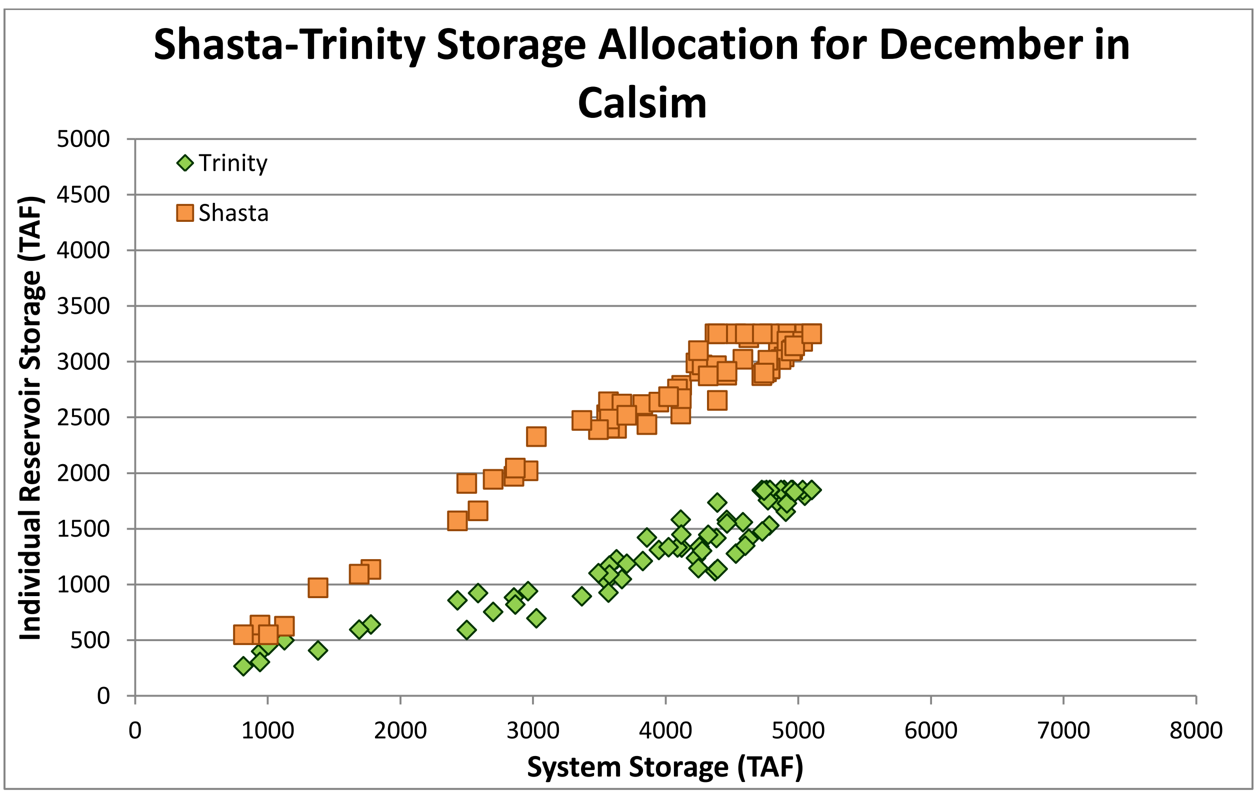


Figure B-24: Storage Allocation Between Shasta and Trinity for December in CalSim



Shasta-Trinity-Oroville Storage Allocation

Figure B-25: Storage Allocation Between Shasta, Trinity, and Oroville for January in CALVIN

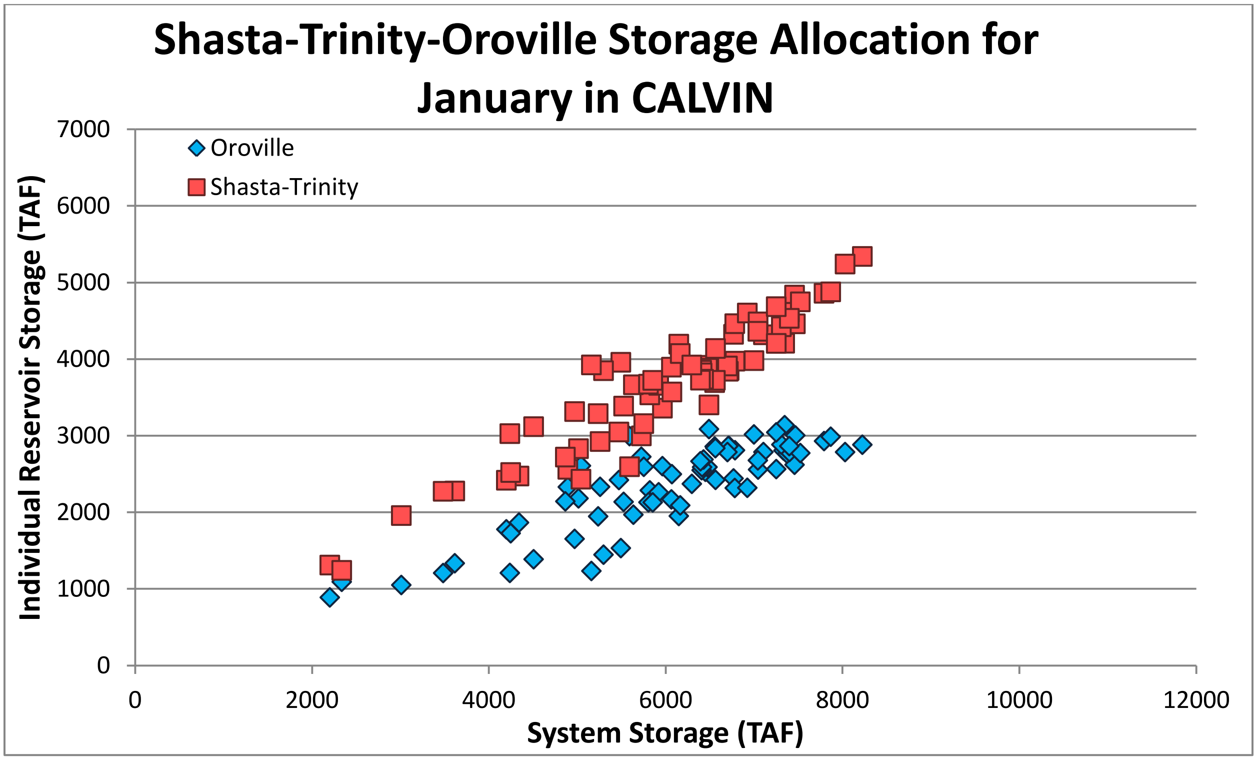


Figure B-26: Storage Allocation Between Shasta, Trinity, and Oroville for February in CALVIN

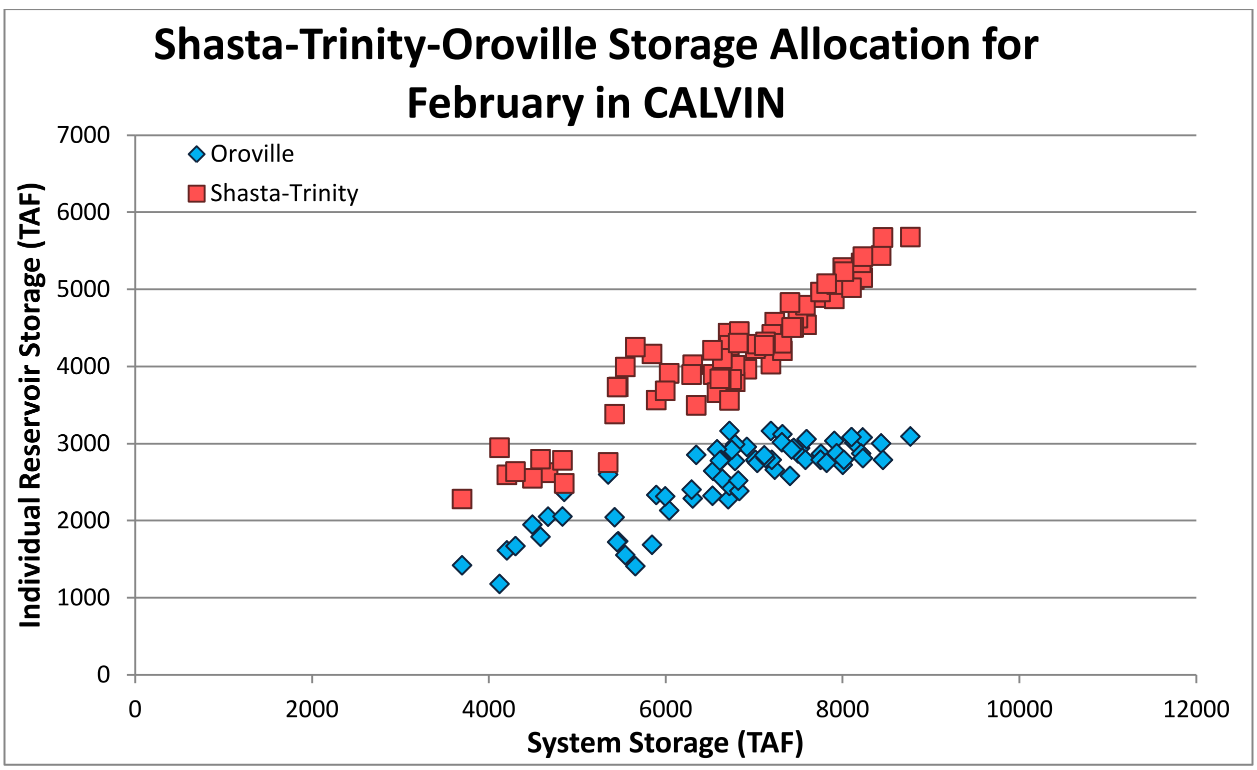


Figure B-27: Storage Allocation Between Shasta, Trinity, and Oroville for March in CALVIN

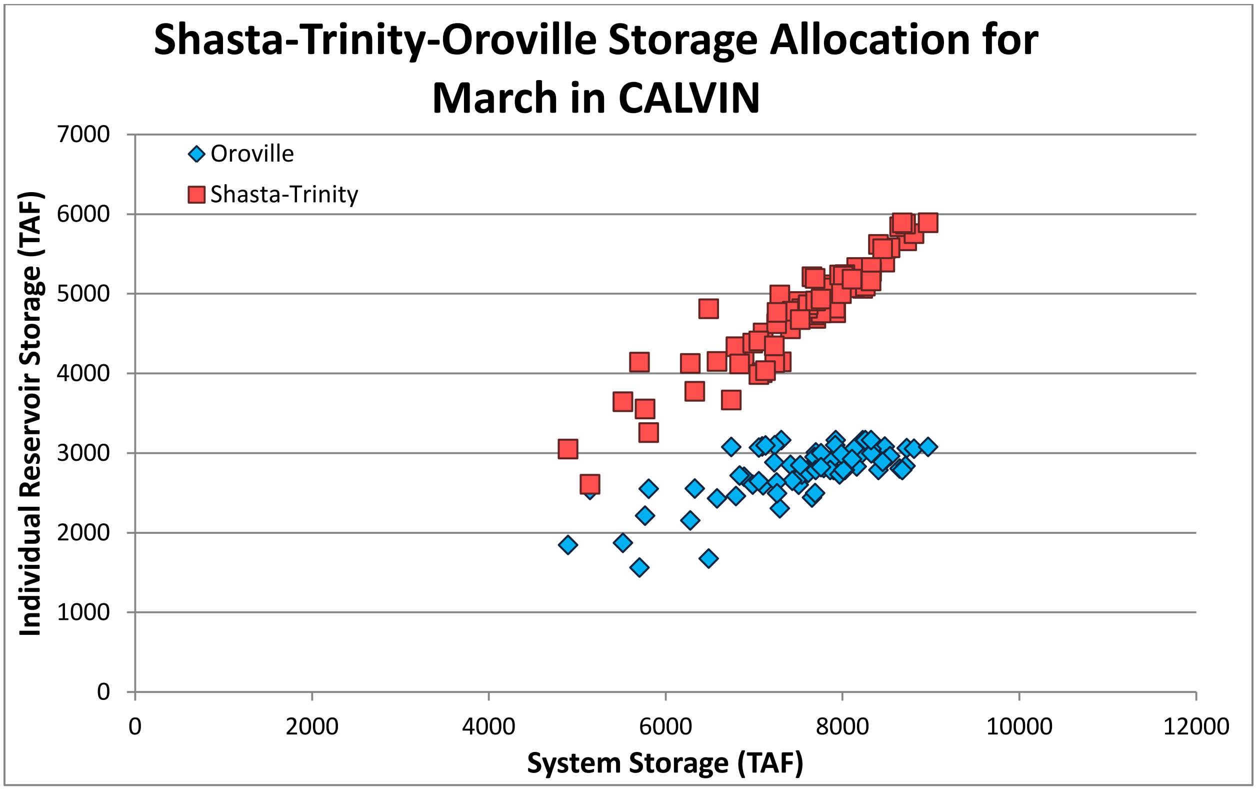


Figure B-28: Storage Allocation Between Shasta, Trinity, and Oroville for April in CALVIN

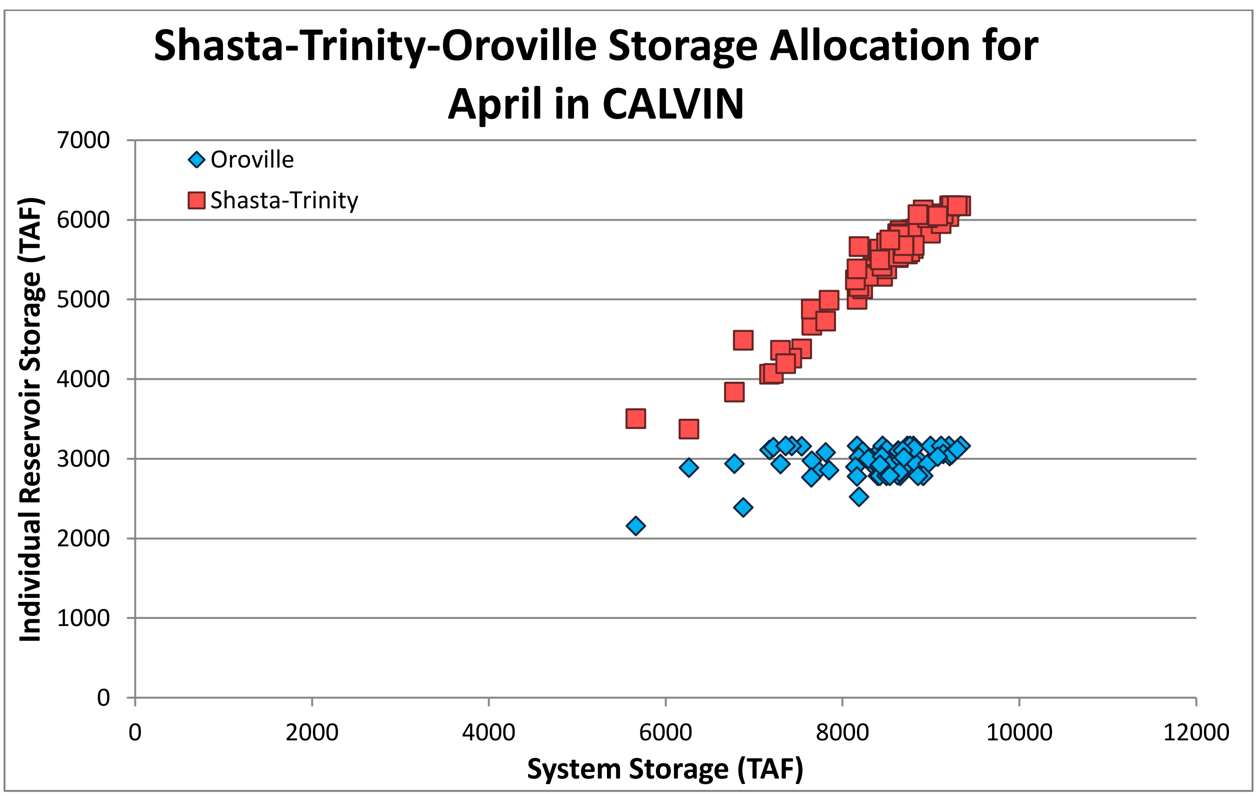


Figure B-29: Storage Allocation Between Shasta, Trinity, and Oroville for May in CALVIN

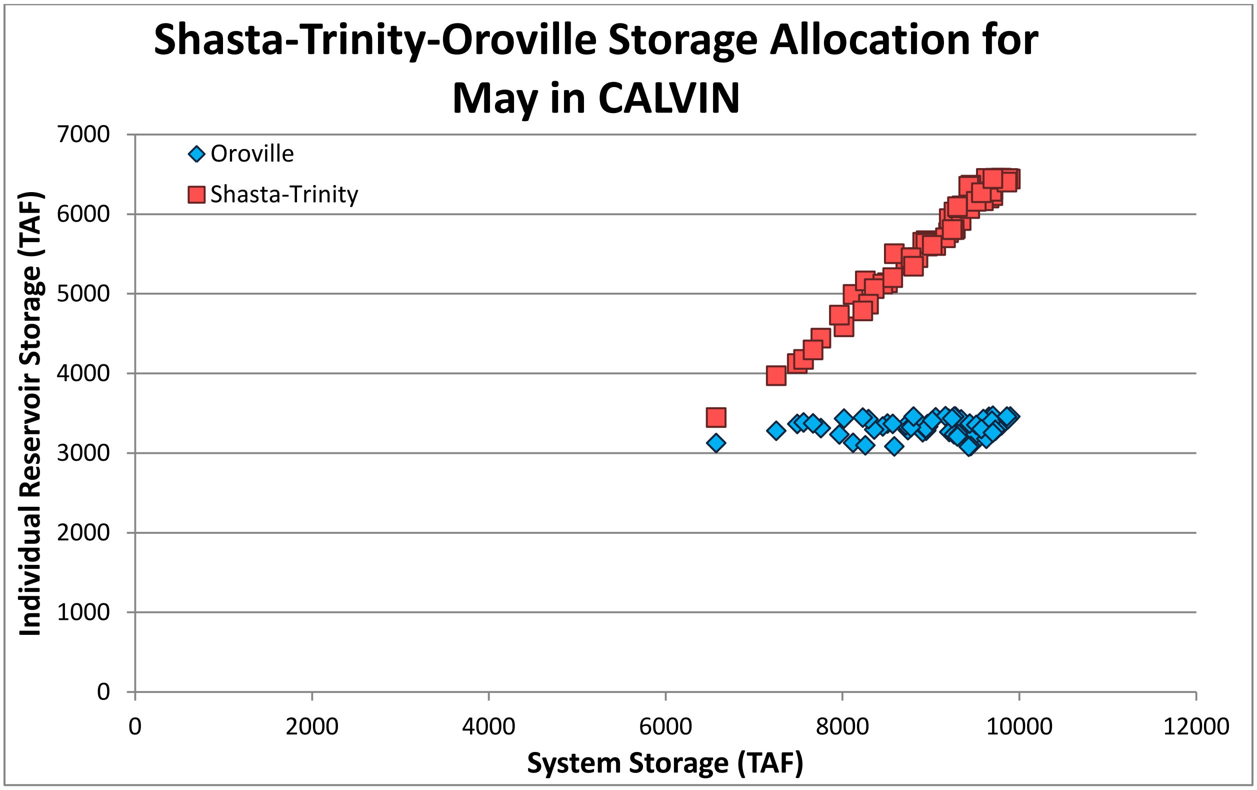


Figure B-30: Storage Allocation Between Shasta, Trinity, and Oroville for June in CALVIN

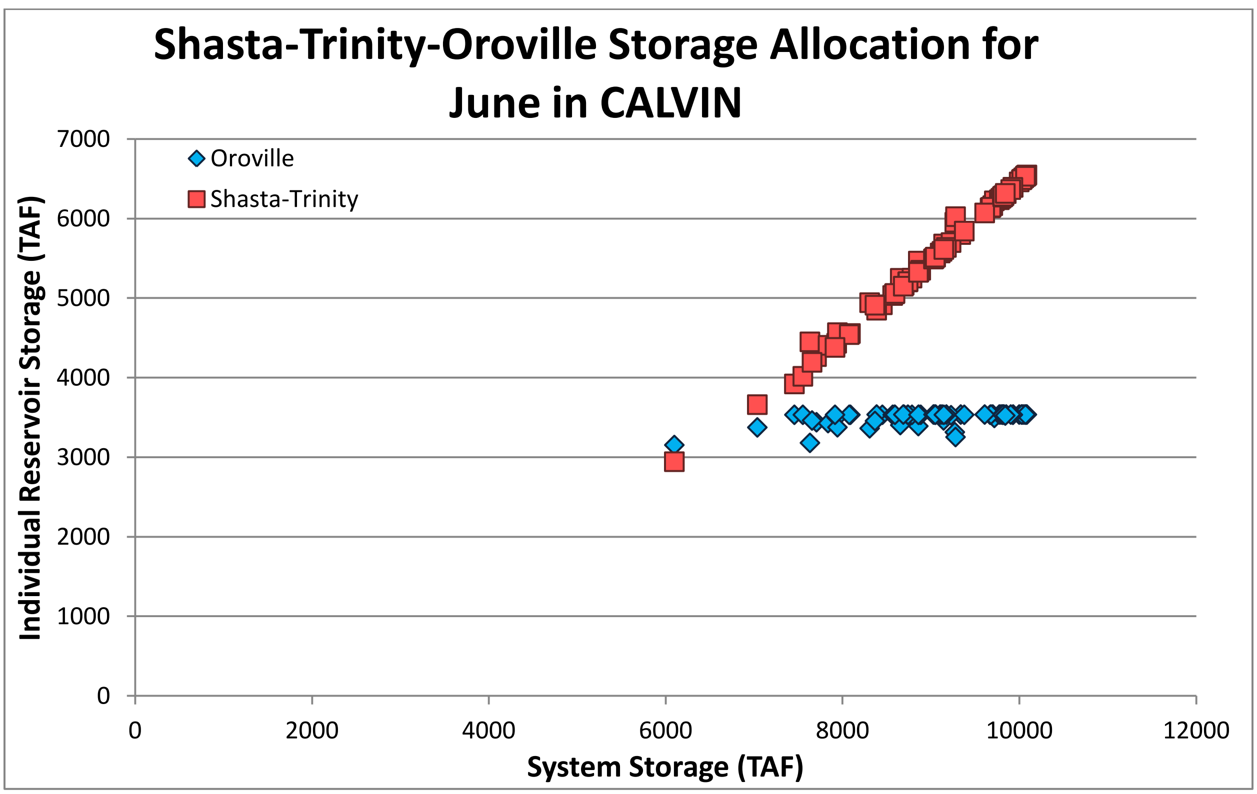


Figure B-31: Storage Allocation Between Shasta, Trinity, and Oroville for July in CALVIN

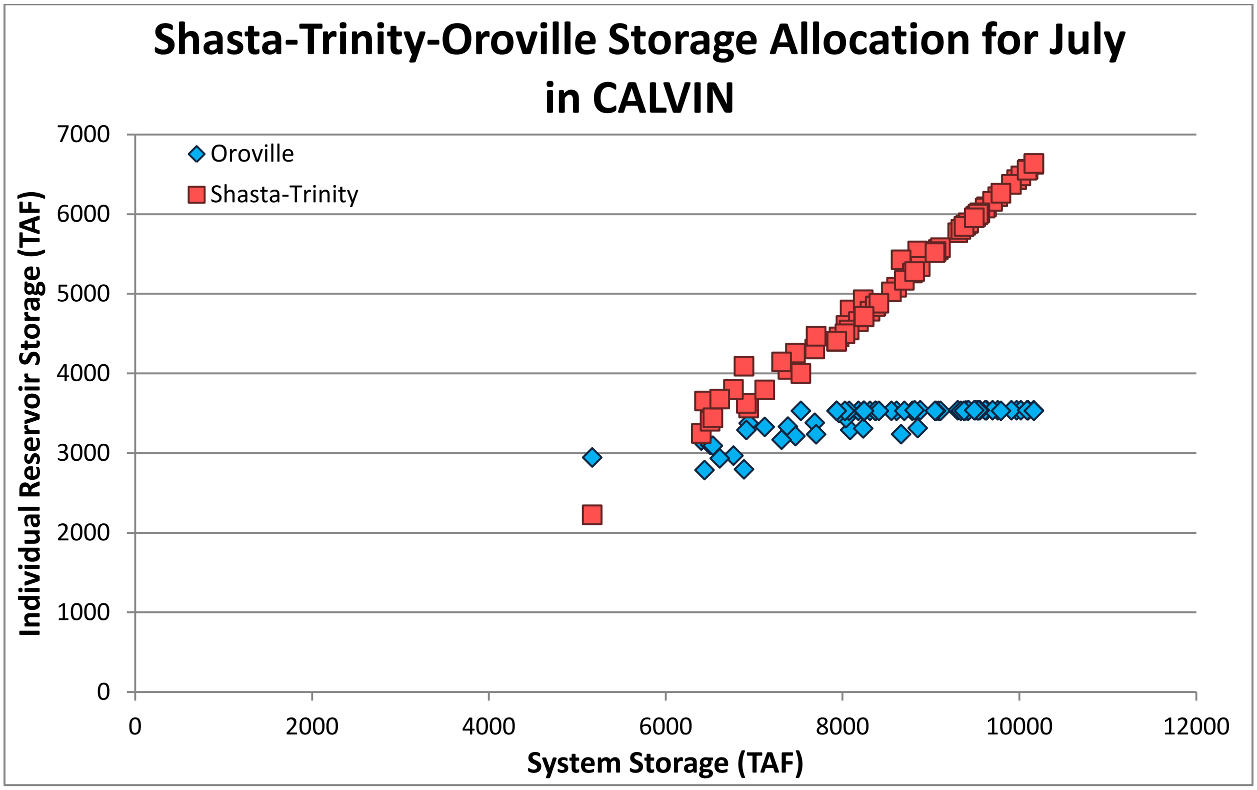


Figure B-32: Storage Allocation Between Shasta, Trinity, and Oroville for August in CALVIN

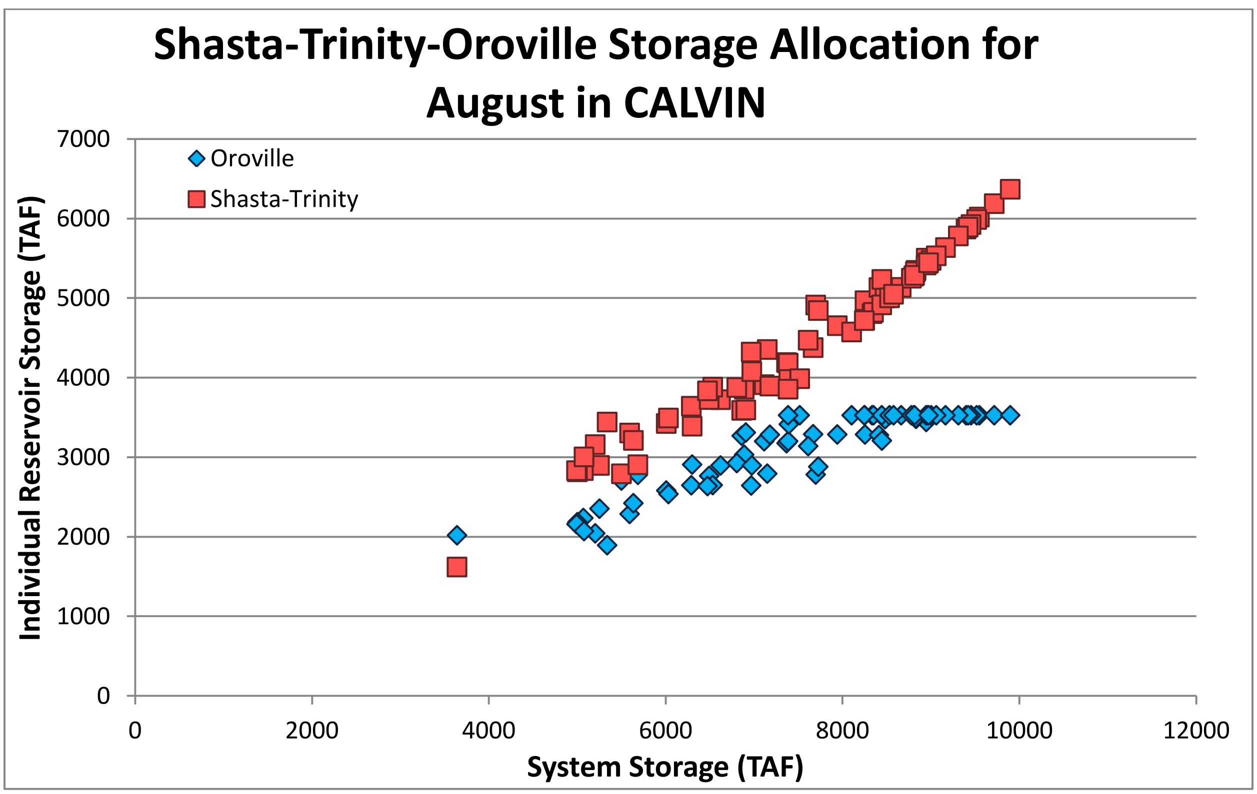


Figure B-33: Storage Allocation Between Shasta, Trinity, and Oroville for September in CALVIN

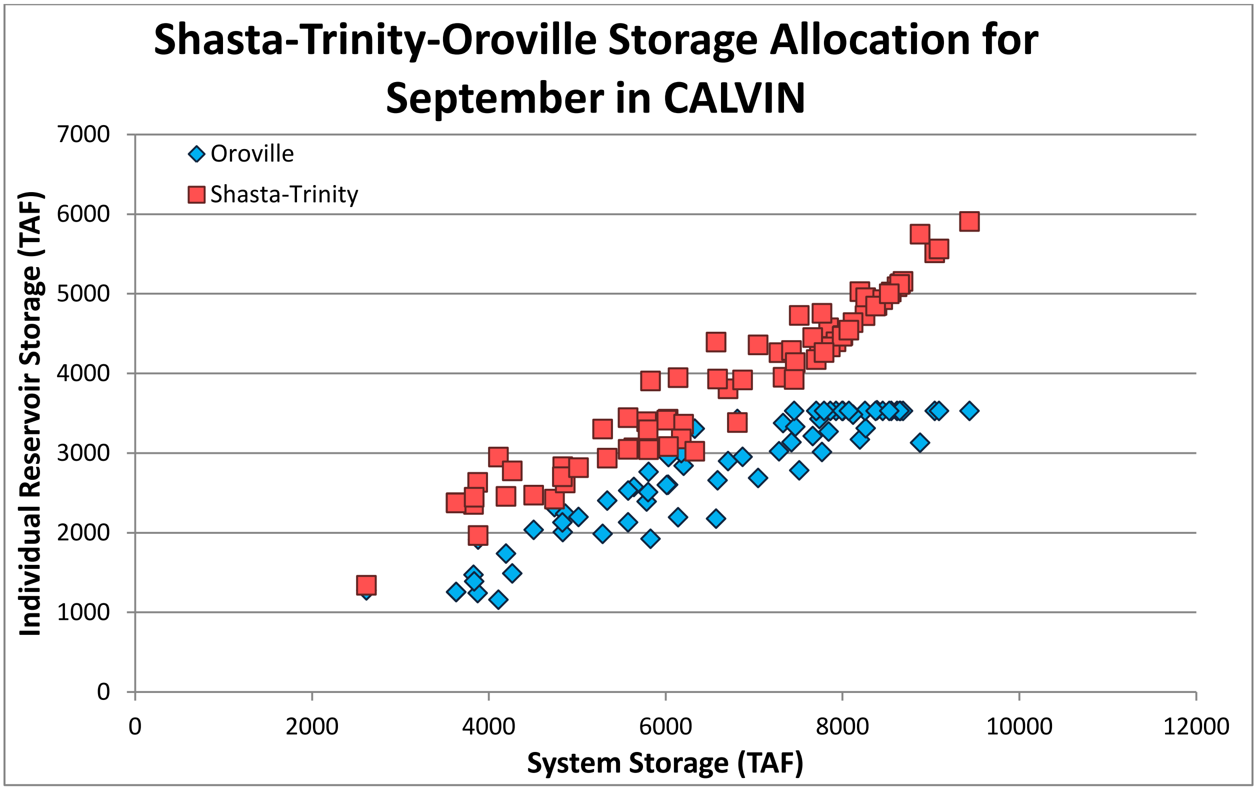


Figure B-34: Storage Allocation Between Shasta, Trinity, and Oroville for October in CALVIN

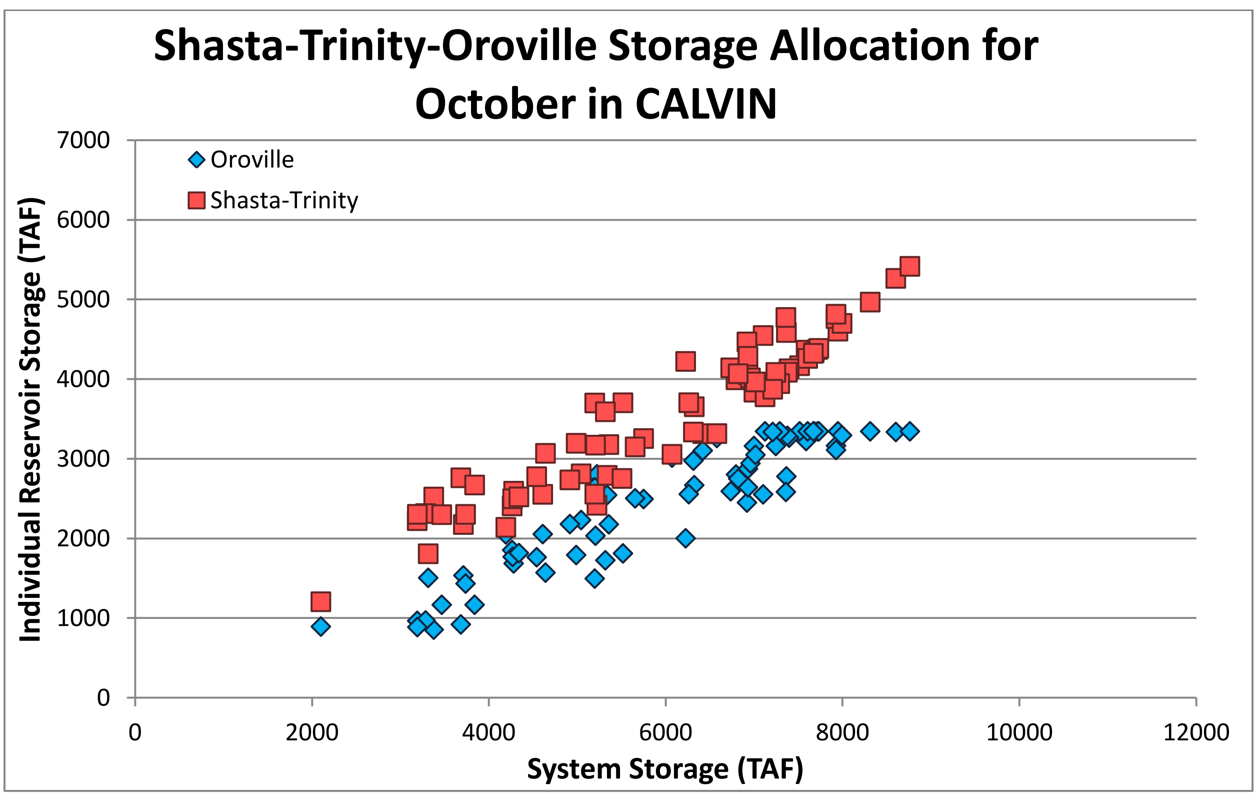


Figure B-35: Storage Allocation Between Shasta, Trinity, and Oroville for November in CALVIN

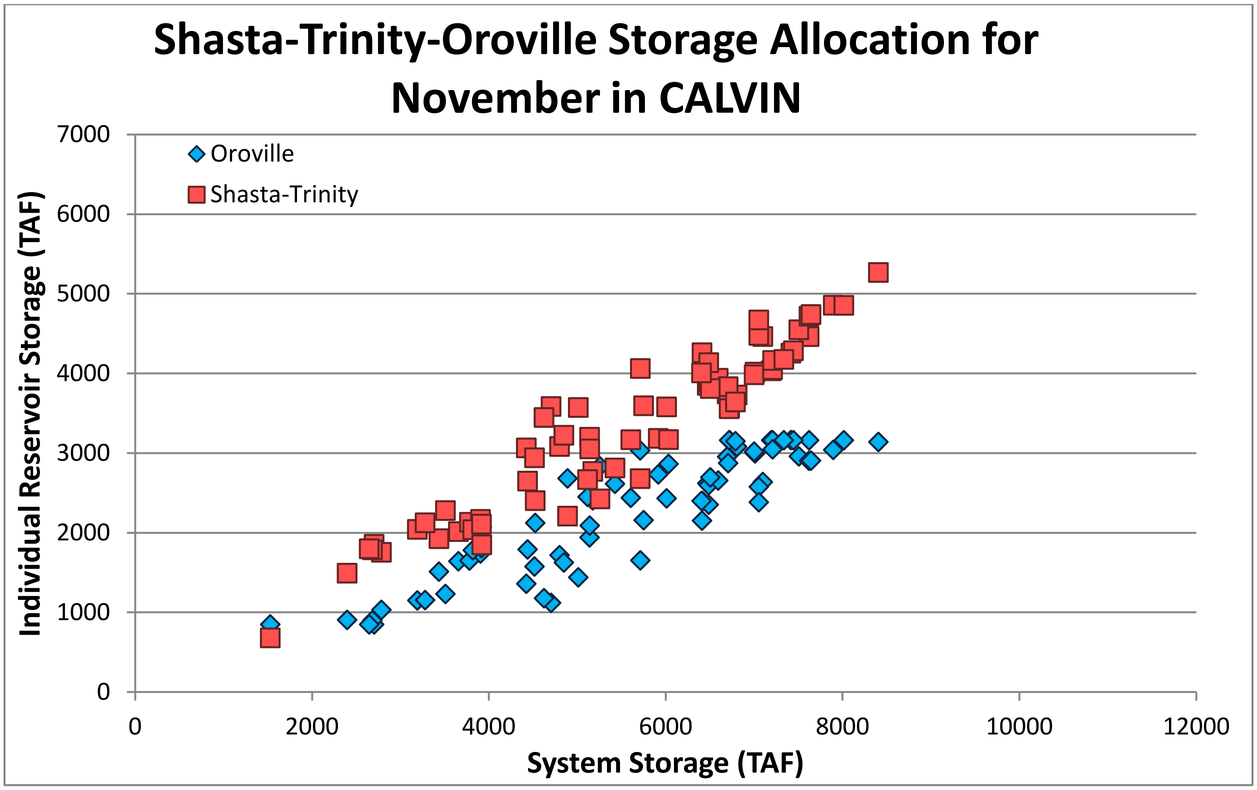


Figure B-36: Storage Allocation Between Shasta, Trinity, and Oroville for December in CALVIN

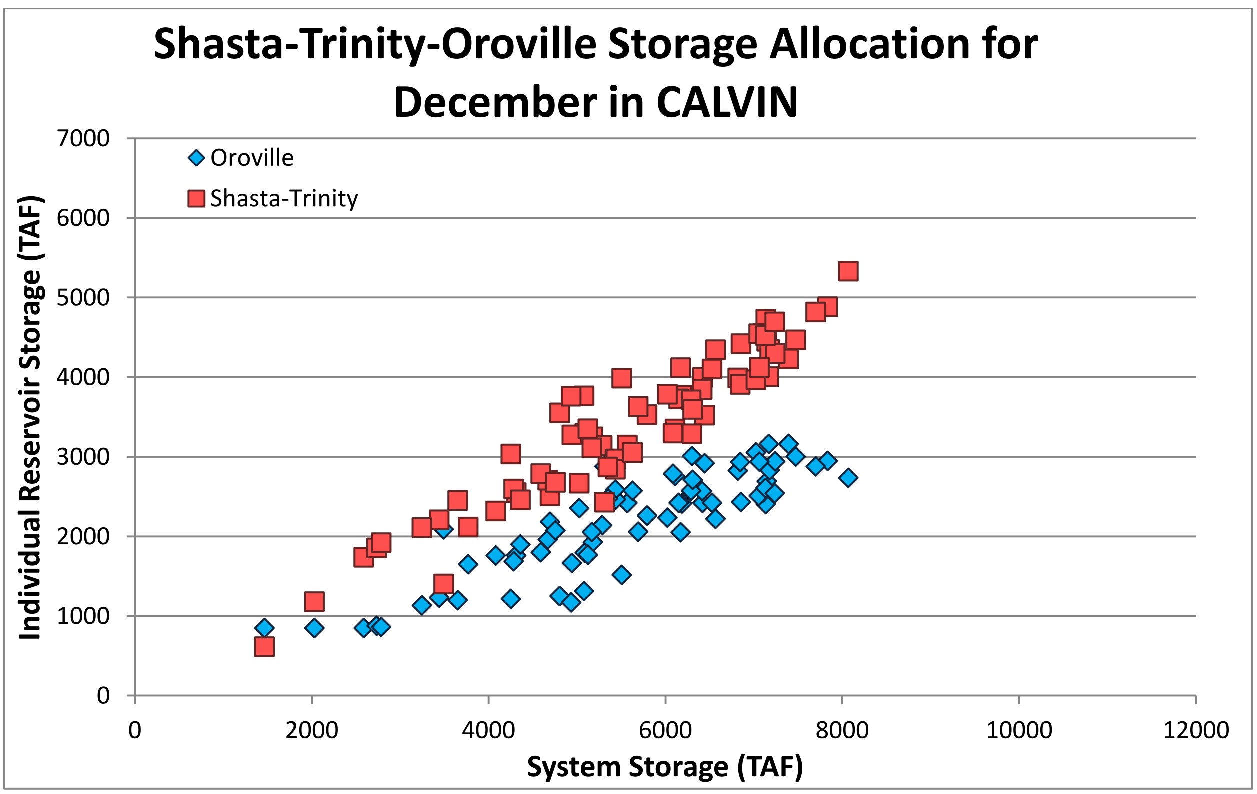


Figure B-37: Storage Allocation Between Shasta, Trinity, and Oroville for January in CalSim

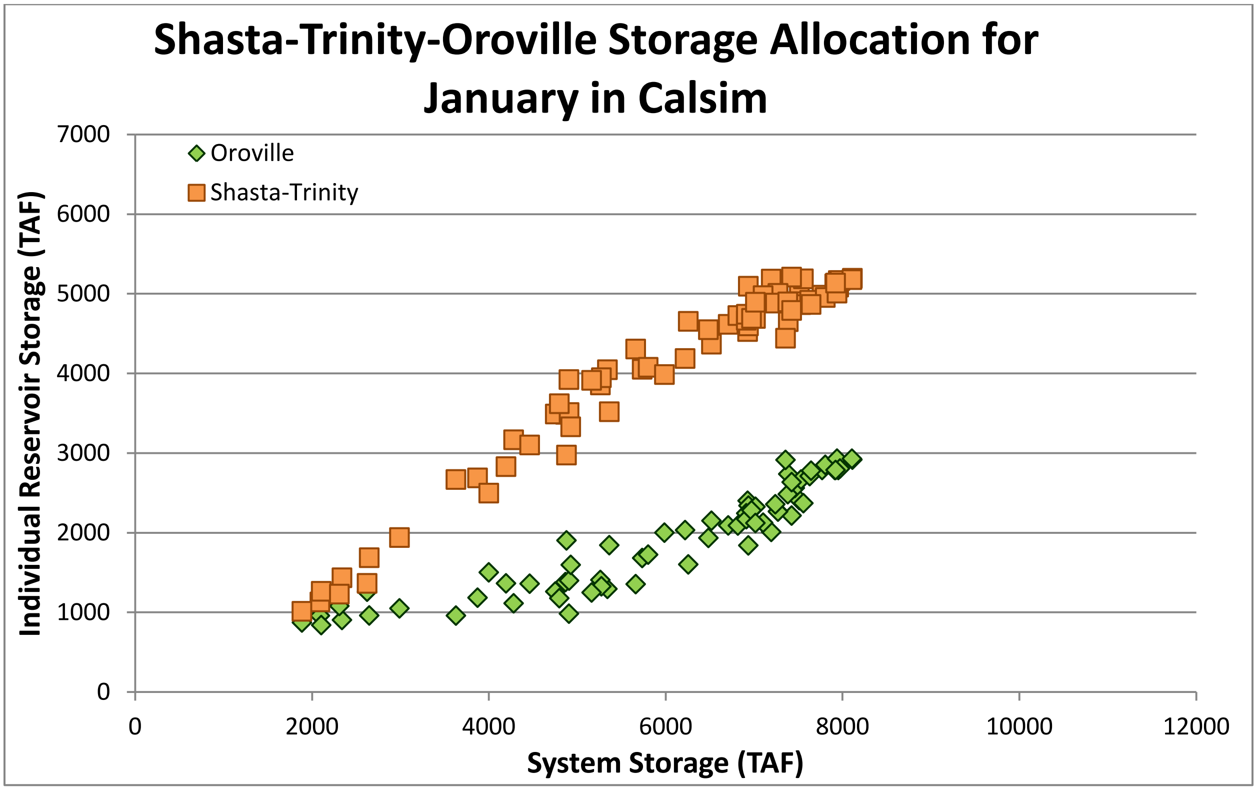


Figure B-38: Storage Allocation Between Shasta, Trinity, and Oroville for February in CalSim

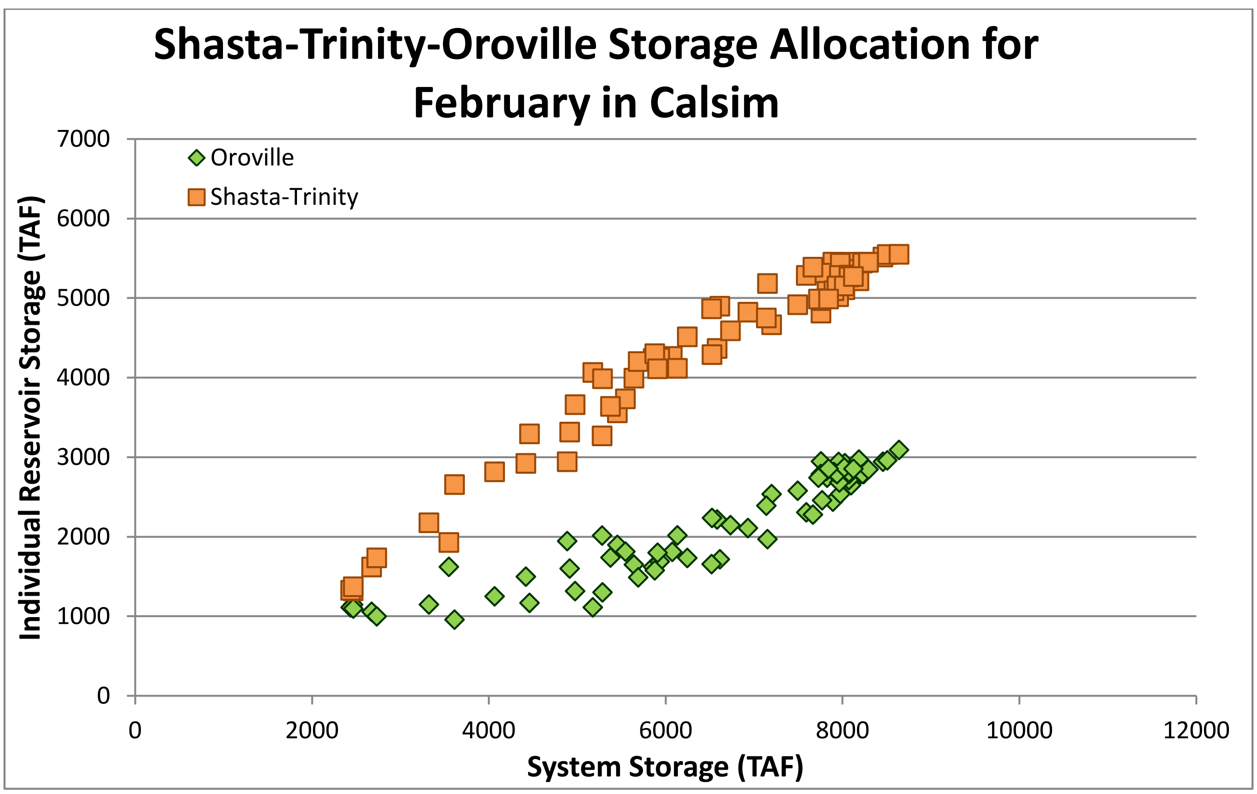


Figure B-39: Storage Allocation Between Shasta, Trinity, and Oroville for March in CalSim

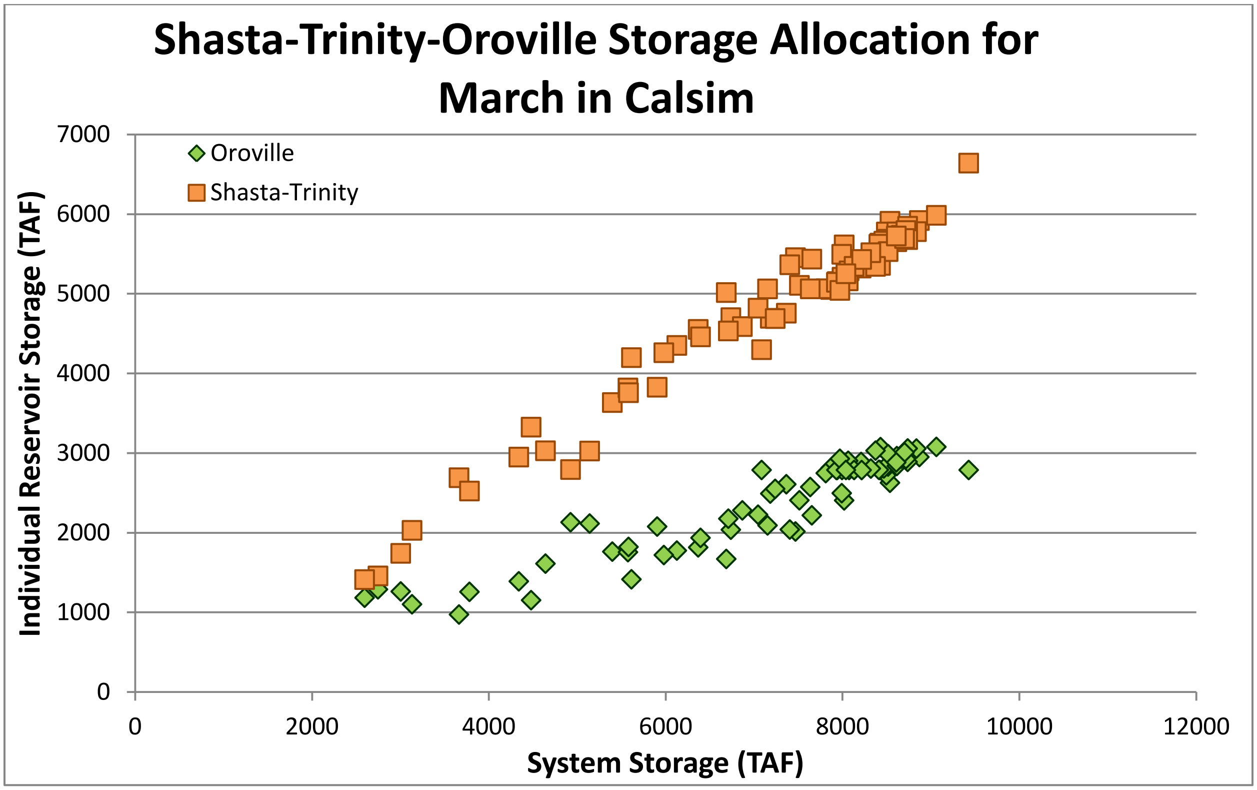


Figure B-40: Storage Allocation Between Shasta, Trinity, and Oroville for April in CalSim

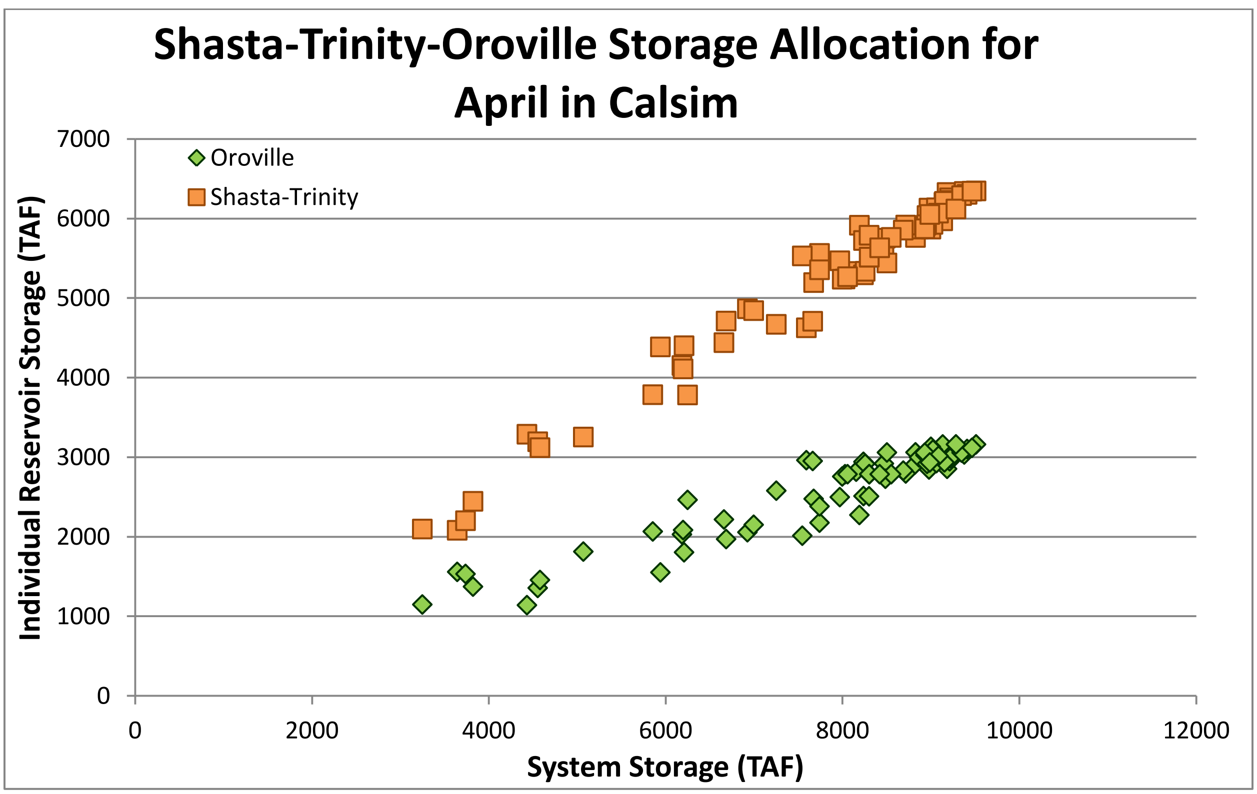


Figure B-41: Storage Allocation Between Shasta, Trinity, and Oroville for May in CalSim

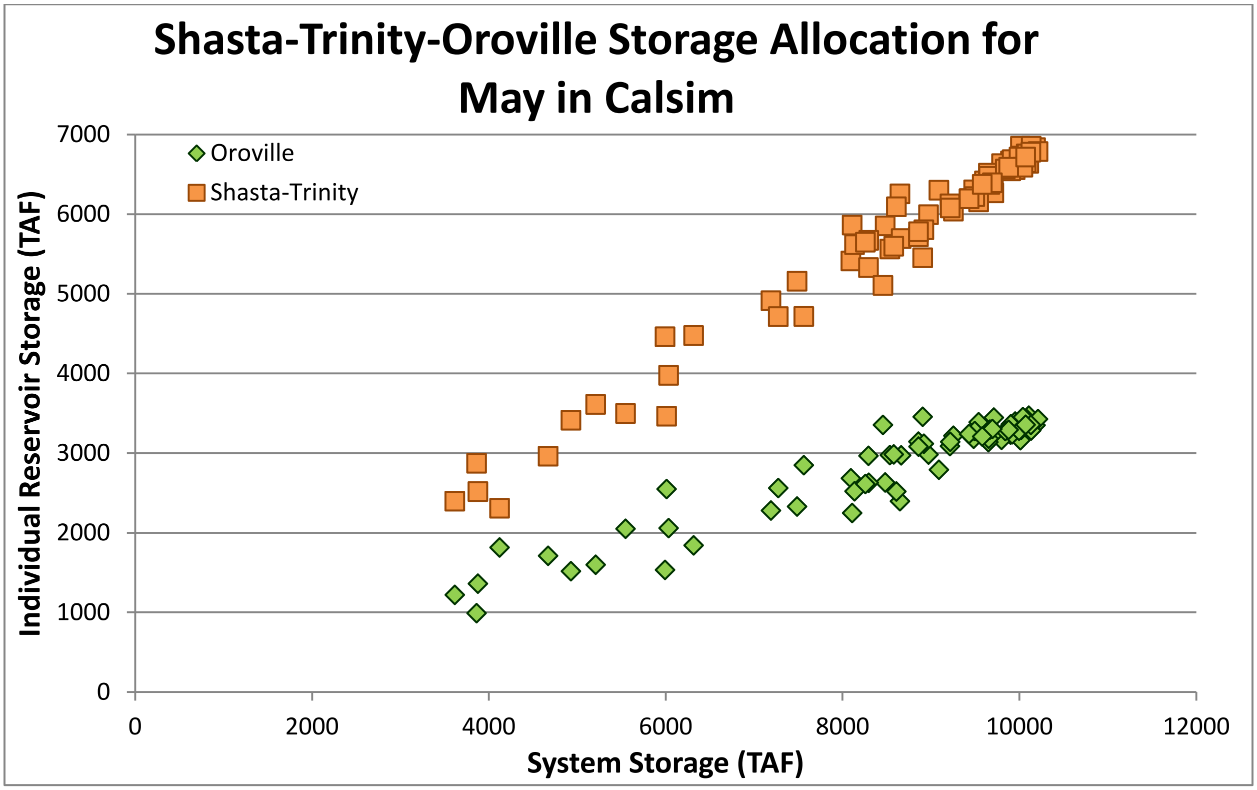


Figure B-42: Storage Allocation Between Shasta, Trinity, and Oroville for June in CalSim

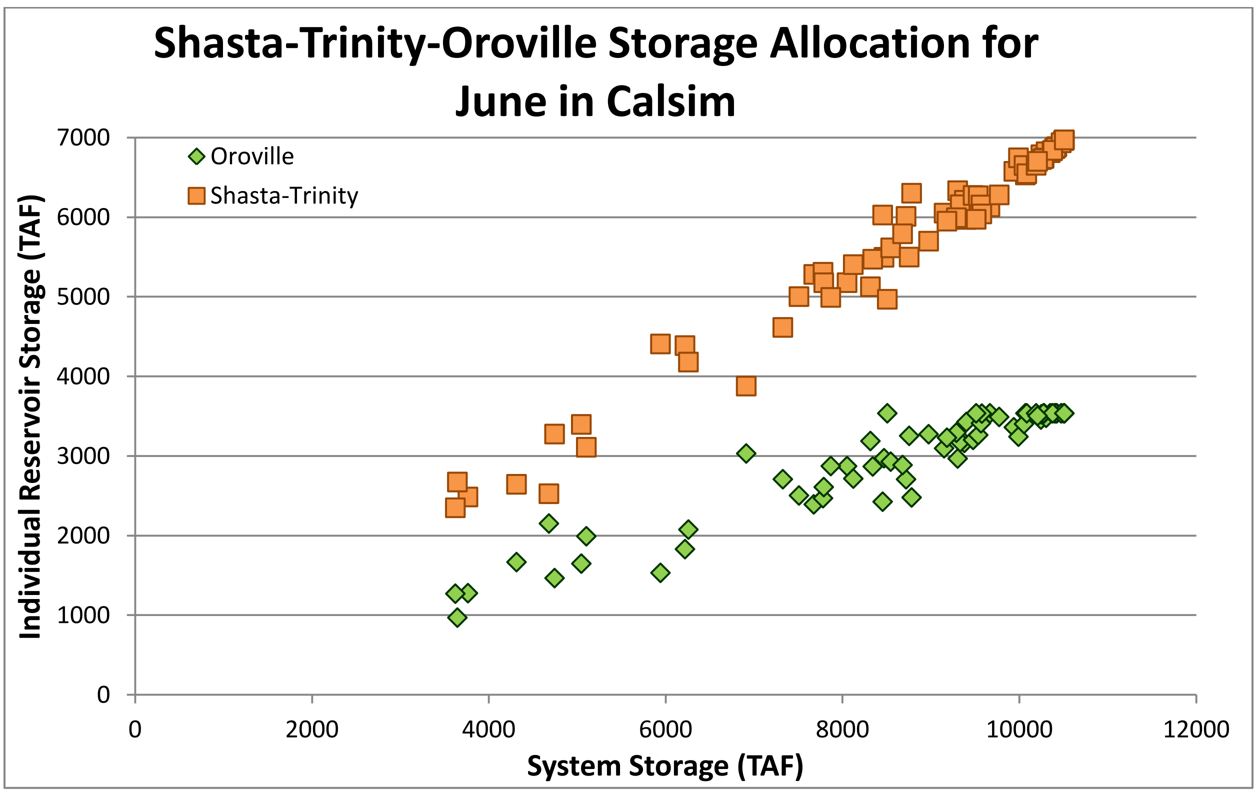


Figure B-43: Storage Allocation Between Shasta, Trinity, and Oroville for July in CalSim

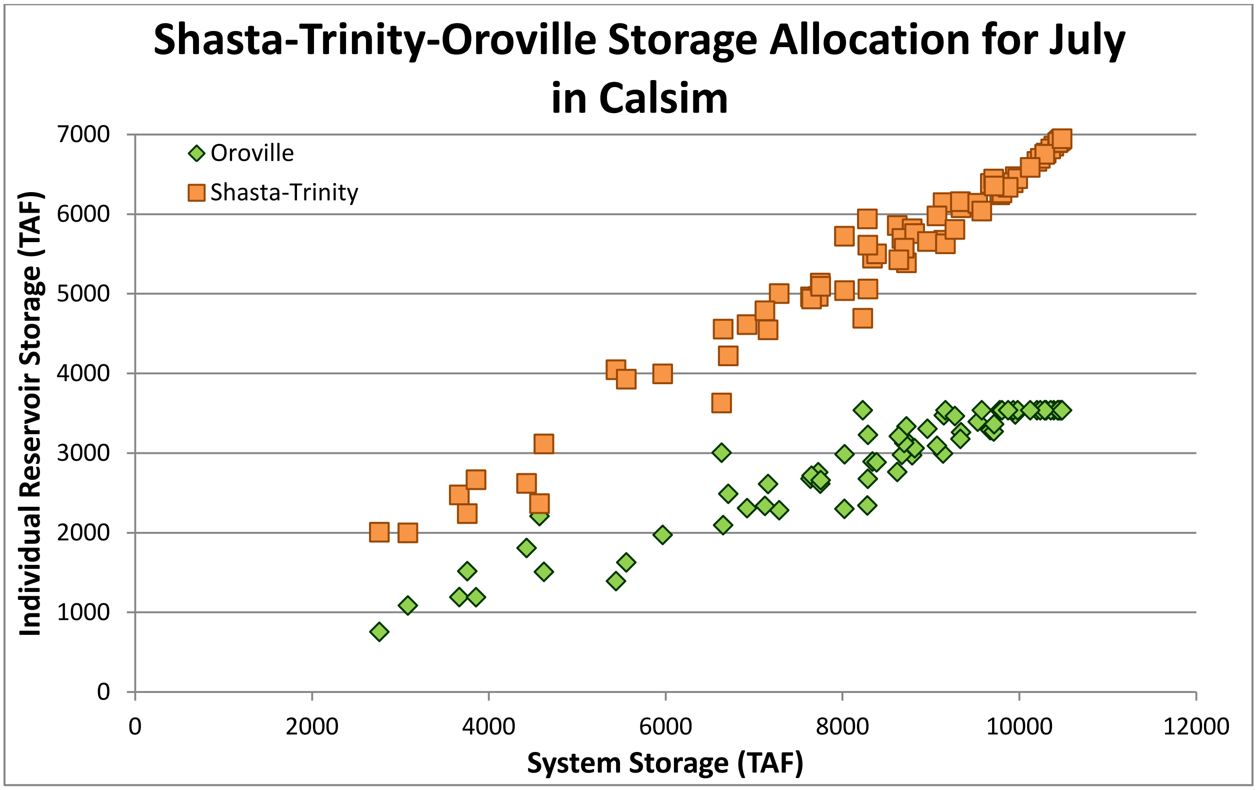


Figure B-44: Storage Allocation Between Shasta, Trinity, and Oroville for August in CalSim

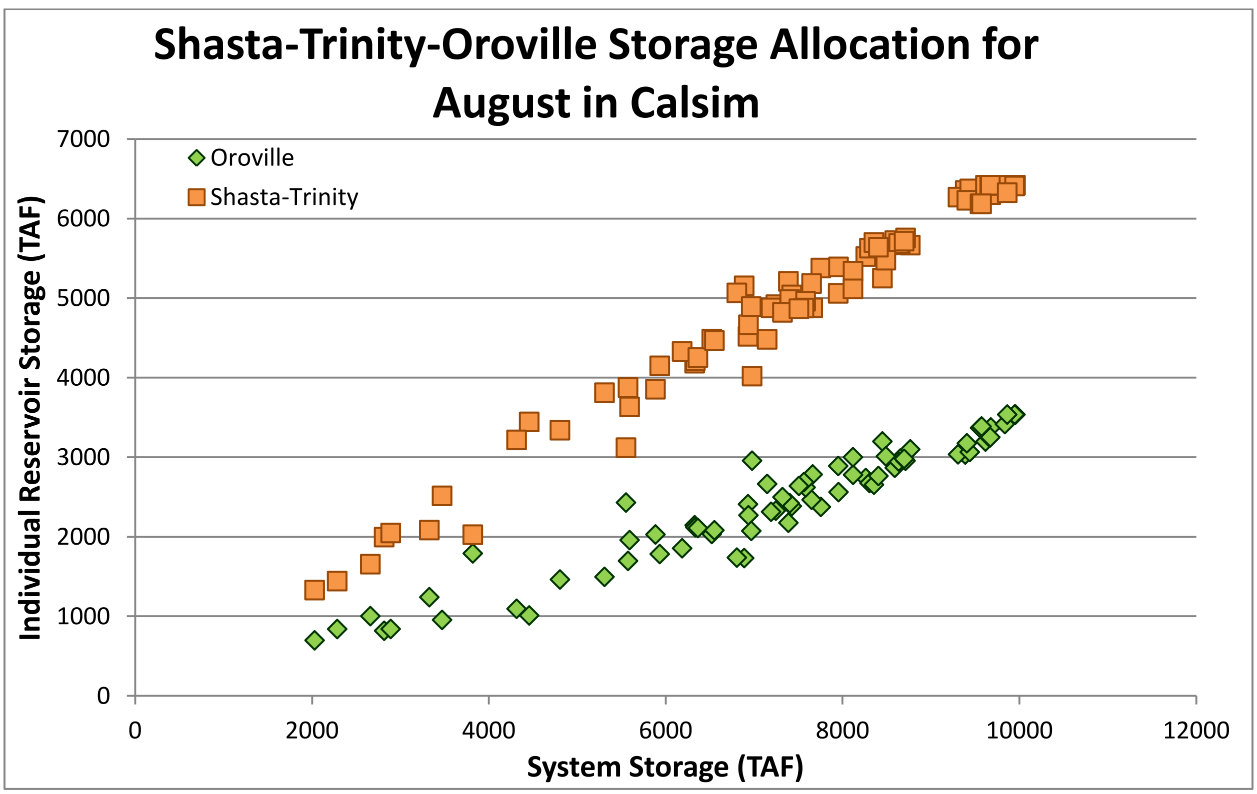


Figure B-45: Storage Allocation Between Shasta, Trinity, and Oroville for September in CalSim

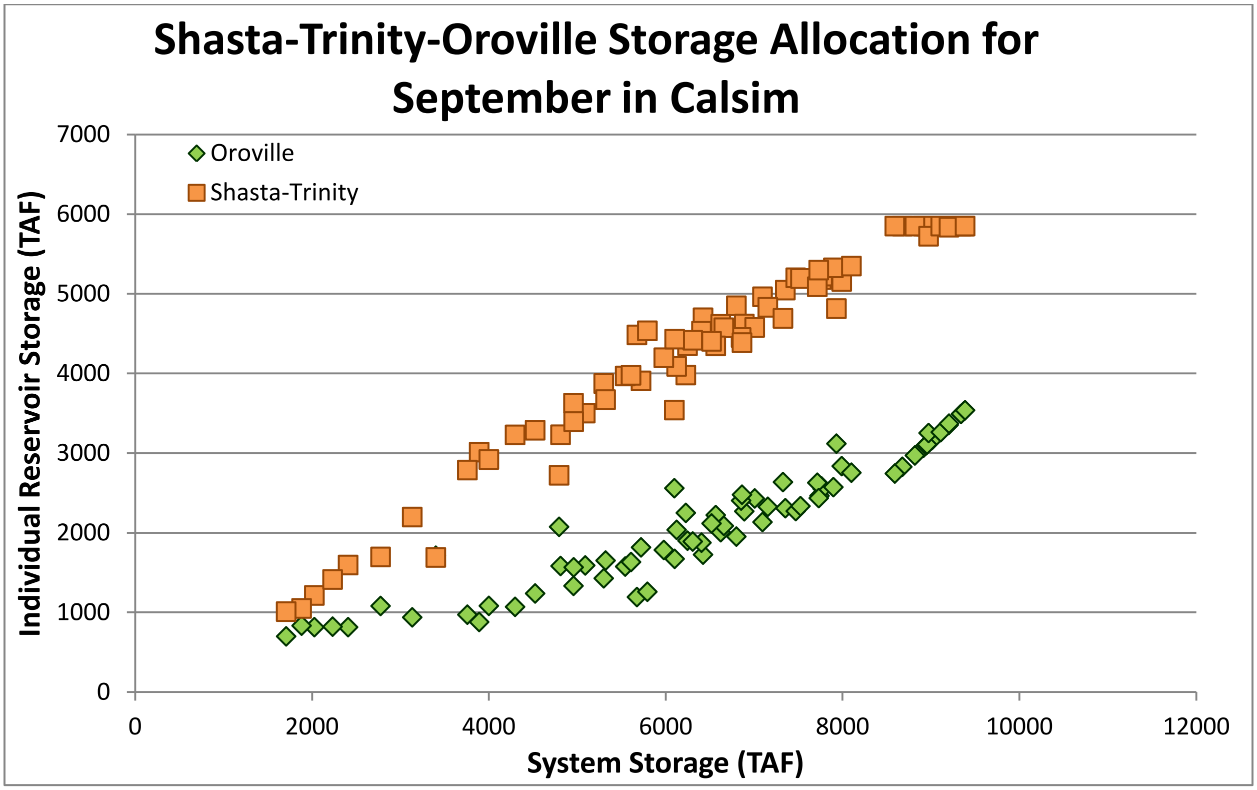


Figure B-46: Storage Allocation Between Shasta, Trinity, and Oroville for October in CalSim

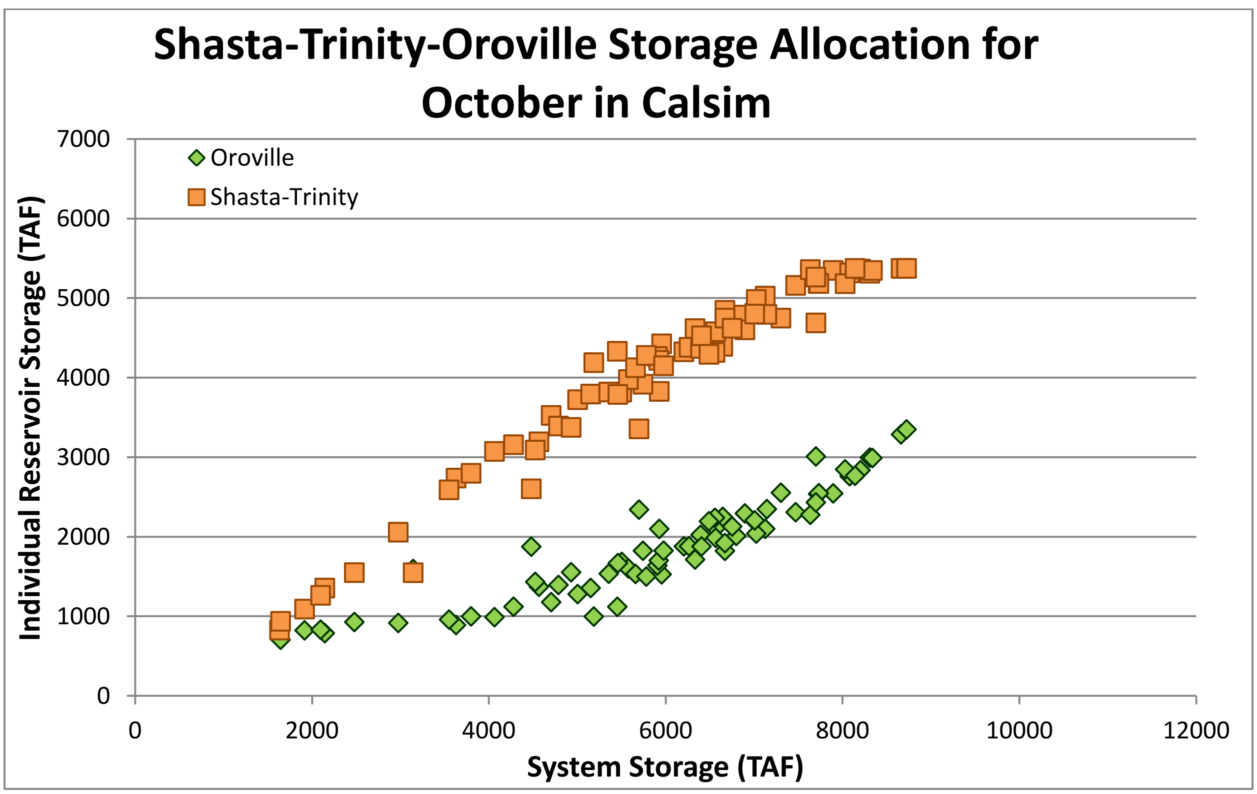


Figure B-47: Storage Allocation Between Shasta, Trinity, and Oroville for November in CalSim

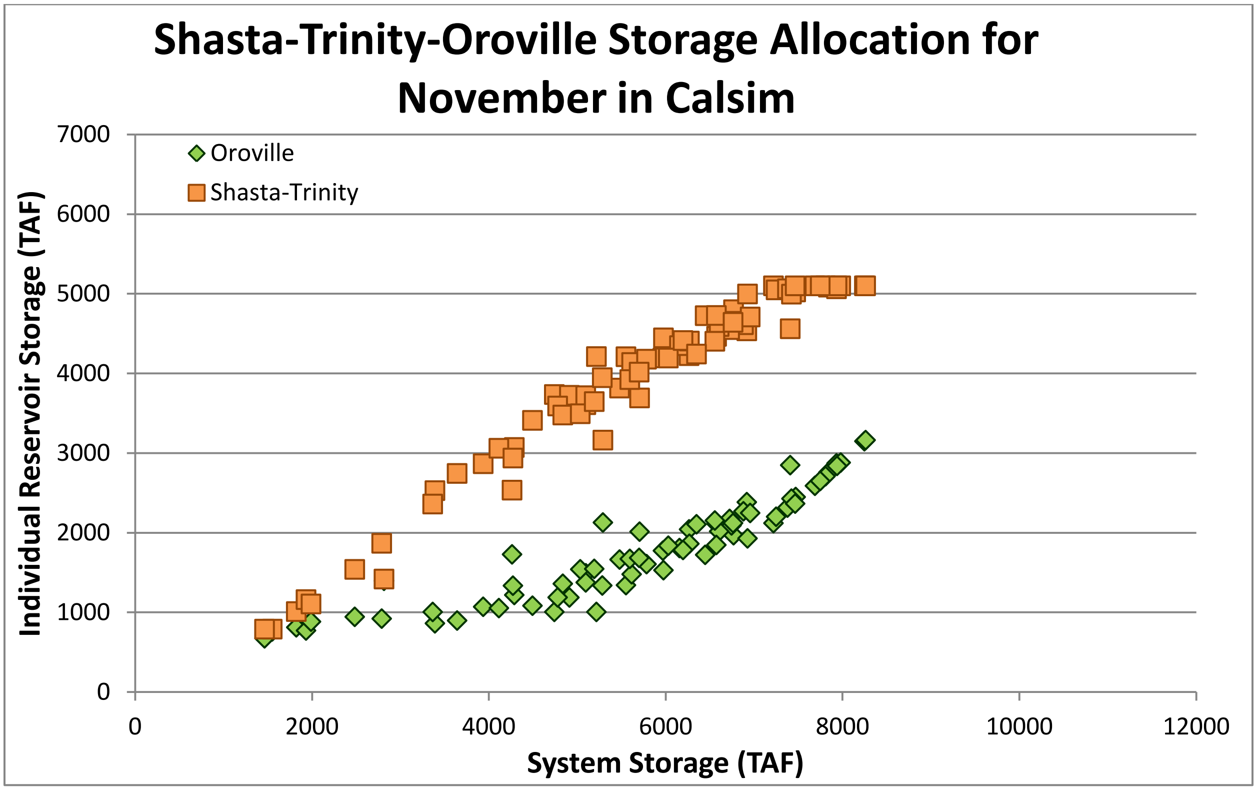
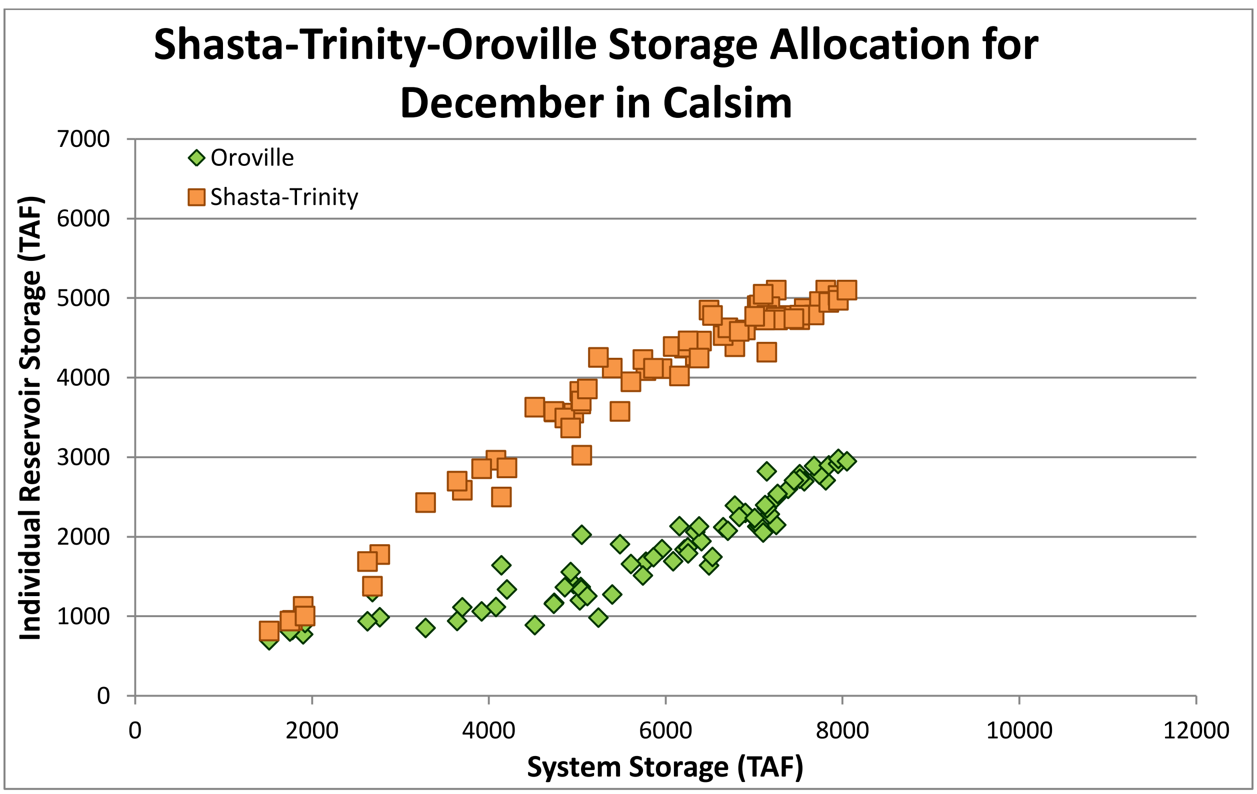


Figure B-48: Storage Allocation Between Shasta, Trinity, and Oroville for December in CalSim



Shasta-Trinity-Oroville-Folsom Storage Allocation (only Folsom is shown)

Figure B-49: Folsom Storage Allocation for January in CALVIN

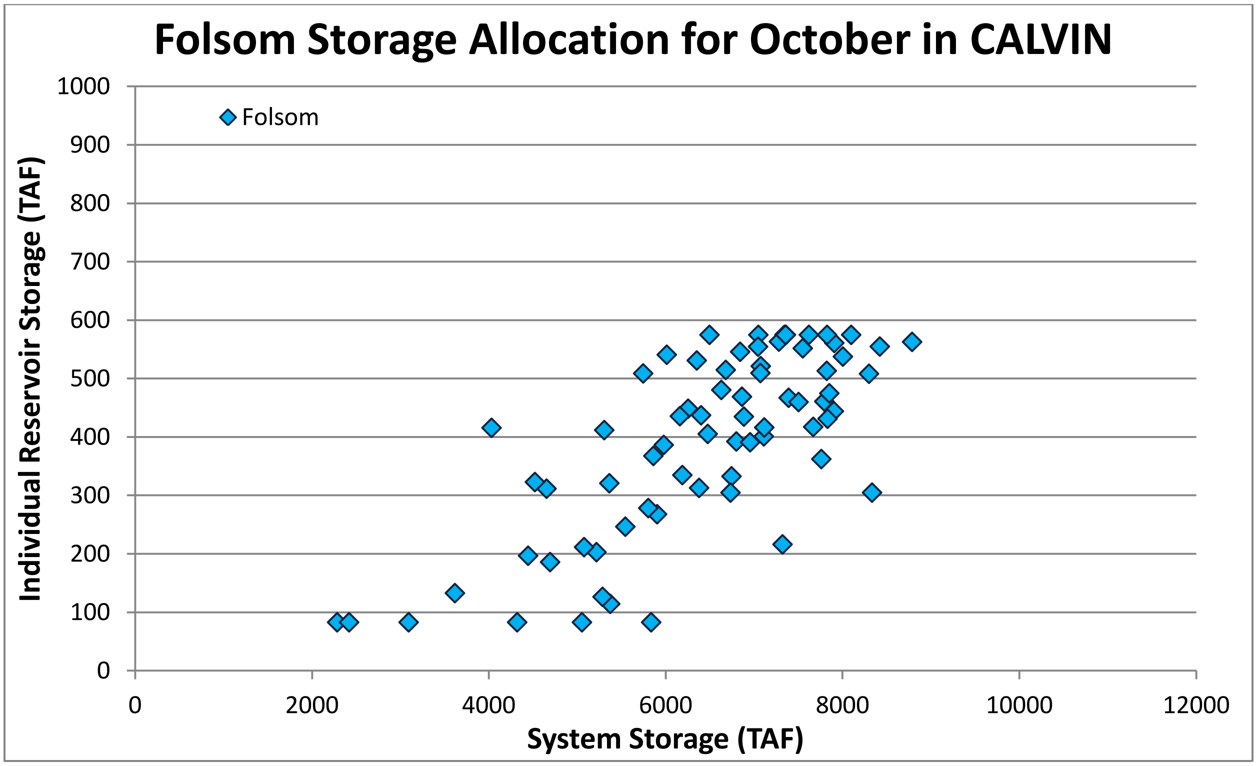


Figure B-50: Folsom Storage Allocation for February in CALVIN

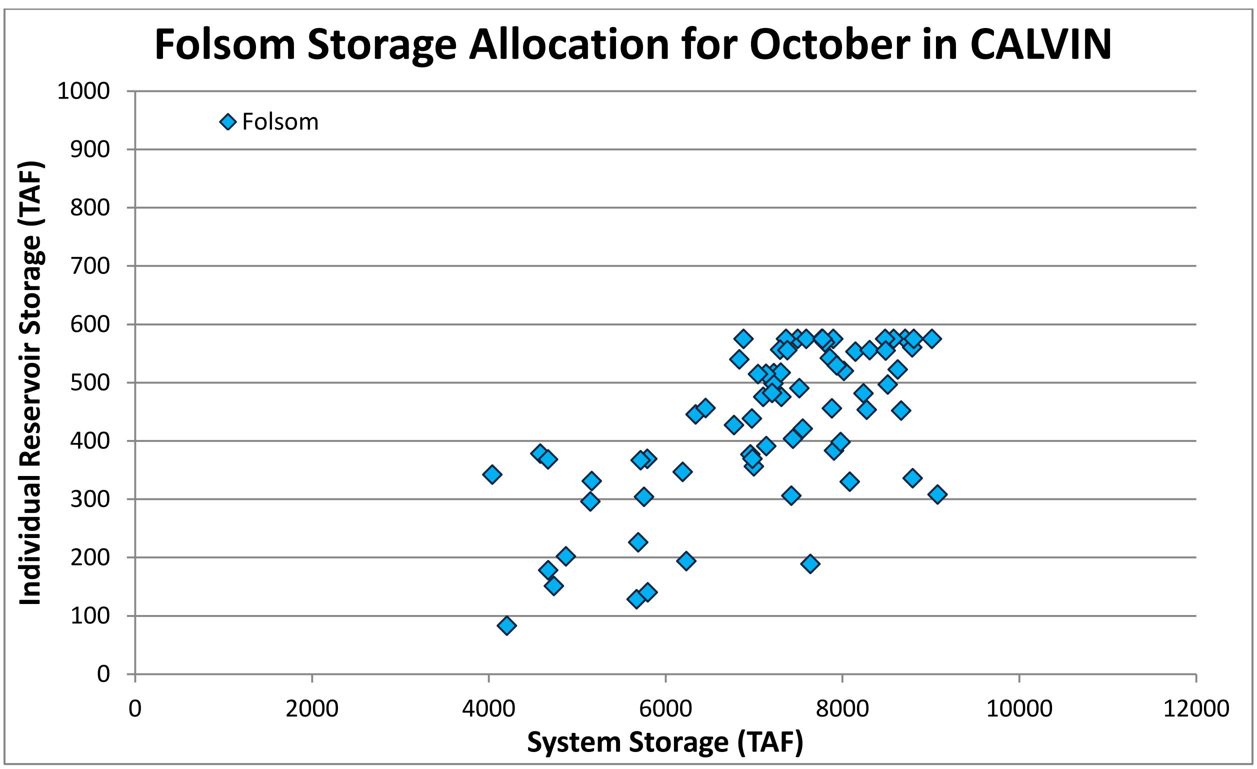


Figure B-51: Folsom Storage Allocation for March in CALVIN

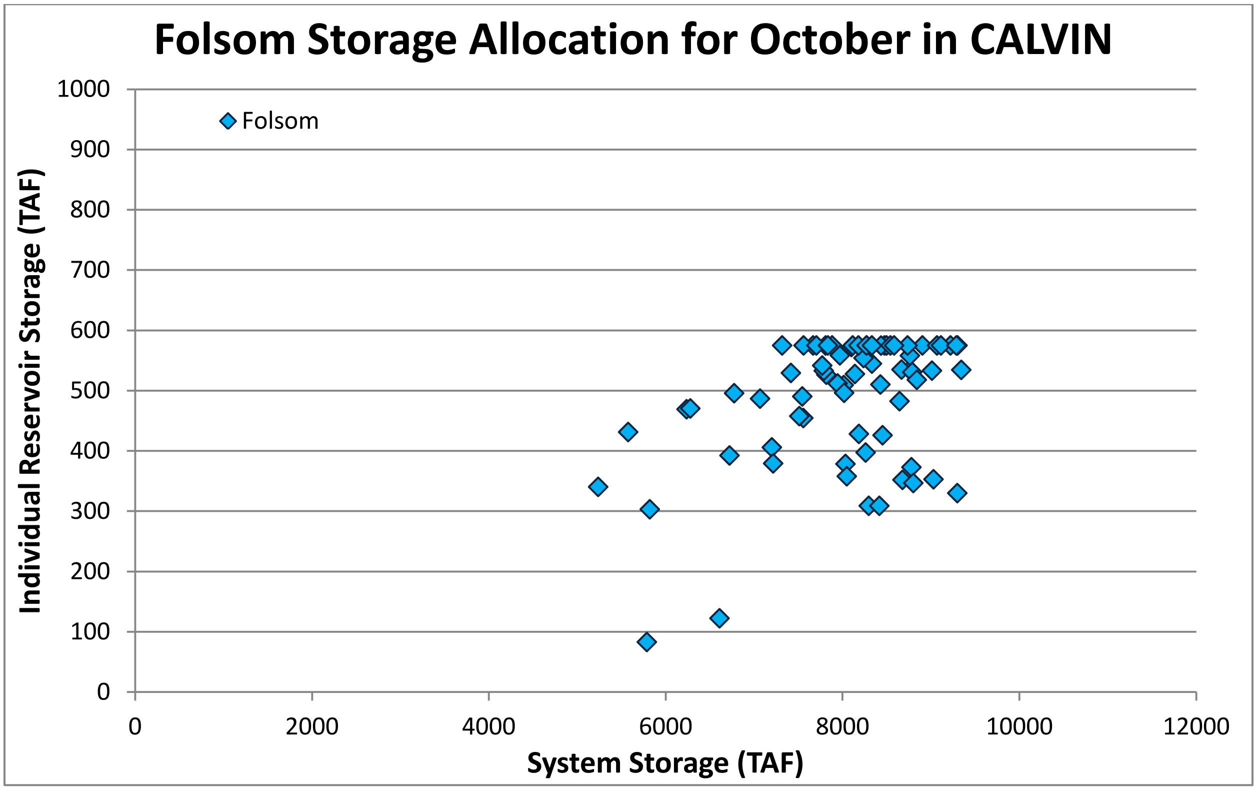


Figure B-52: Folsom Storage Allocation for April in CALVIN

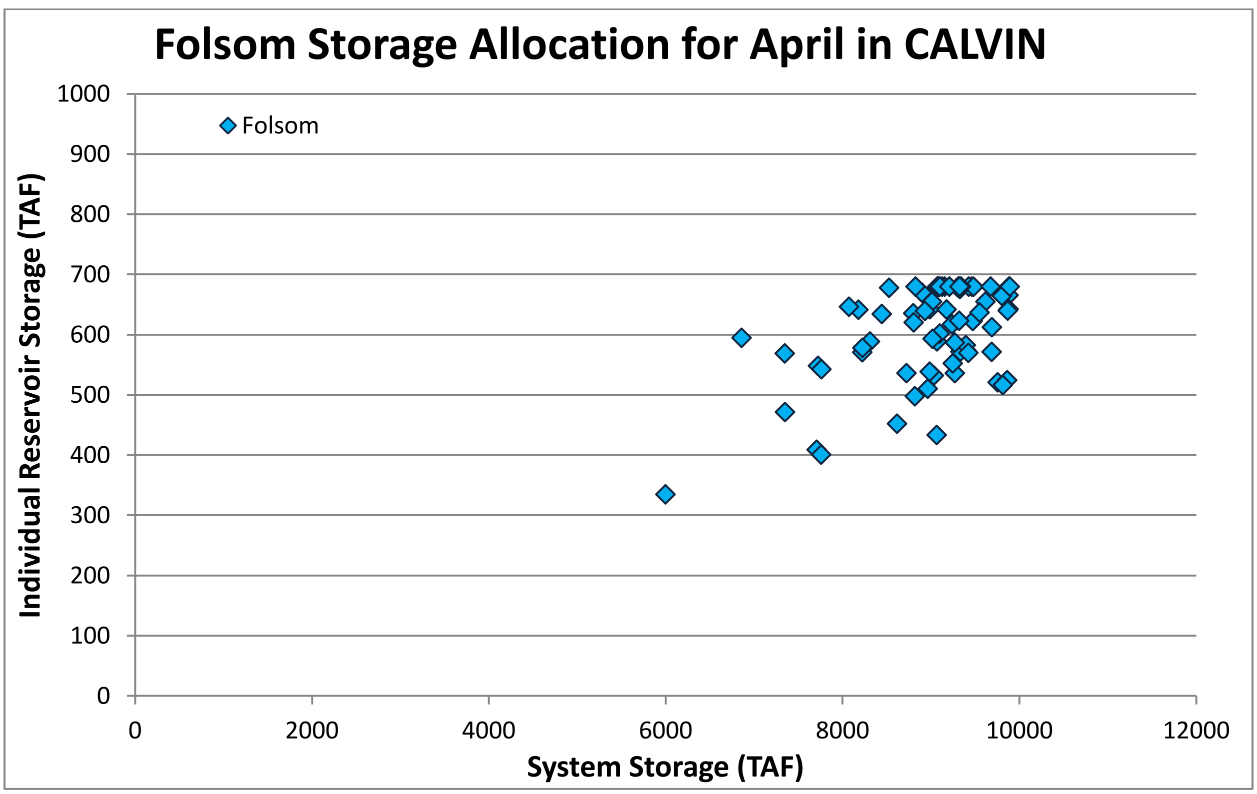


Figure B-53: Folsom Storage Allocation for May in CALVIN

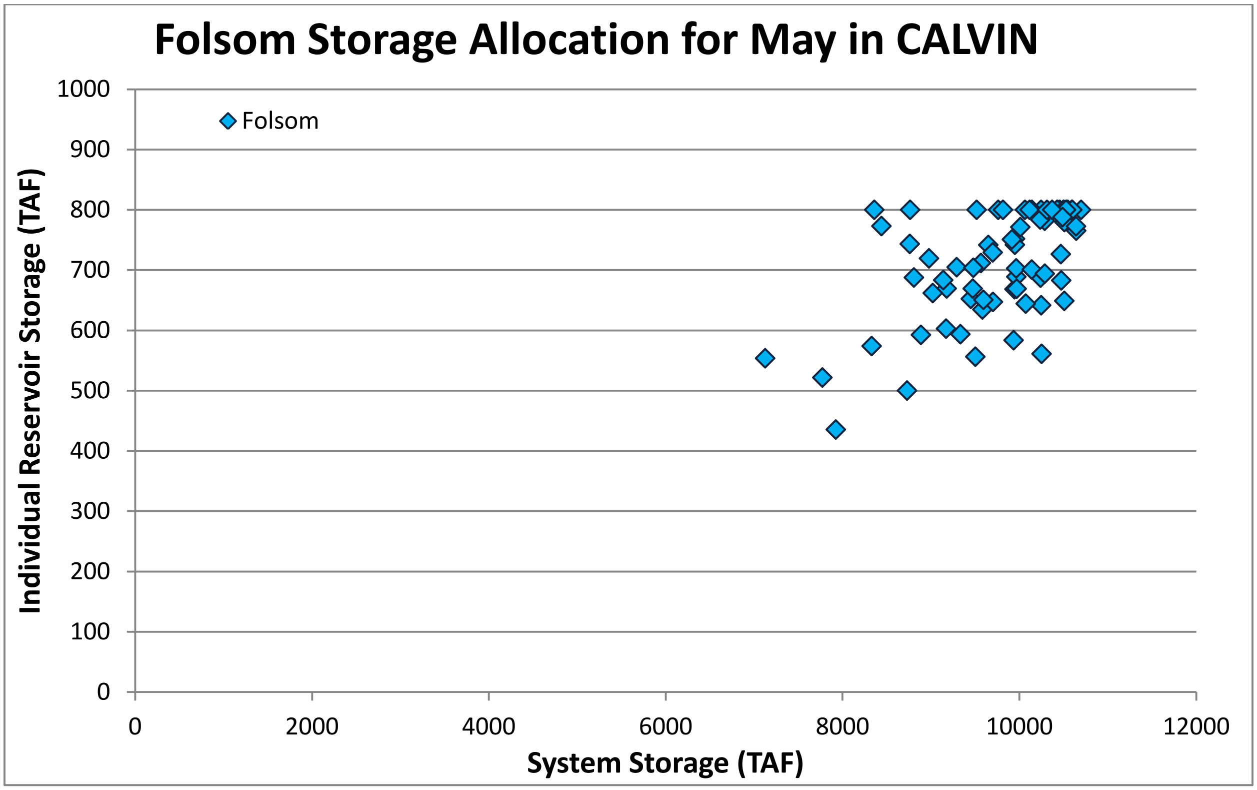


Figure B-54: Folsom Storage Allocation for June in CALVIN

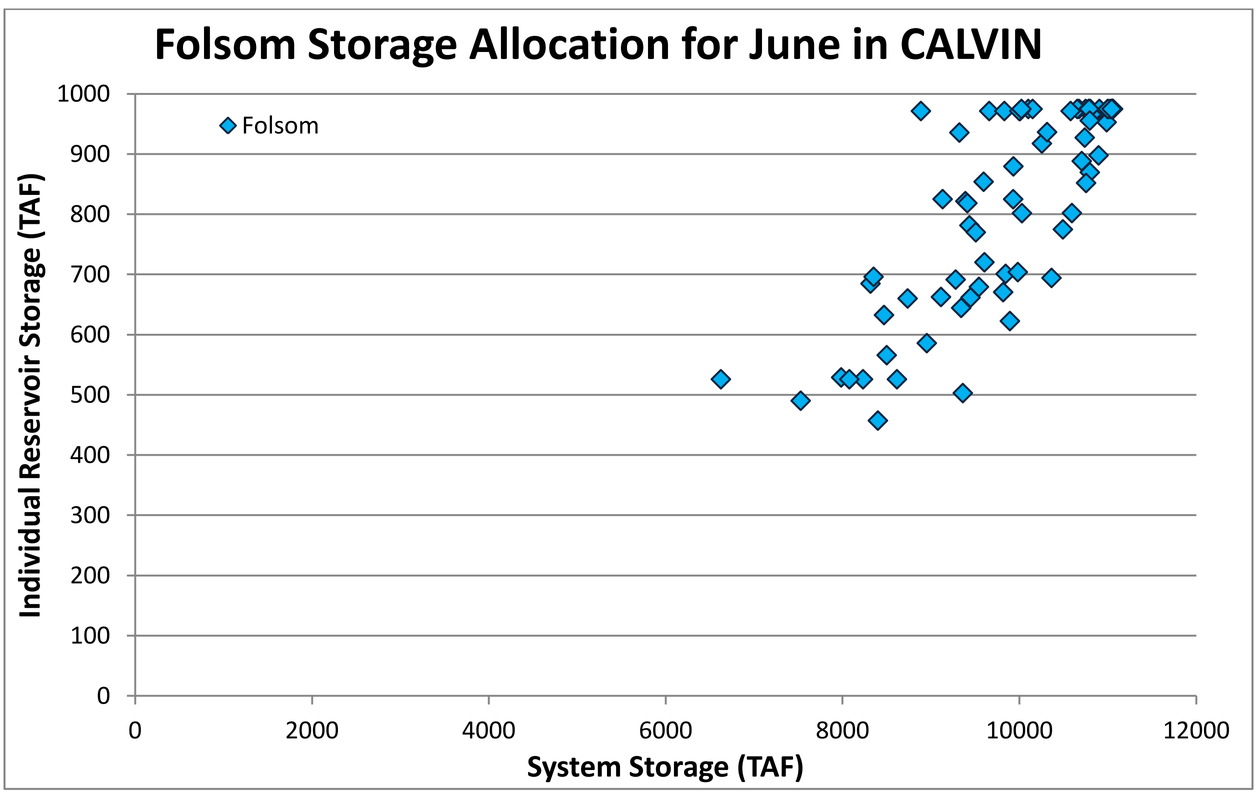


Figure B-55: Folsom Storage Allocation for July in CALVIN

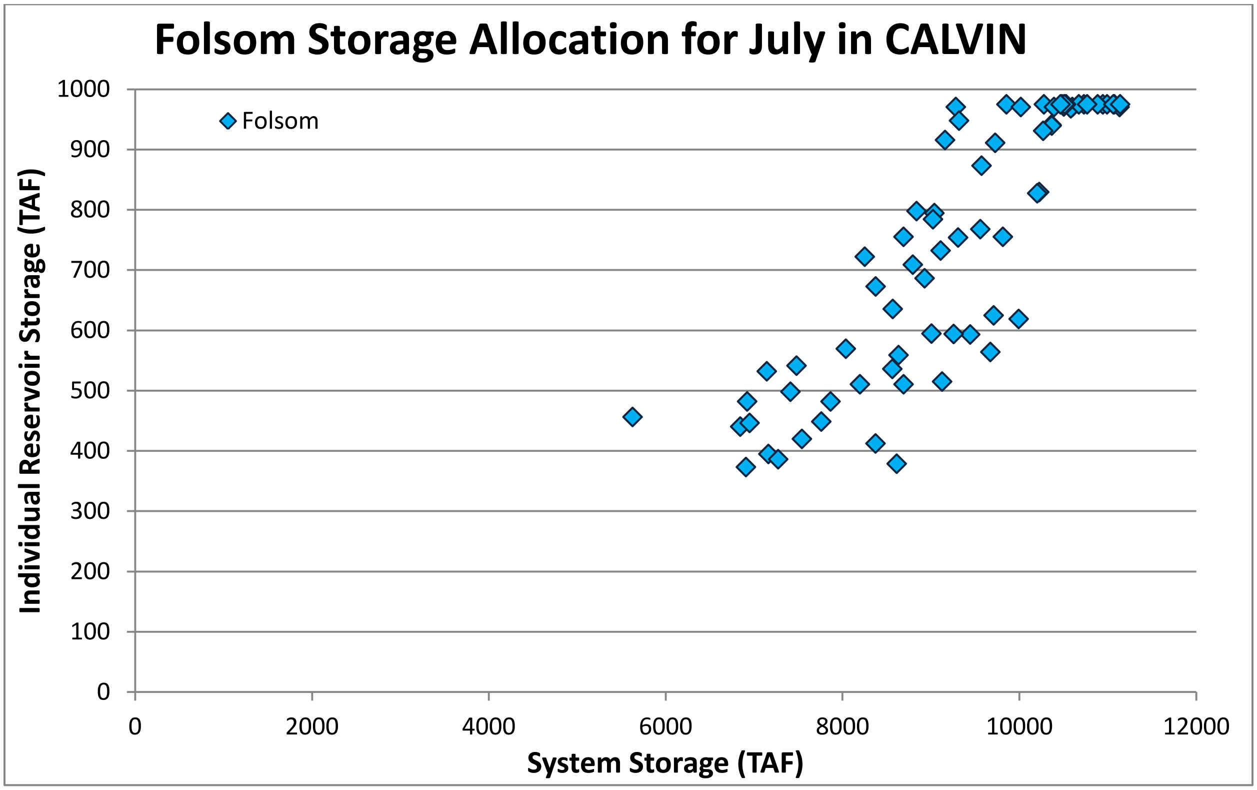


Figure B-56: Folsom Storage Allocation for August in CALVIN

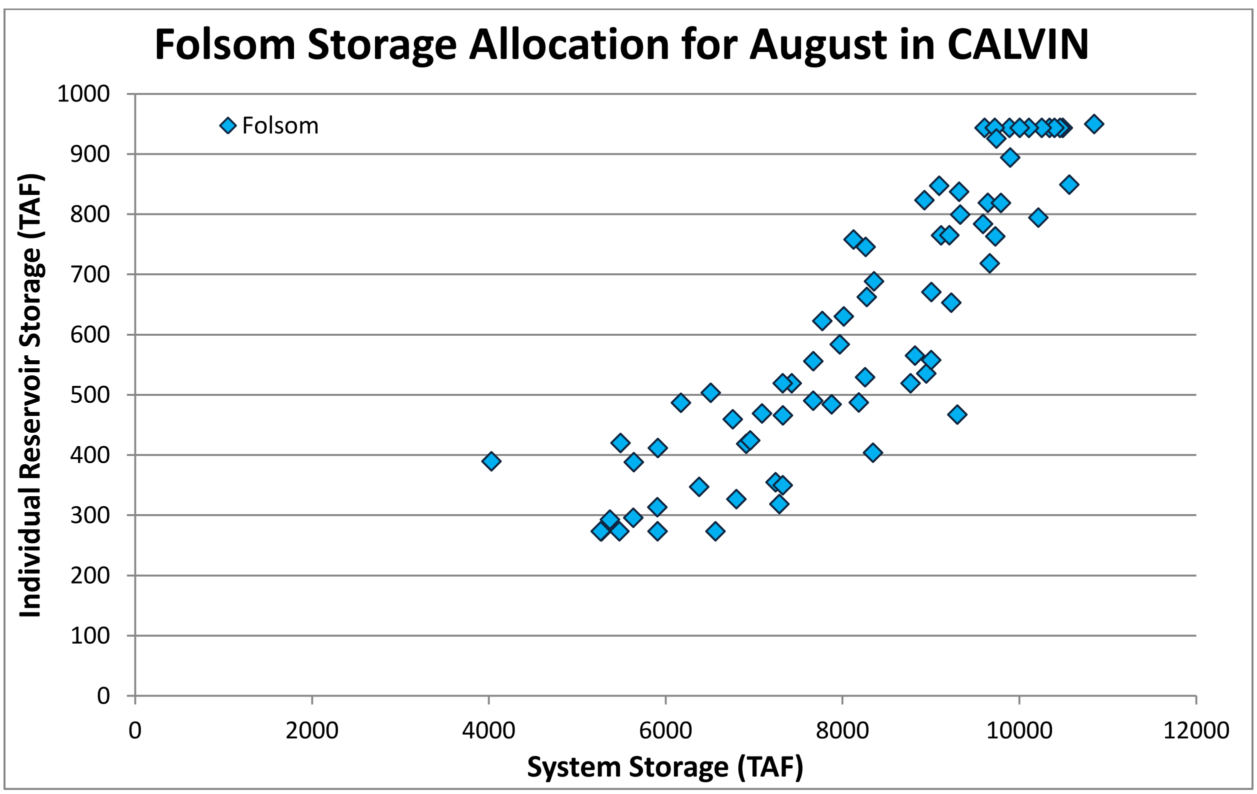


Figure B-57: Folsom Storage Allocation for September in CALVIN

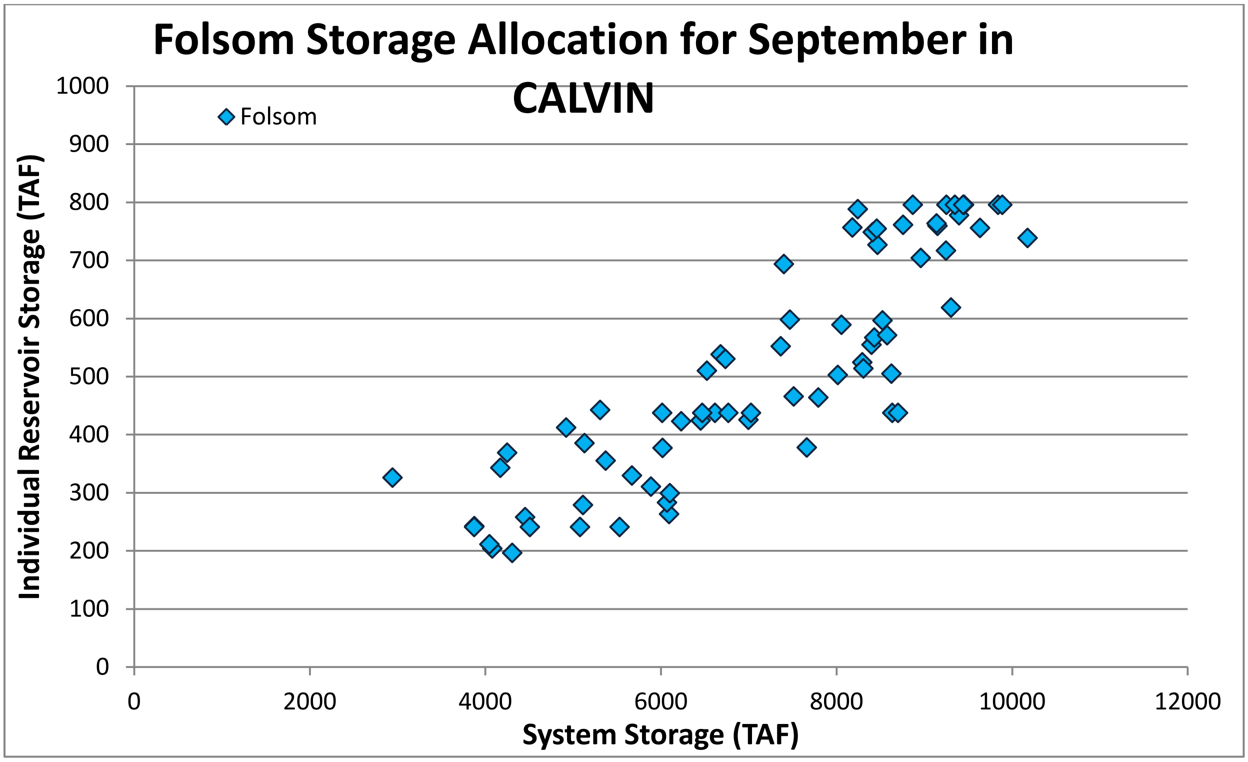


Figure B-58: Folsom Storage Allocation for October in CALVIN

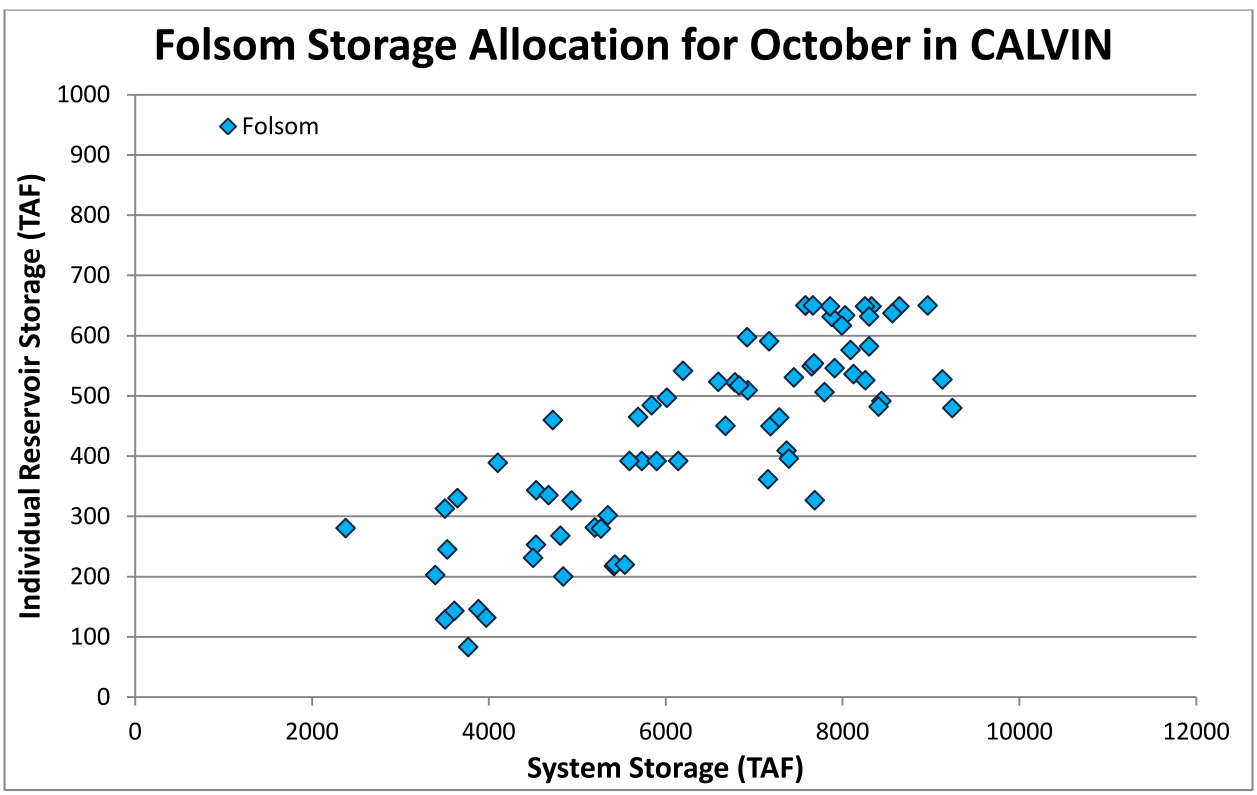


Figure B-59: Folsom Storage Allocation for November in CALVIN

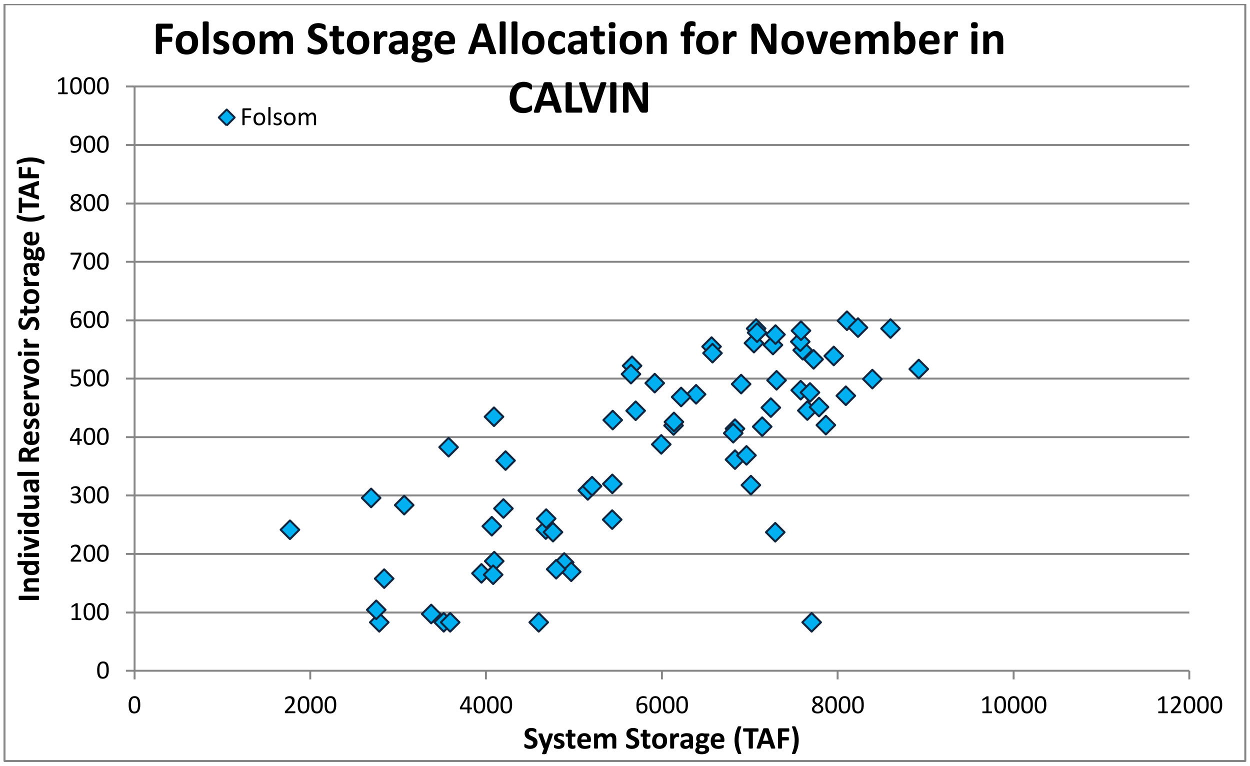


Figure B-60: Folsom Storage Allocation for December in CALVIN

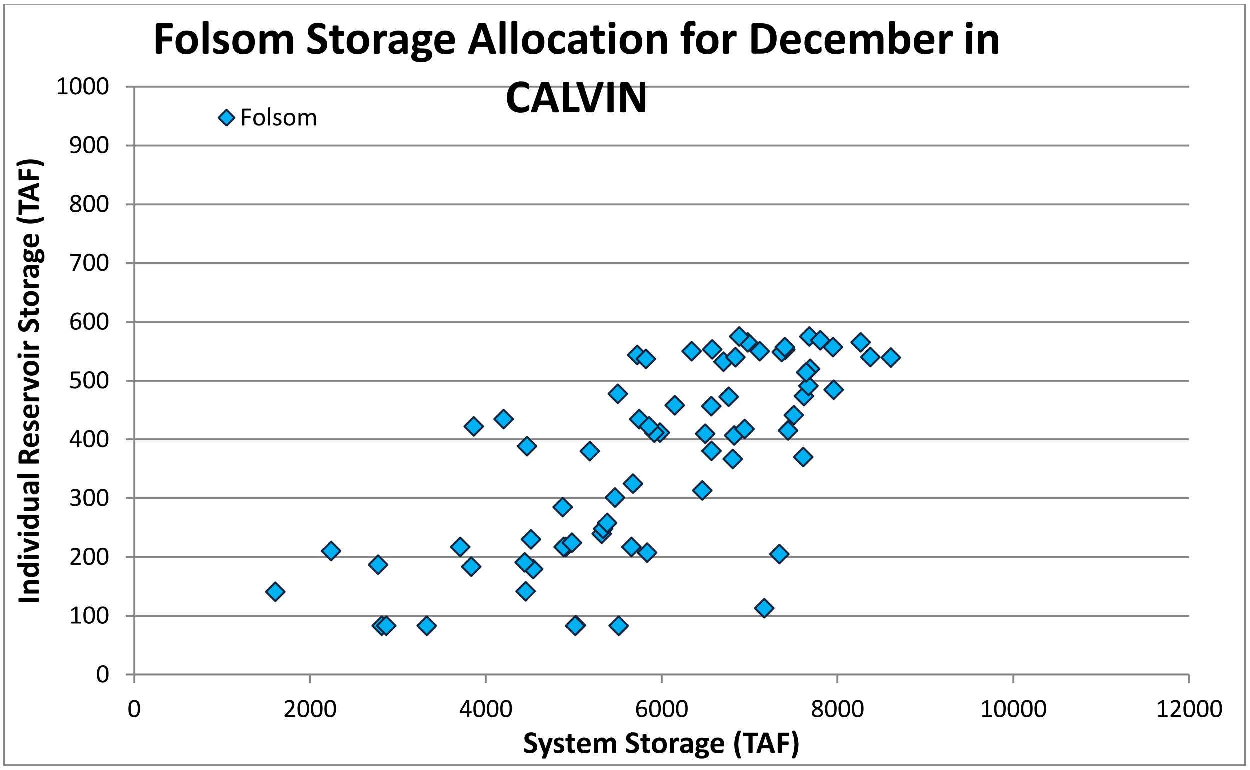


Figure B-61: Folsom Storage Allocation for January in CalSim

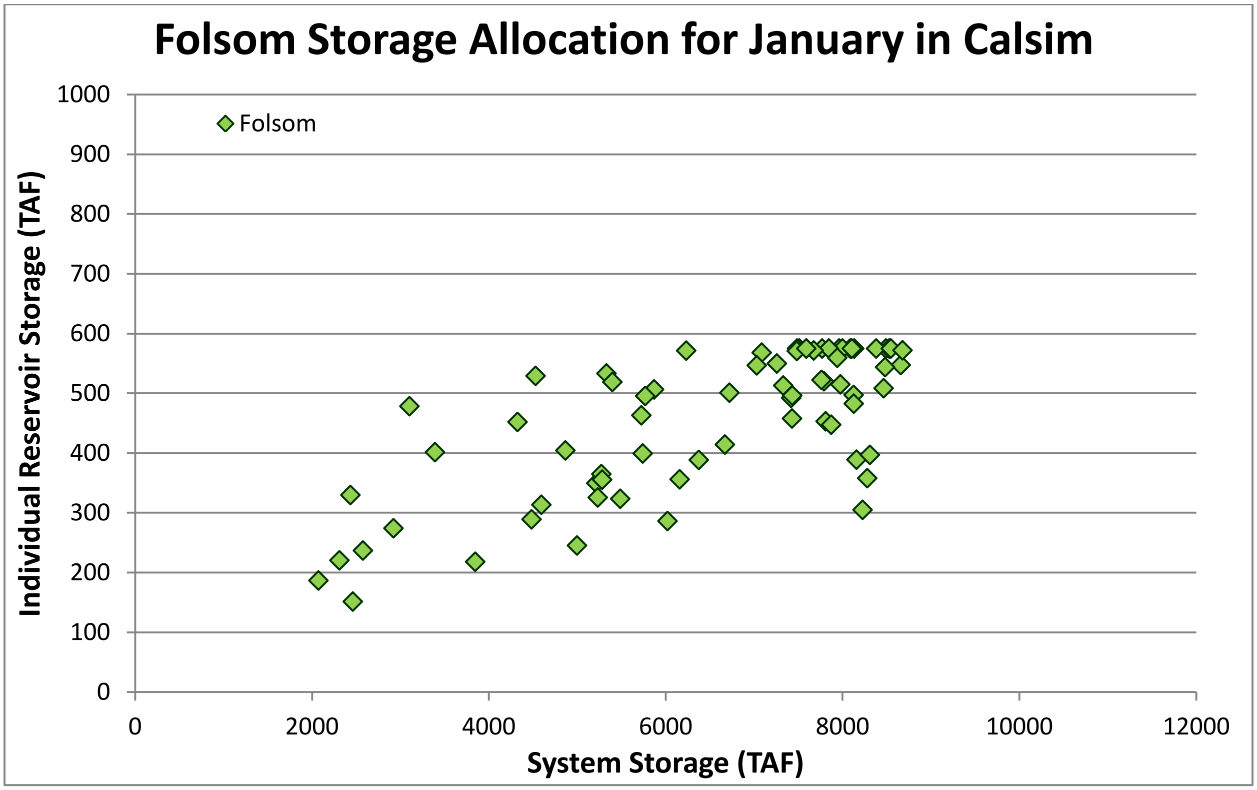


Figure B-62: Folsom Storage Allocation for February in CalSim

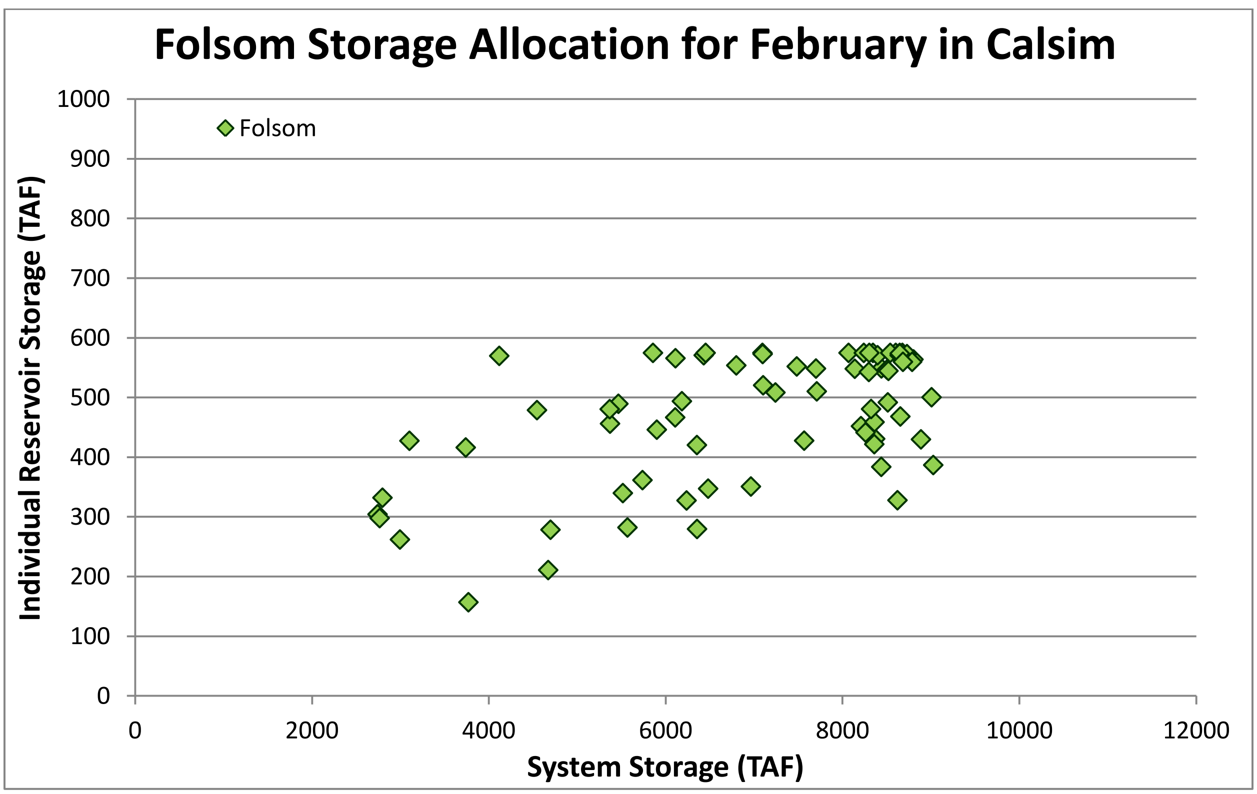


Figure B-63: Folsom Storage Allocation for March in CalSim

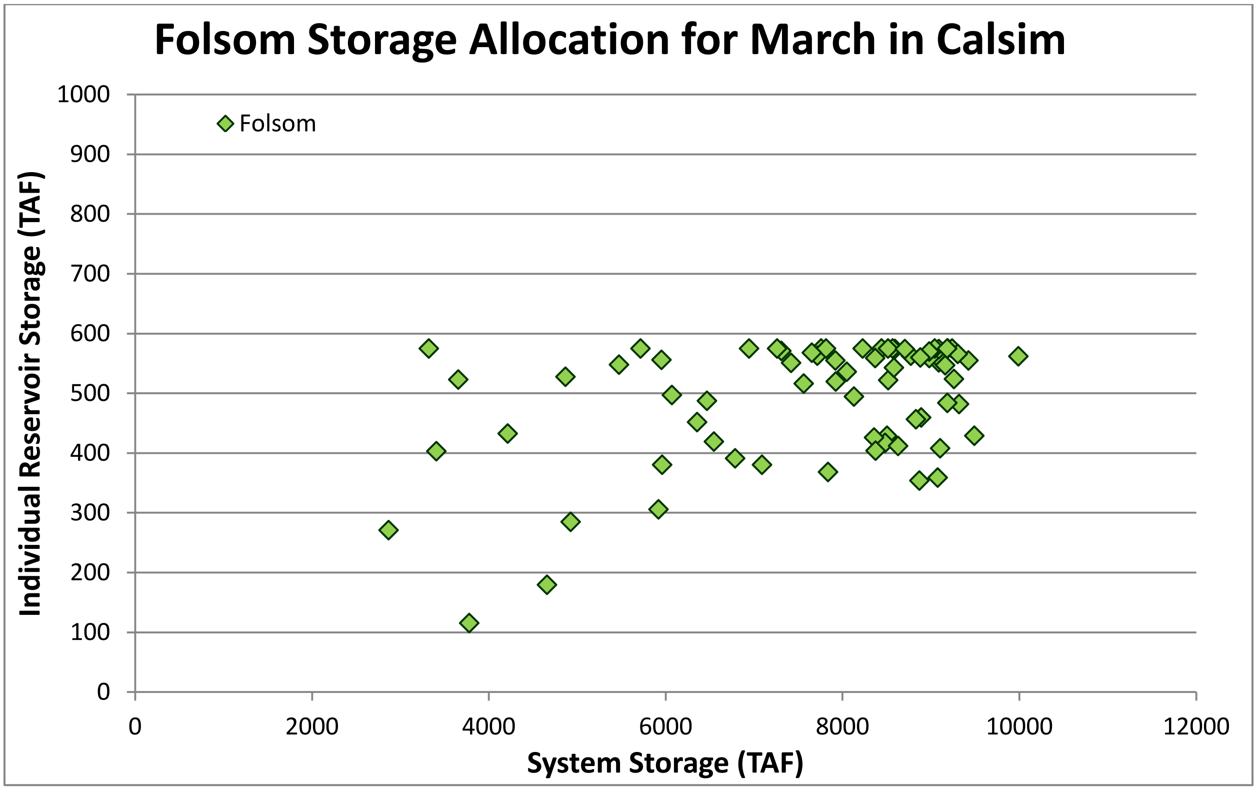


Figure B-64: Folsom Storage Allocation for April in CalSim

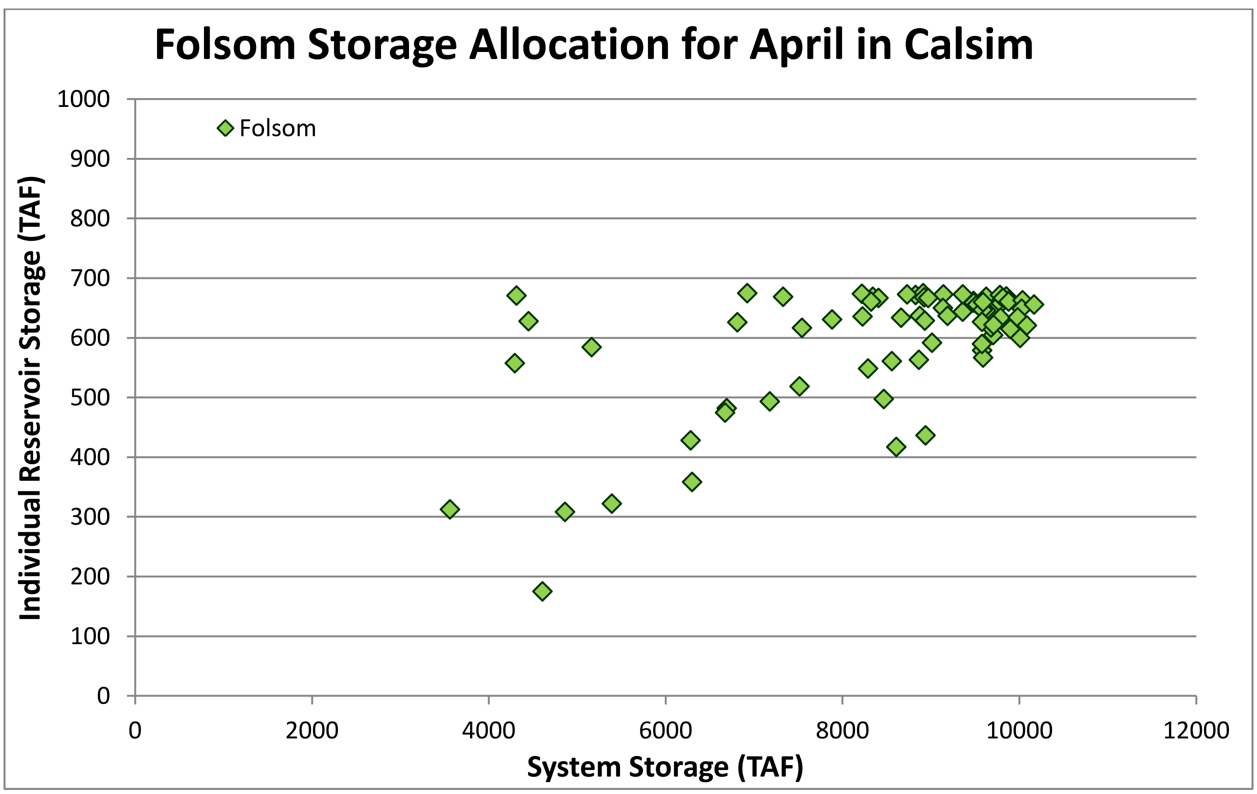


Figure B-65: Folsom Storage Allocation for May in CalSim

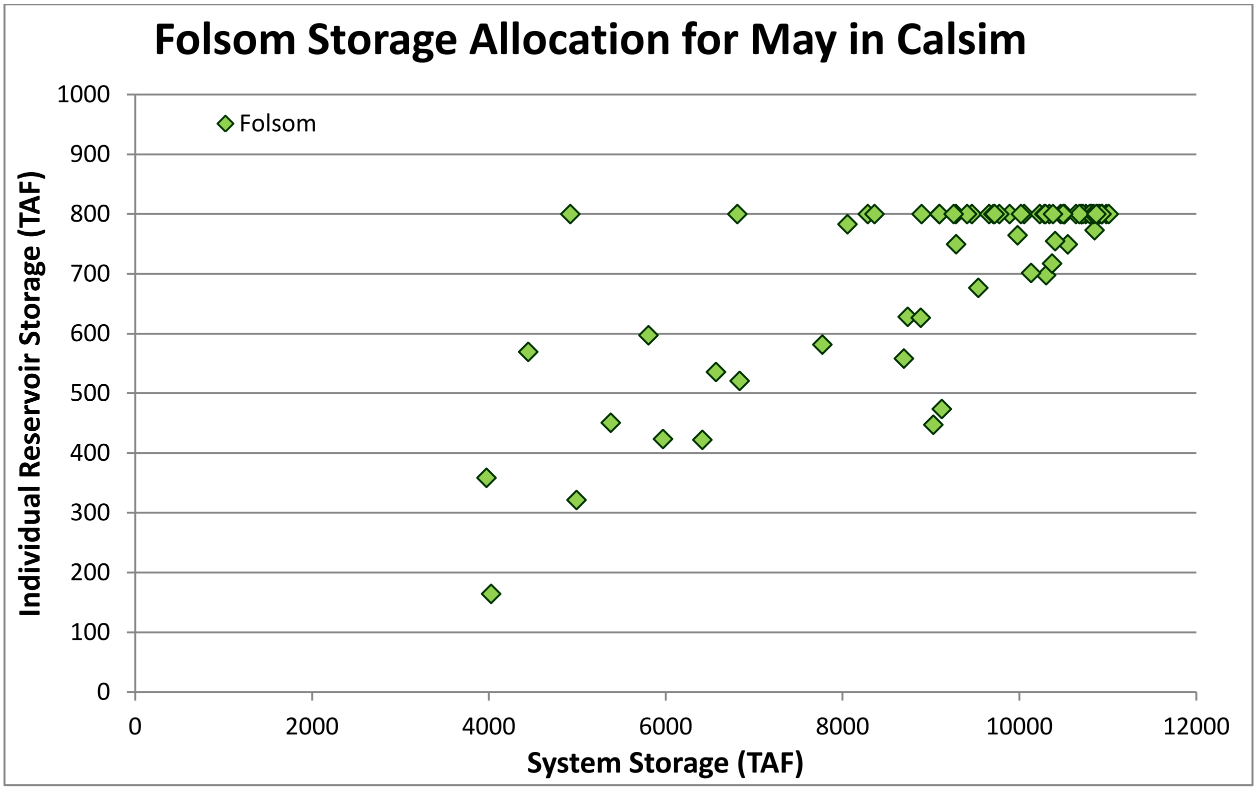


Figure B-66: Folsom Storage Allocation for June in CalSim

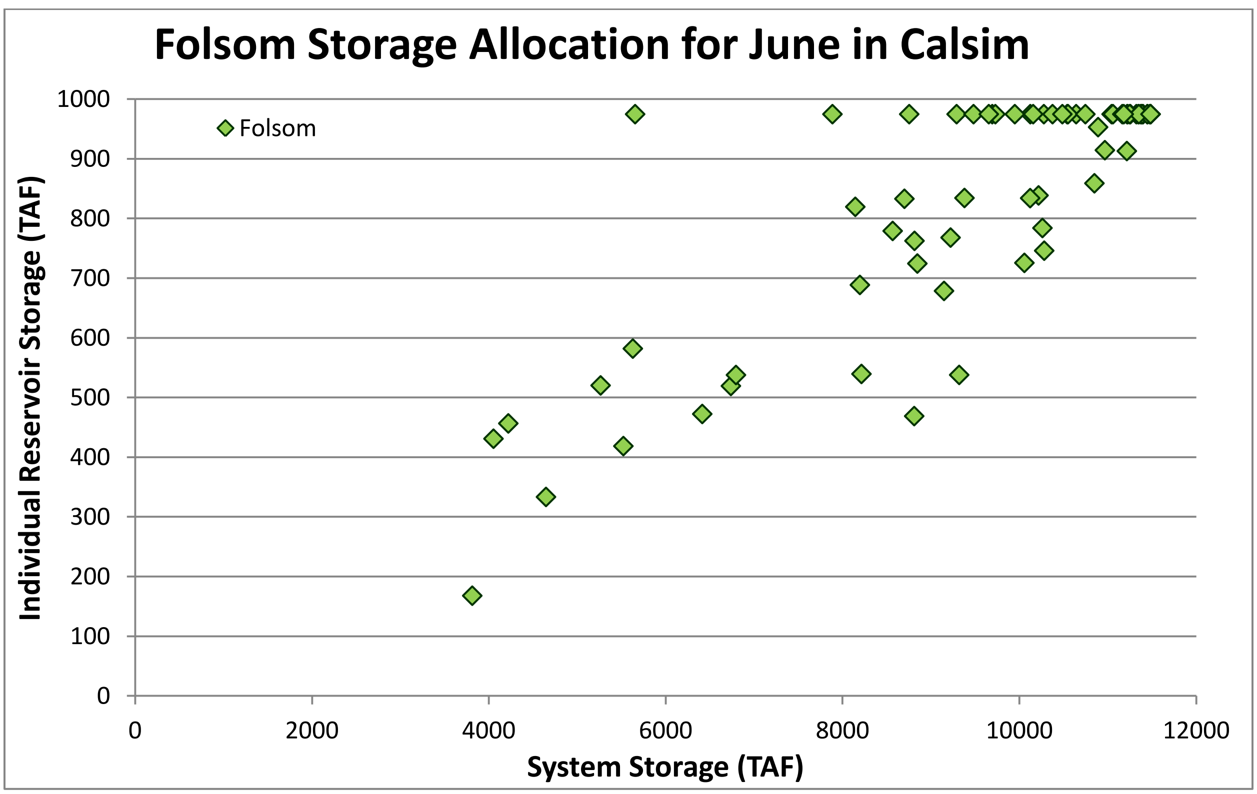


Figure B-67: Folsom Storage Allocation for July in CalSim

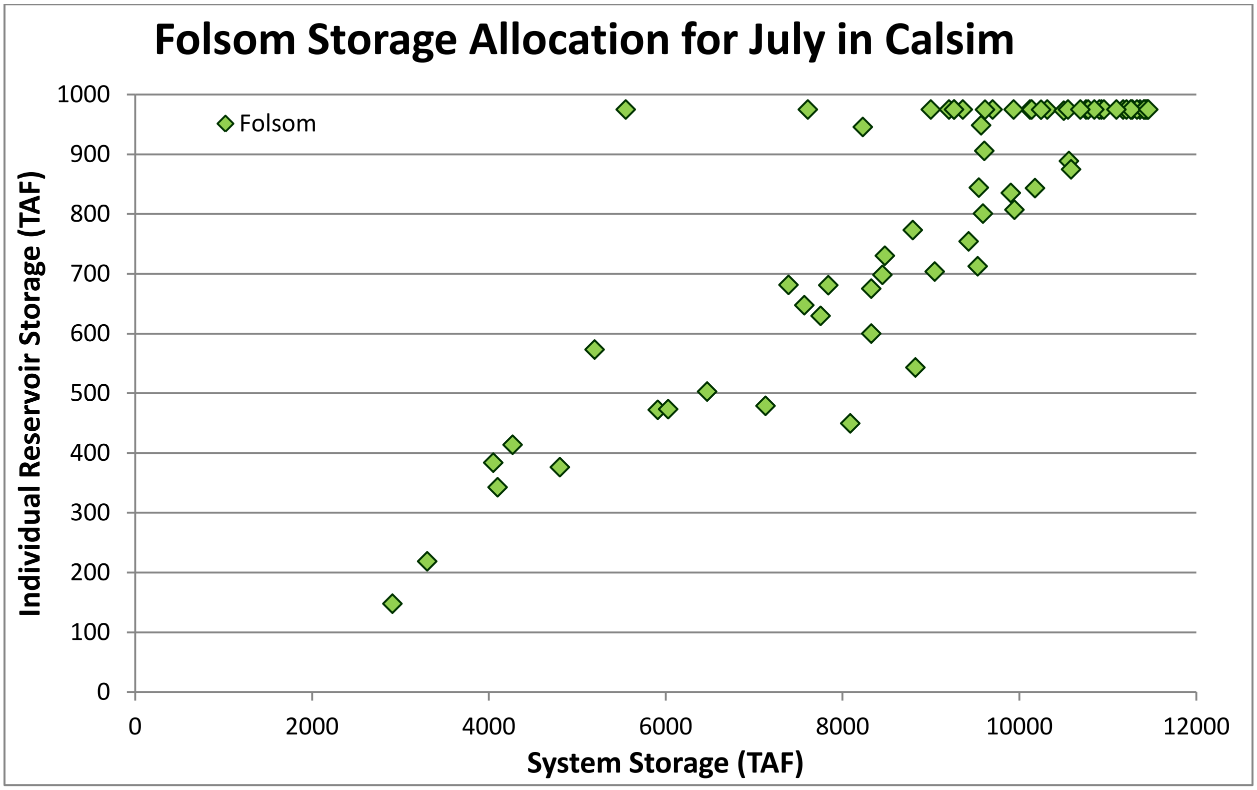


Figure B-68: Folsom Storage Allocation for August in CalSim

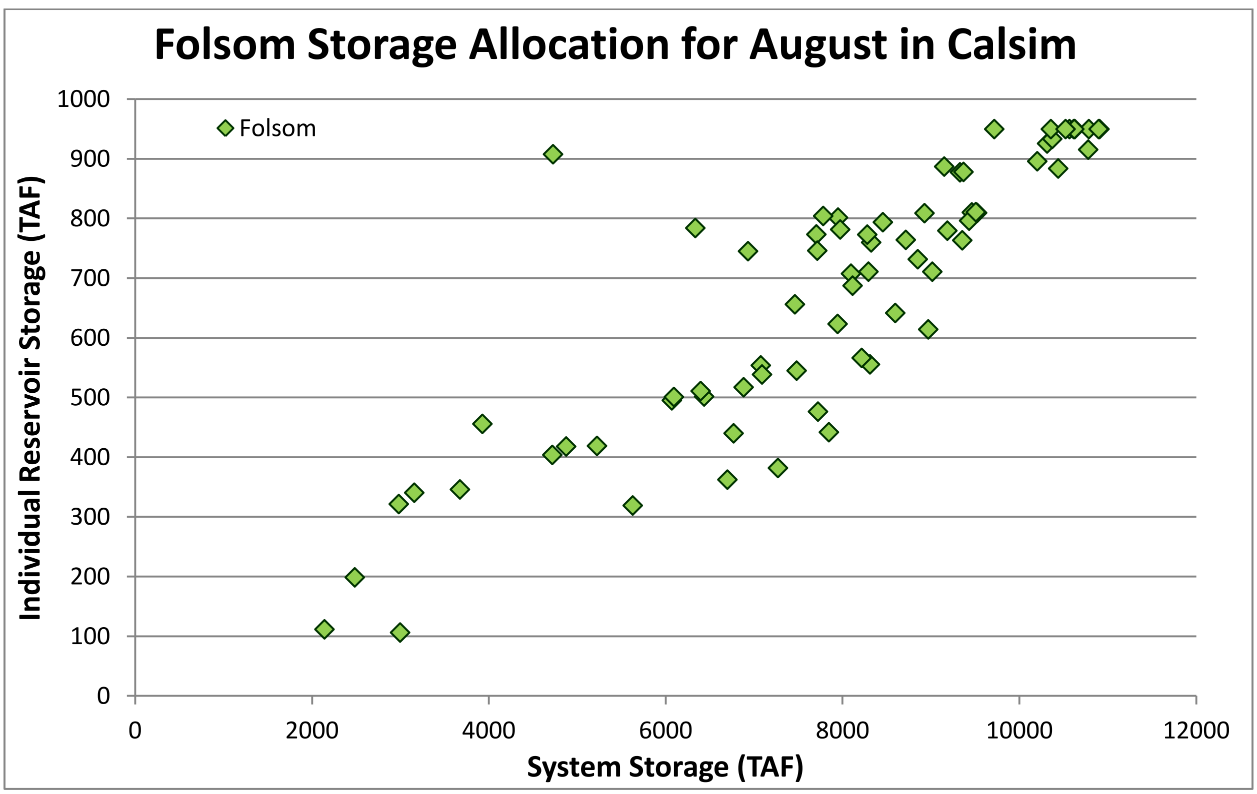


Figure B-69: Folsom Storage Allocation for September in CalSim

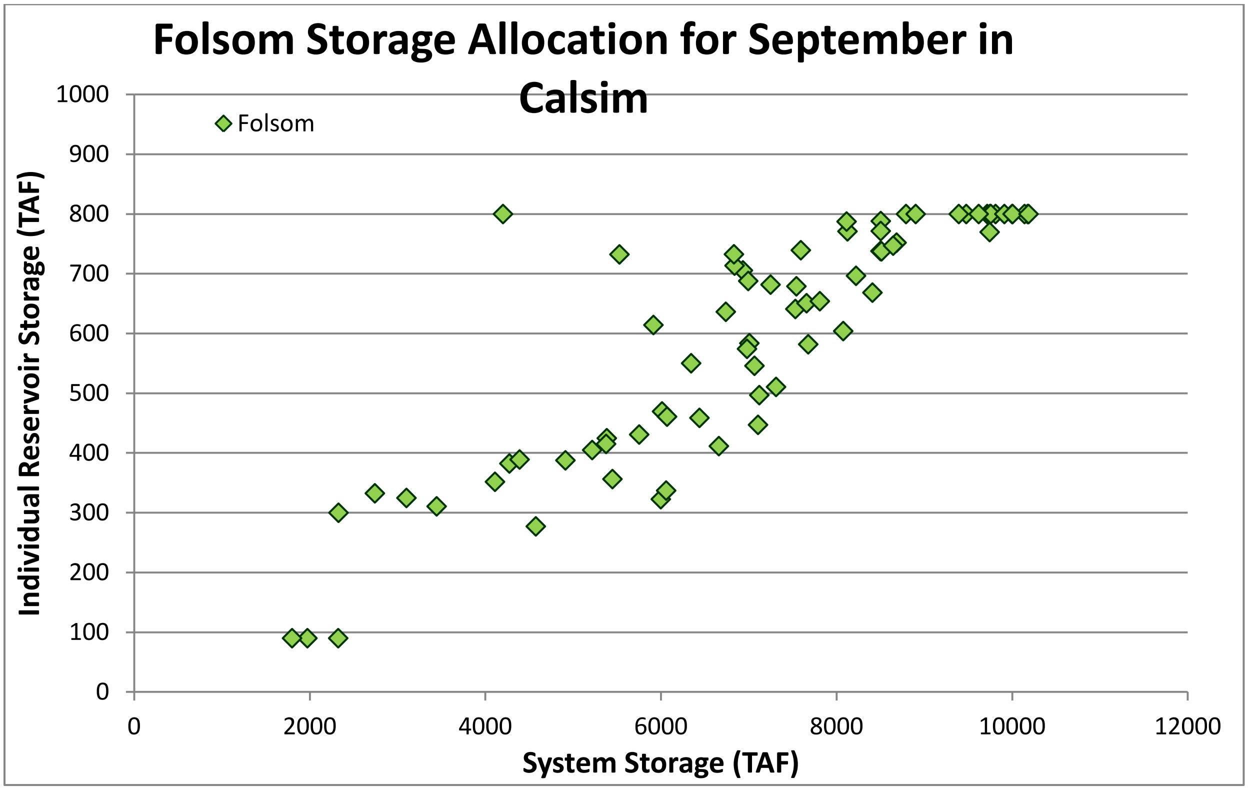


Figure B-70: Folsom Storage Allocation for October in CalSim

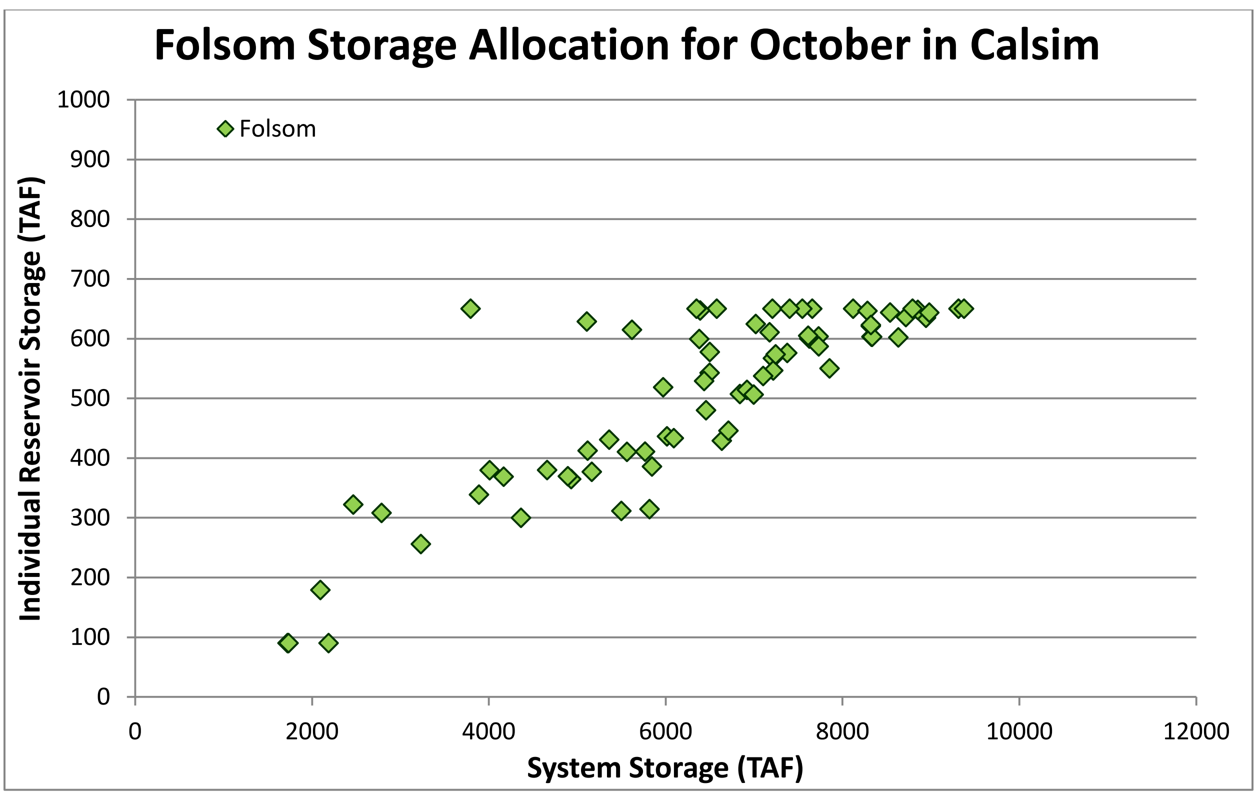


Figure B-71: Folsom Storage Allocation for November in CalSim

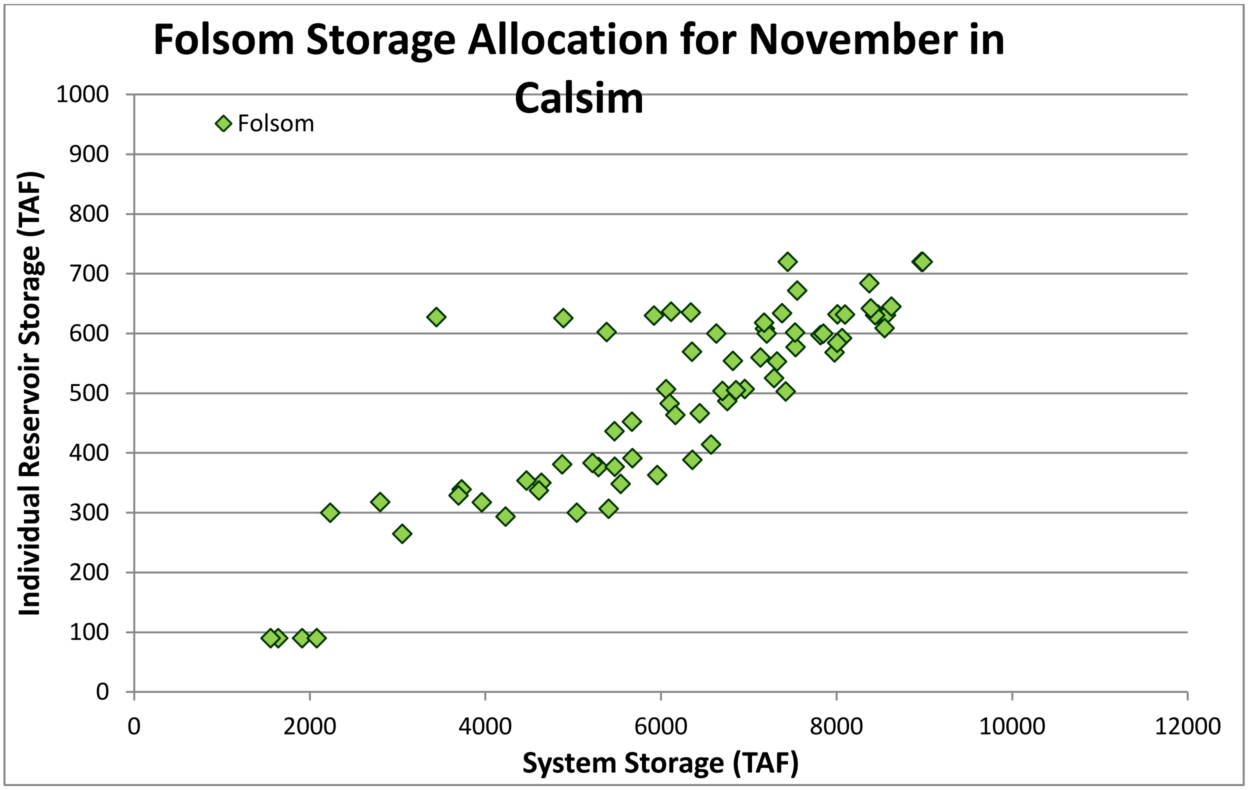
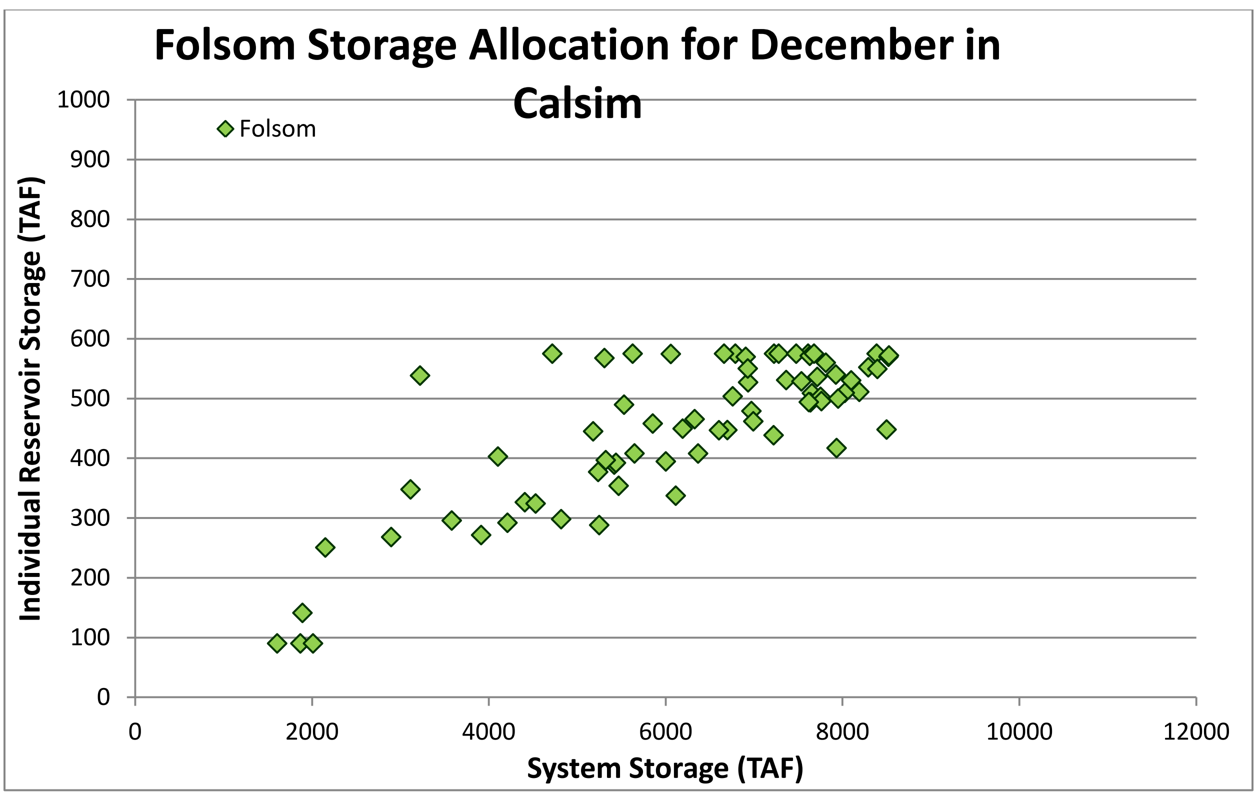


Figure B-72: Folsom Storage Allocation for December in CalSim



Oroville-New Bullards Bar Storage Allocation (only New Bullards Bar is shown)

Figure B-73: New Bullards Bar Storage Allocation for January in CALVIN

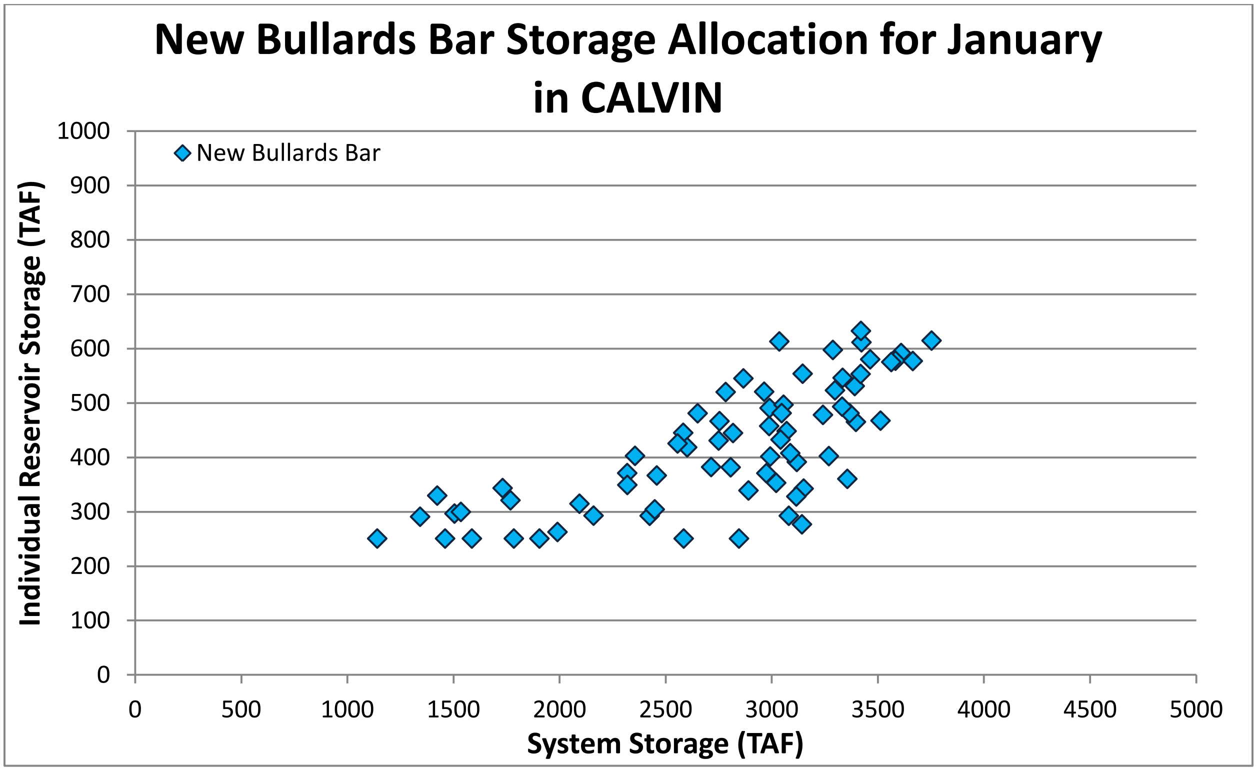


Figure B-74: New Bullards Bar Storage Allocation for February in CALVIN

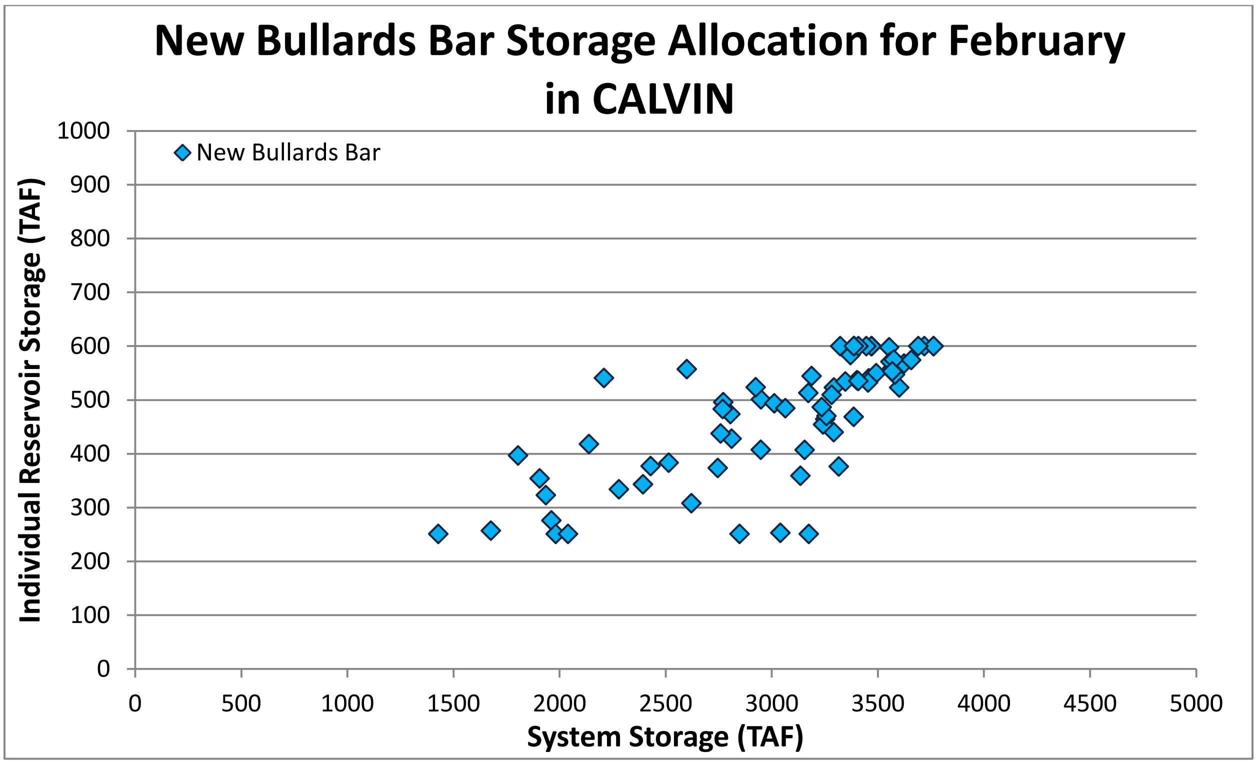


Figure B-75: New Bullards Bar Storage Allocation for March in CALVIN

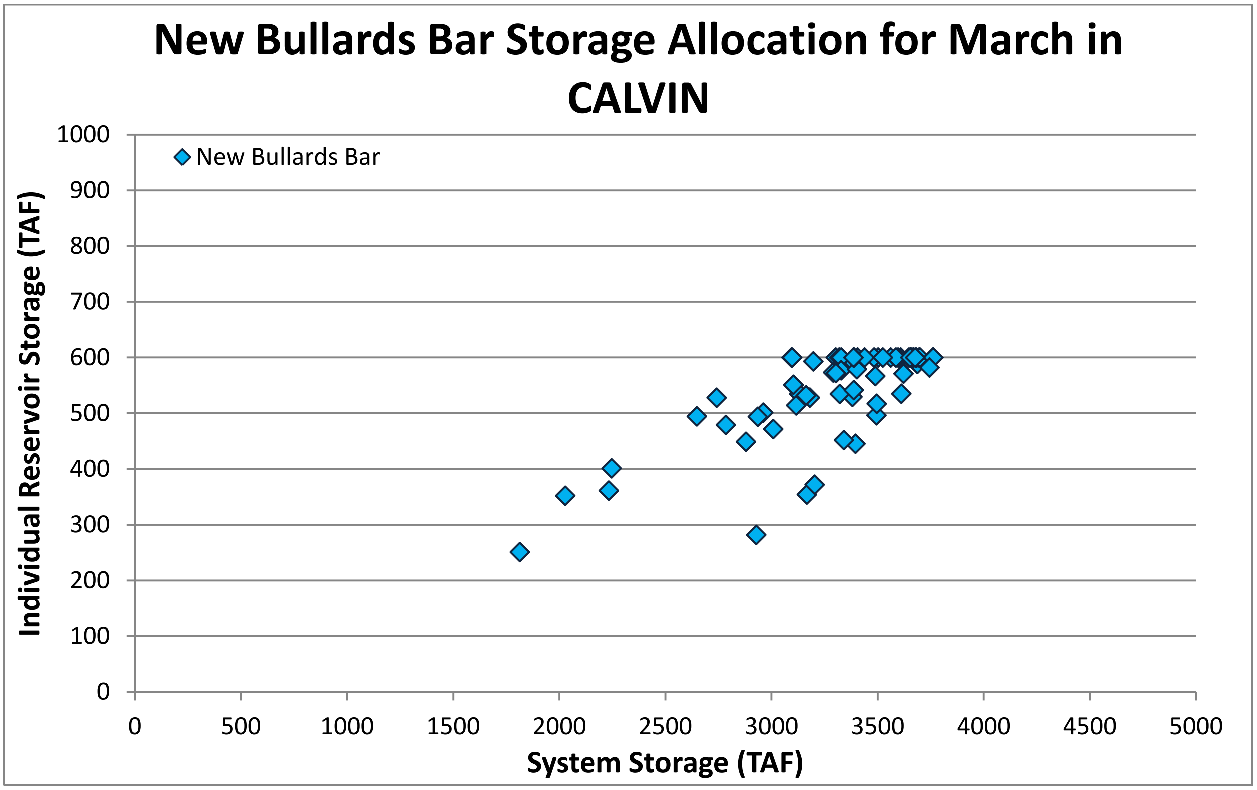


Figure B-76: New Bullards Bar Storage Allocation for April in CALVIN

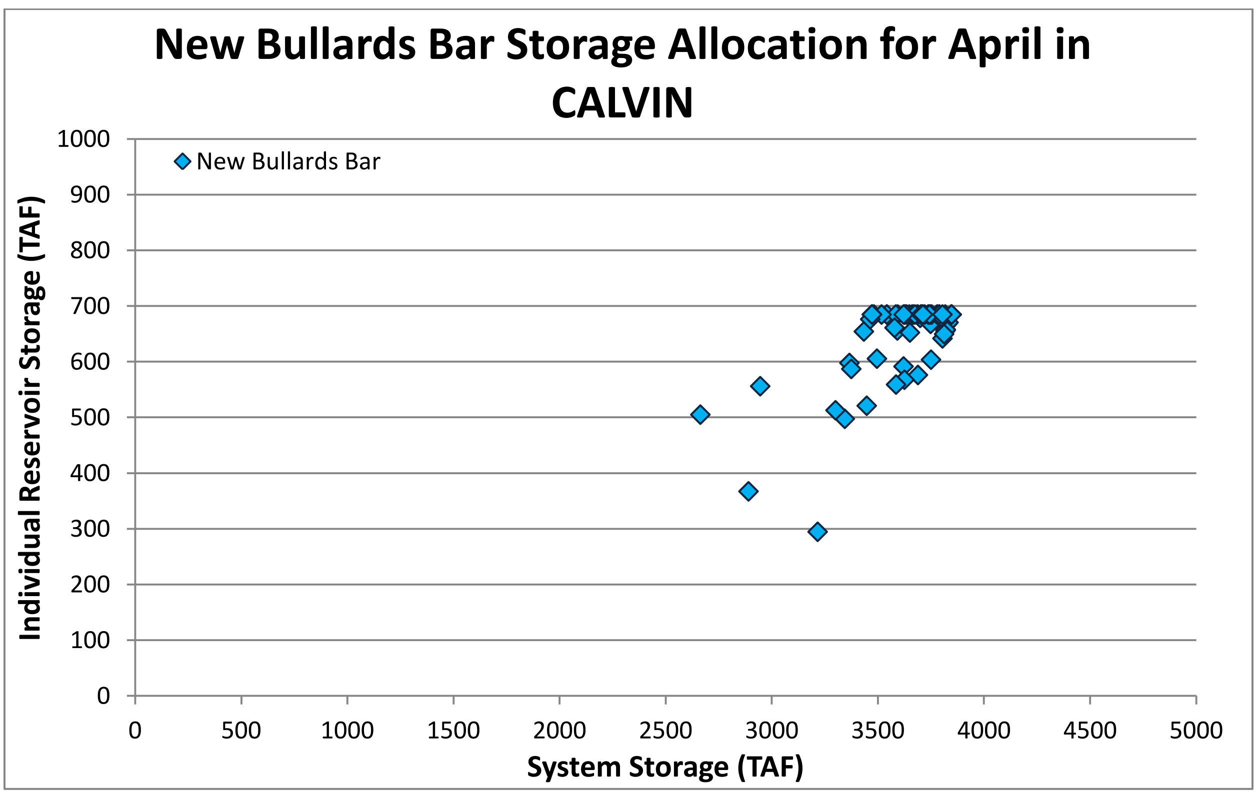


Figure B-77: New Bullards Bar Storage Allocation for May in CALVIN

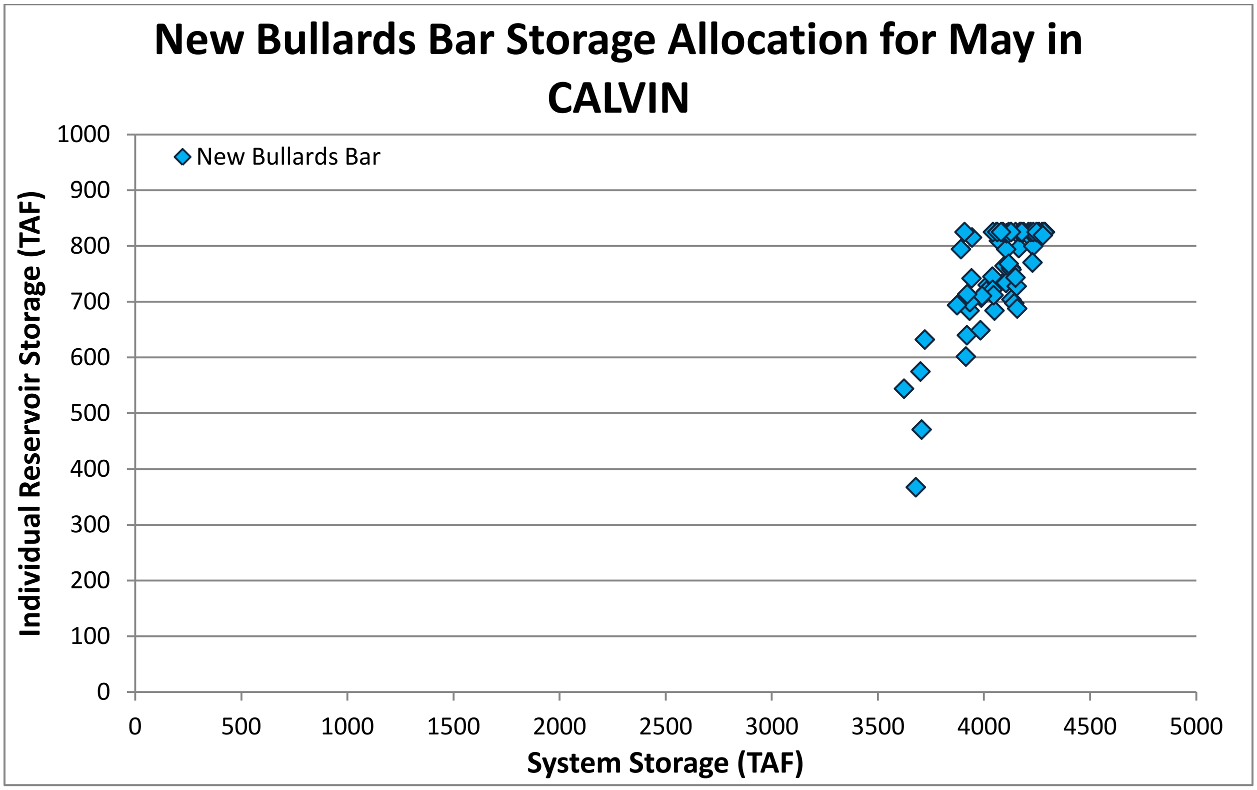


Figure B-78: New Bullards Bar Storage Allocation for June in CALVIN

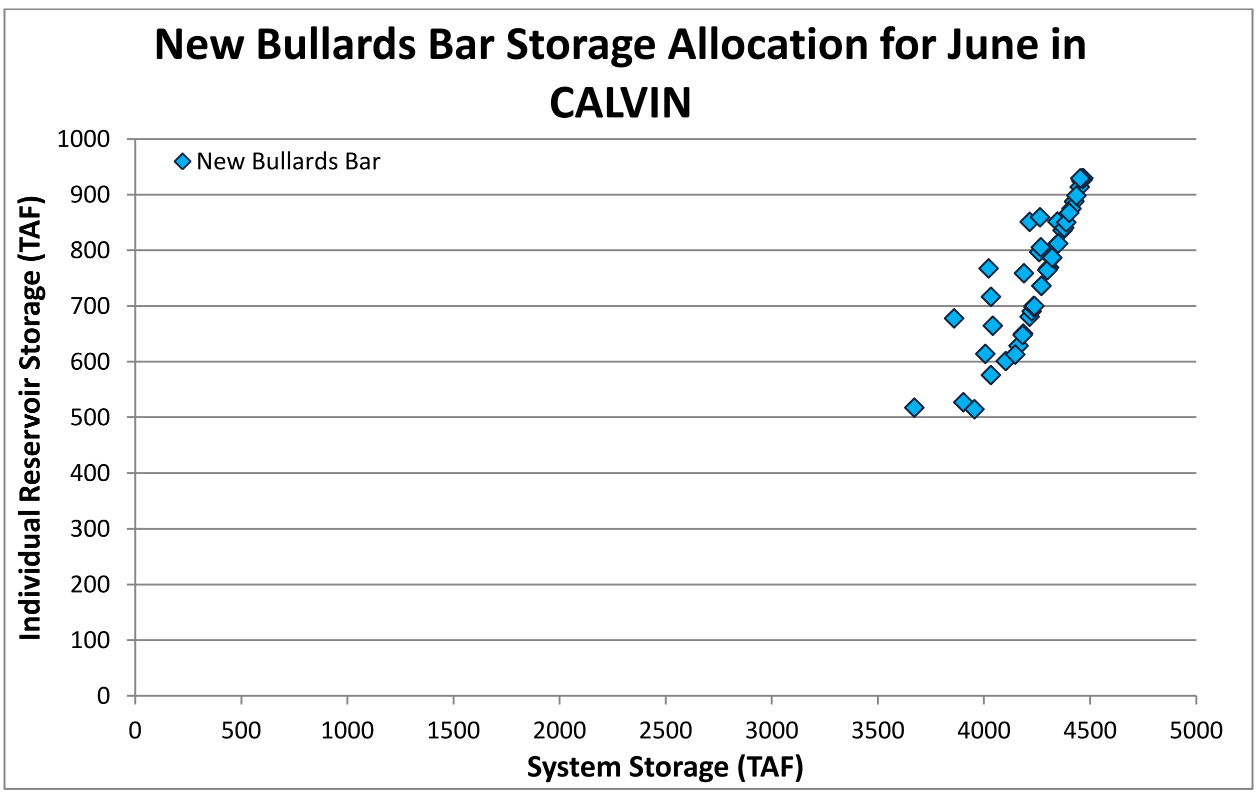


Figure B-79: New Bullards Bar Storage Allocation for July in CALVIN

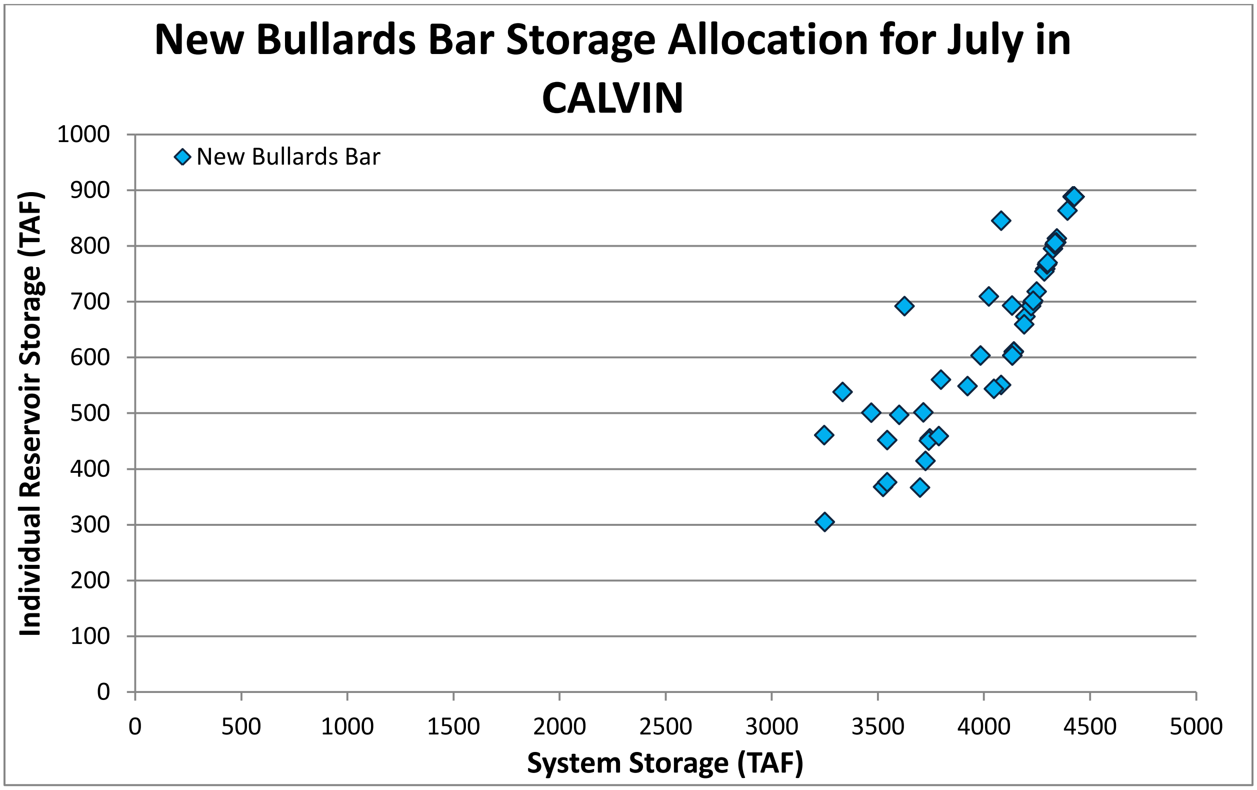


Figure B-80: New Bullards Bar Storage Allocation for August in CALVIN

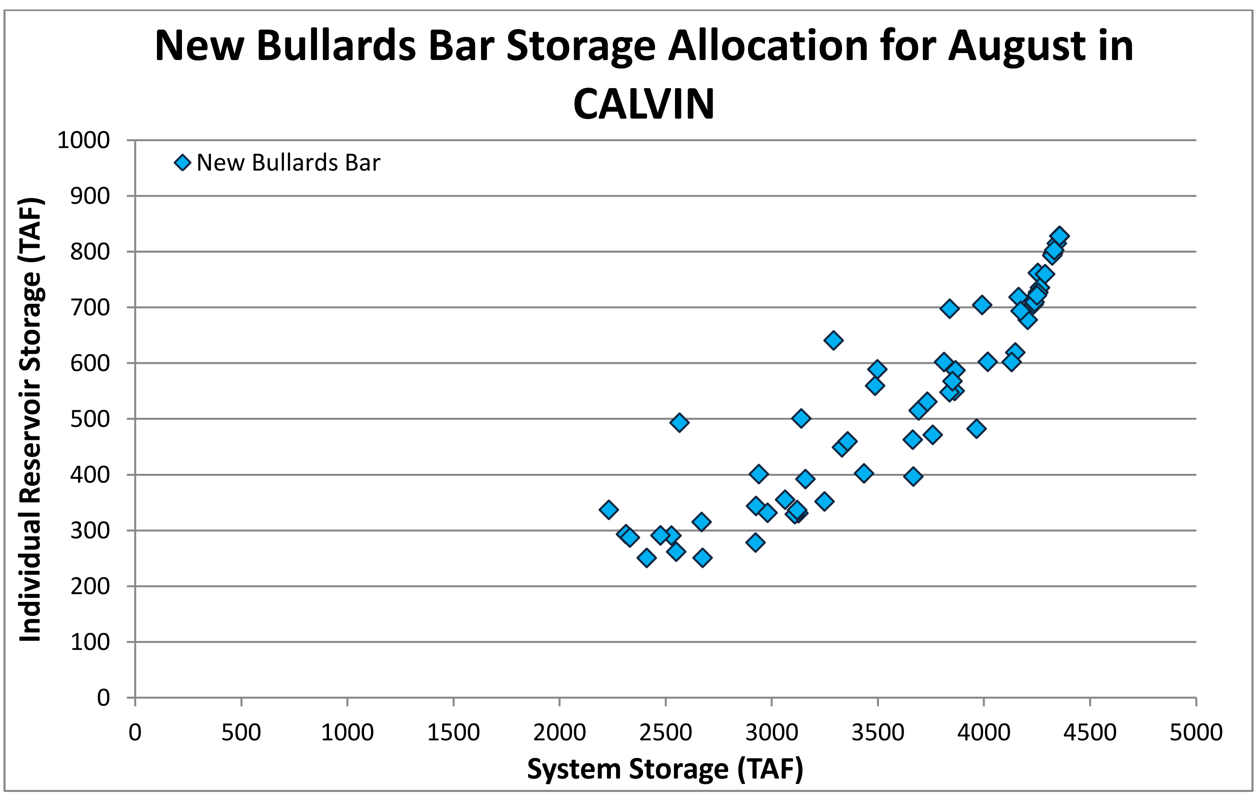


Figure B-81: New Bullards Bar Storage Allocation for September in CALVIN

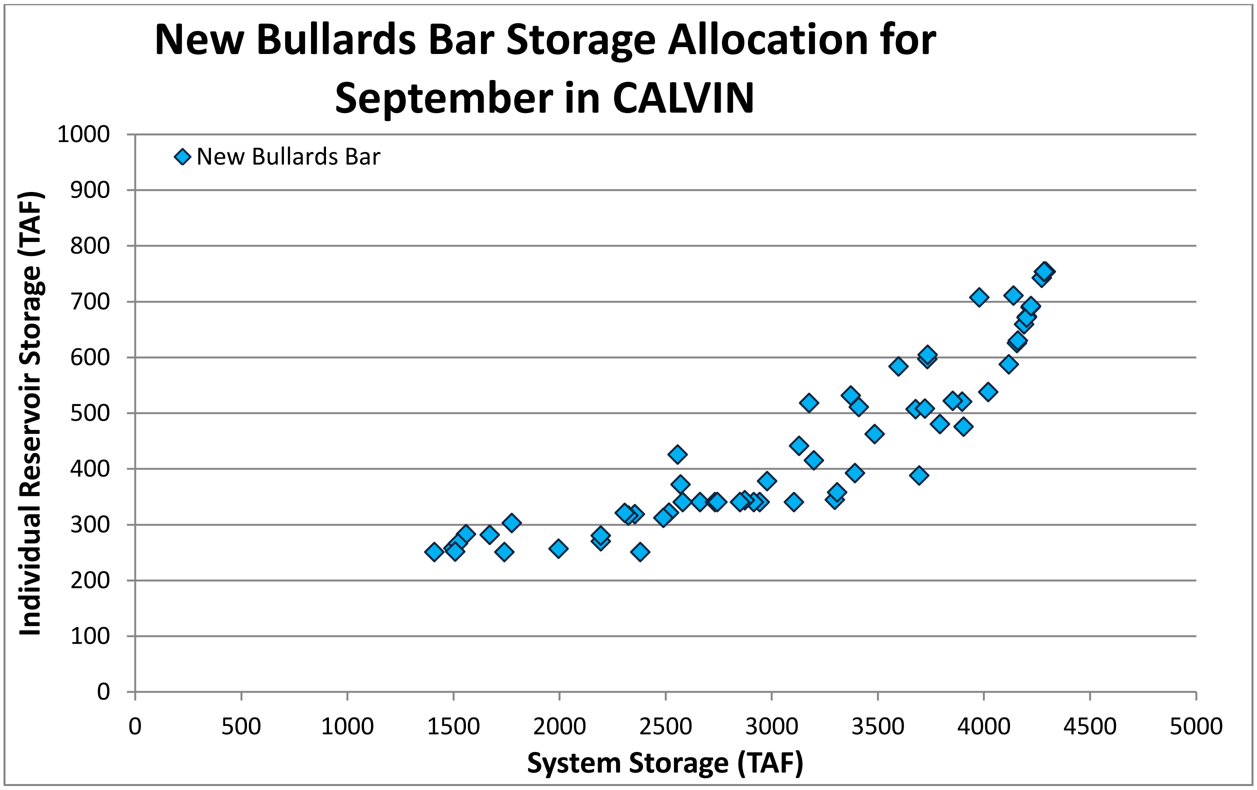


Figure B-82: New Bullards Bar Storage Allocation for October in CALVIN

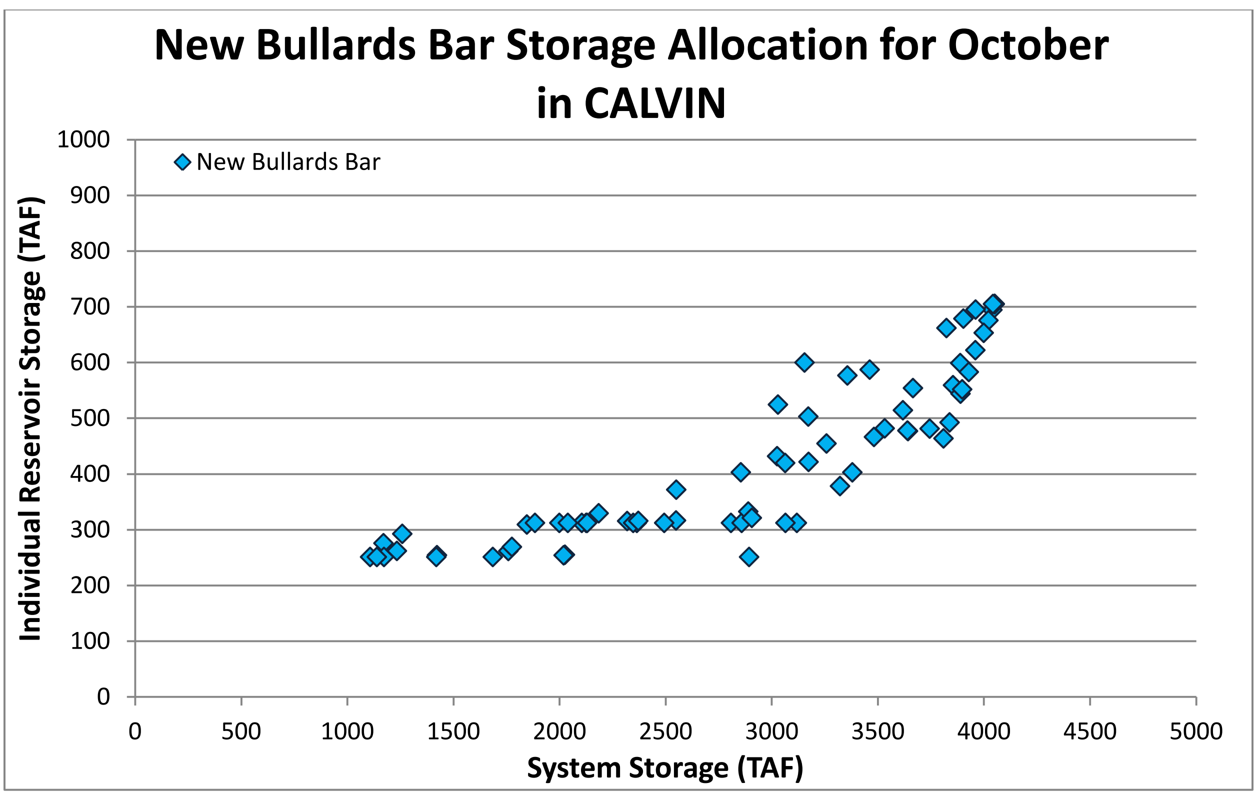


Figure B-83: New Bullards Bar Storage Allocation for November in CALVIN

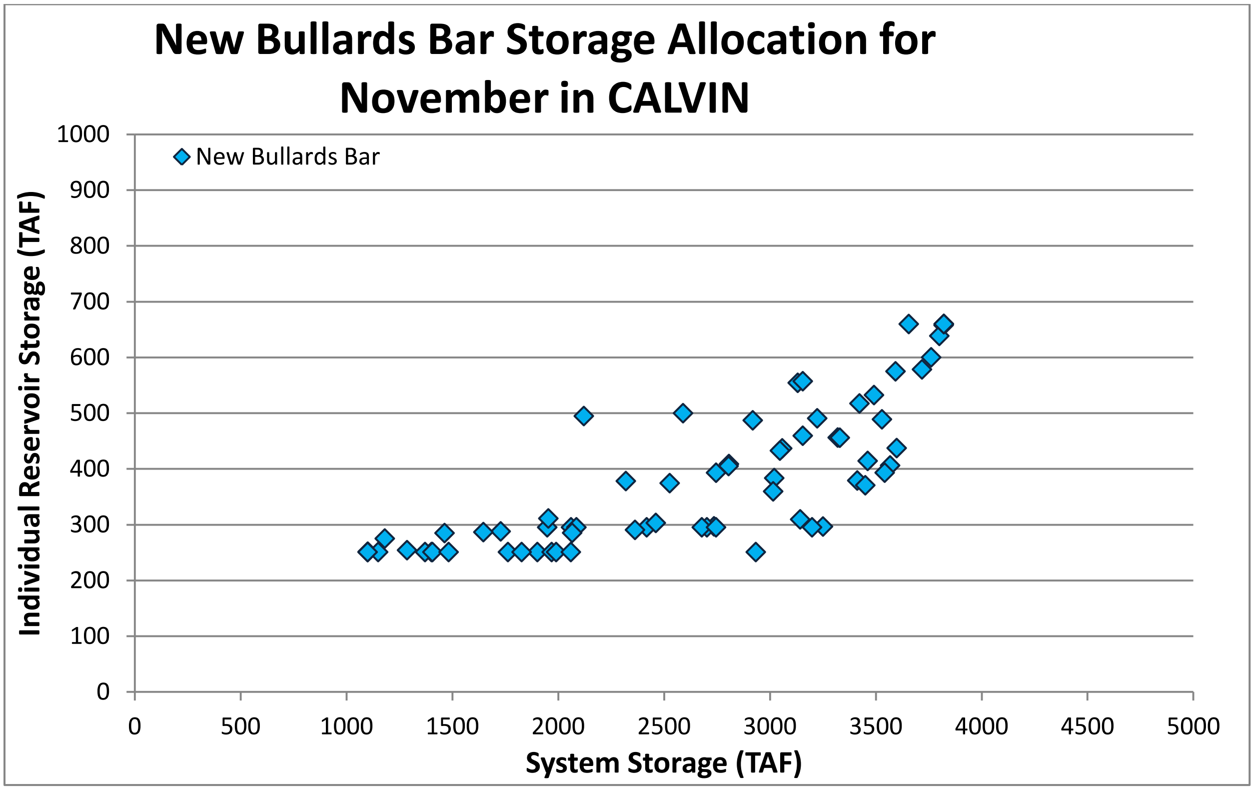
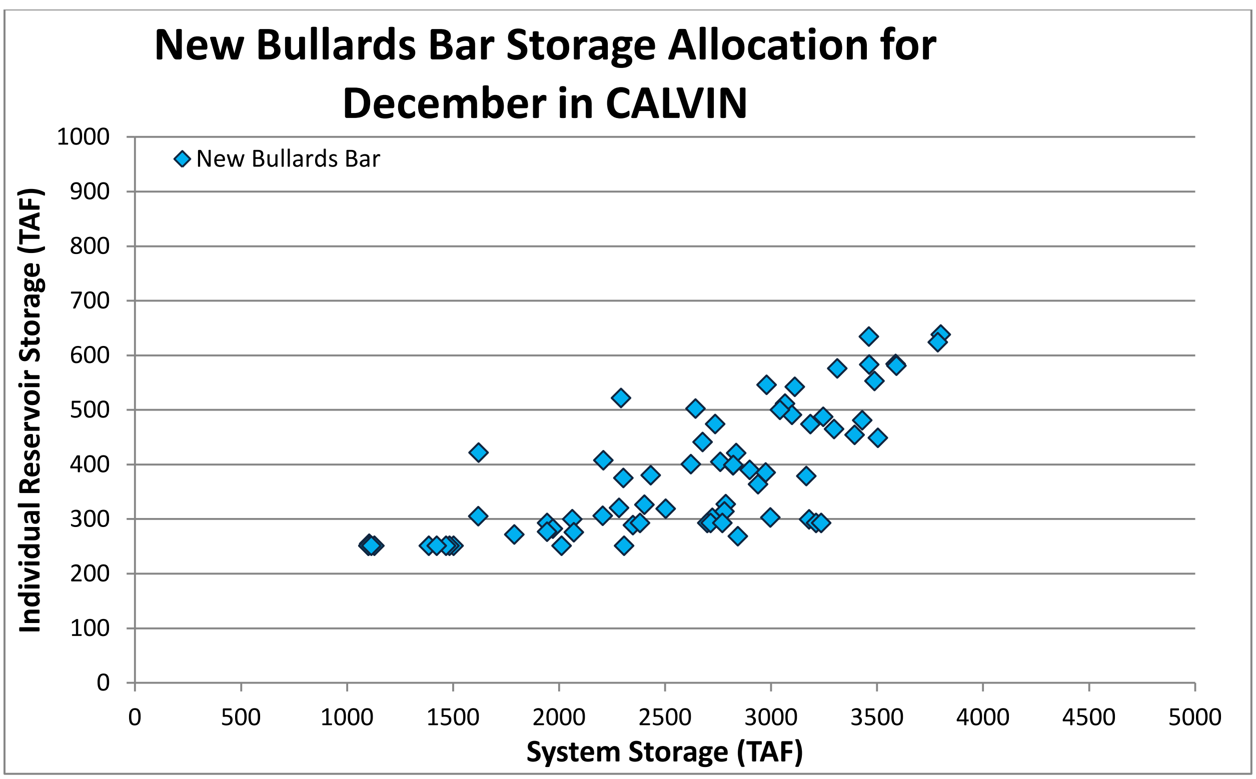


Figure B-84: New Bullards Bar Storage Allocation for December in CALVIN



Appendix C

For the release rules here are some common abbreviations:

- IOPY - Inflow over the Previous Year
- RS - Regional Storage (Total storage in Shasta, Trinity, Oroville, New Bullards Bar, and Folsom)
- AW - Available Water

If the storage minus the suggested release would ever remain greater than the maximum storage then continue releasing so that ending storage equals the maximum storage. If the storage minus the suggested release would ever fall below the minimum storage then reduce release so that ending storage equals the minimum storage. All releases are in thousand acre feet (TAF).

Release Rule Tables

Table C-1: Monthly Shasta Release Rules Derived from CALVIN Results

	Shasta			
	Max storage (TAF)	Min storage (TAF)	Release Rule	Target Release (TAF)
January	3828	116	release the target	205
February	4042	116	release the target	175
March	4330	116	release the target	190
April	4552	116	if (AW) >4677 TAF then release = .8714*(AW)-3863, else release the target	213
May	4552	116	release the target	if (IOPY) < 4350 then the target = 410, else the target = 850
June	4552	116	if 3165<(AW)<3819 TAF then release = .63*(AW)-1494, else if 4466<(AW)<5000 TAF then release = -.75*(AW)+4263, else release the target.	if the (AW)>=5000 or if (AW)<=3165 then the target =500, else the target = 900
July	4300	116	if 2531 <(AW)<3343 TAF then release=.46*(AW)-733, else if 4554 < (AW) < 4800 TAF then release = -1.12*(AW)+5894, else release the target.	if (AW)<3000 then target =429, else if (AW)>4600 then target = 527, else the target = 802
August	4000	116	if (IOPY) < 5625 TAF release = .12*(IOPY)+124, else release the target.	800
September	3700	1900	If 6000<(IOPY)<7300 TAF then release = .28*(IOPY) - 1236, else release the target	If (IOPY) > 7300 then target = 800, else the target = 355
October	3400	116	if (IOPY) < 5023 TAF then release = .05*(IOPY)+89, else release the target	350
November	3252	116	release the target	230
December	3368	116	release the target	230

Table C-2: Monthly Trinity Release Rules Derived from CALVIN Results

	Trinity			
	Max Storage (TAF)	Min Storage (TAF)	Release Rule	Target Release (TAF)
January	1850	400	if Shasta release (SR) < 209 TAF then release = -1.02*(SR)+230, else release the target	15
February	1900	400	if Shasta release (SR)< 154 TAF then release = -.81*(SR)+140, else release the target	15
March	2000	400	if Shasta release (SR)< 173 TAF then release = -1.22*(SR)+226, else release the target	15
April	2100	400	if Shasta release (SR)< 350 TAF then release = -.93*(SR)+338, else release the target	if Shasta inflow (SI) < 700 then the target = 230, else the target = 15
May	2300	400	Release the target	250
June	2420	400	if 720 < Trinity storage (TS) < 1160 TAF then release = .62*(TS)-441, else release the target	if Trinity Storage (TS) <= 720 then the target = 45, else the target = 240
July	2447	400	if 800 < Trinity storage (TS) < 1000 TAF then release = 1.11*(TS)-858, else release the target	if Trinity storage (TS) < 800 then the target = 32, else the target = 240
August	2270	400	Release the target	if (IOPY) <1000 then the target = 40, else the target = 230
September	2150	400	Release the target	if (IOPY) <1050 then the target = 35, else the target = 220
October	1975	400	if Shasta release (SR)< 292 TAF then release = -1.06*(SR)+340, else release the target	30
November	1850	400	Release the target	20
December	1850	400	if Shasta release (SR)< 200 TAF then release = -1.34*(SR)+293, else release the target	20

Table C-3: Monthly Oroville Release Rules Derived from CALVIN Results

	Oroville			
	Max Storage	**Min Storage**	**Release Rule**	**Target Release**
	(TAF)	**(TAF)**		**(TAF)**
January	3105	850	if (AW) > 3100 TAF then release = 1.28*(AW)-3870, else release the target	if (AW)<2300 and (IOPY)<3000 then the target = 0, else if (AW)>=2300 and (IOPY)<3000 then the target = 39, else if the (IOPY) >= 3000 then the target = 95
February	2813	850	if (AW) > 3150 TAF then release = 1.41*(AW)-4338, else release the target	if (IOPY) < 2700 then the target = 20, else the target = 90
March	2922	850	if (AW) > 3200 TAF then release = 1.39*(AW)-4375, else release the target	if (IOPY) < 2625 then the target =12, else the target = 94
April	3446	850	if (AW) > 3470 TAF then release = 1.29*(AW)-4425, else release the target	44
May	3538	850	Release the target	39
June	3538	850	if 8568 < (RS) < 10813 TAF then release = -.26*(RS)+2854, else release the target	if (RS) <= 8568 then the target = 636, else the target = 55
July	3538	850	if 8273 <(RS) < 10501 TAF then release = -.40*(RS) + 4370, else if (RS) >= 10501 TAF then release = .1*(RS) - 940, else release the target	1034
August	3538	850	if 4585 < (RS) < 9898 TAF then release = -.16*(RS) + 1719, else if (RS) >= 9898 TAF then release = .06*(RS) + 375, else release the target	1034
September	3350	850	Release the target	if (RS) < 8600 then the target = 440, else the target = 350
October	3163	850	Release the target	if (AW) < 2000 then the target = 100, else the target = 400
November	3163	850	if (AW) > 3200 TAF then release = 2.36*(AW) - 7472, else release the target	99
December	2922	850	if (AW) > 3110 TAF then release = 1.49*(AW) - 4532, else release the target	91

Table C-4: Monthly New Bullards Bar Release Rules Derived from CALVIN Results

	New Bullards Bar			
	Max Storage (TAF)	**Min Storage (TAF)**	**Release Rule**	**Target Release (TAF)**
January	600	251	if (AW) > 675 TAF then release = .94*(AW) - 538, else release the target	11
February	600	251	release the target	0
March	685	251	release the target	0
April	825	251	release the target	32
May	930	251	release the target	if (AW) >= 1000 then target = 71, else the target = 227
June	890	251	release the target	if (AW) >= 1000 then target = 108, else the target = 228
July	830	251	release the target	if (AW) >= 900 then target = 71, else if (AW) < 900 and (IOPY)< 400 then the target = 17, else if (AW)< 900 and 400<=(IOPY)< 650 then the target = 151, else the target = 227
August	755	251	if 630 < (IOPY) < 1250 TAF then release = .34*(IOPY)-200, else release the target	if (IOPY) < 600 then the target = 15, else if (IOPY)>1700 then the target = 99, else the target = 227
September	705	251	if 1160 < (IOPY) < 1950 TAF then release = .26*(IOPY)-287, else release the target	if (IOPY) <=1160 then the target = 19, else the target = 227
October	660	251	release the target	if (IOPY) < 1900 then the target = 38, else the target = 227
November	645	251	release the target	if (IOPY) < 1800 then the target = 29, else the target = 227
December	645	251	if Trinity release (TR) < 16 TAF then release = -21.7951*(TR)+382, else release the target	24

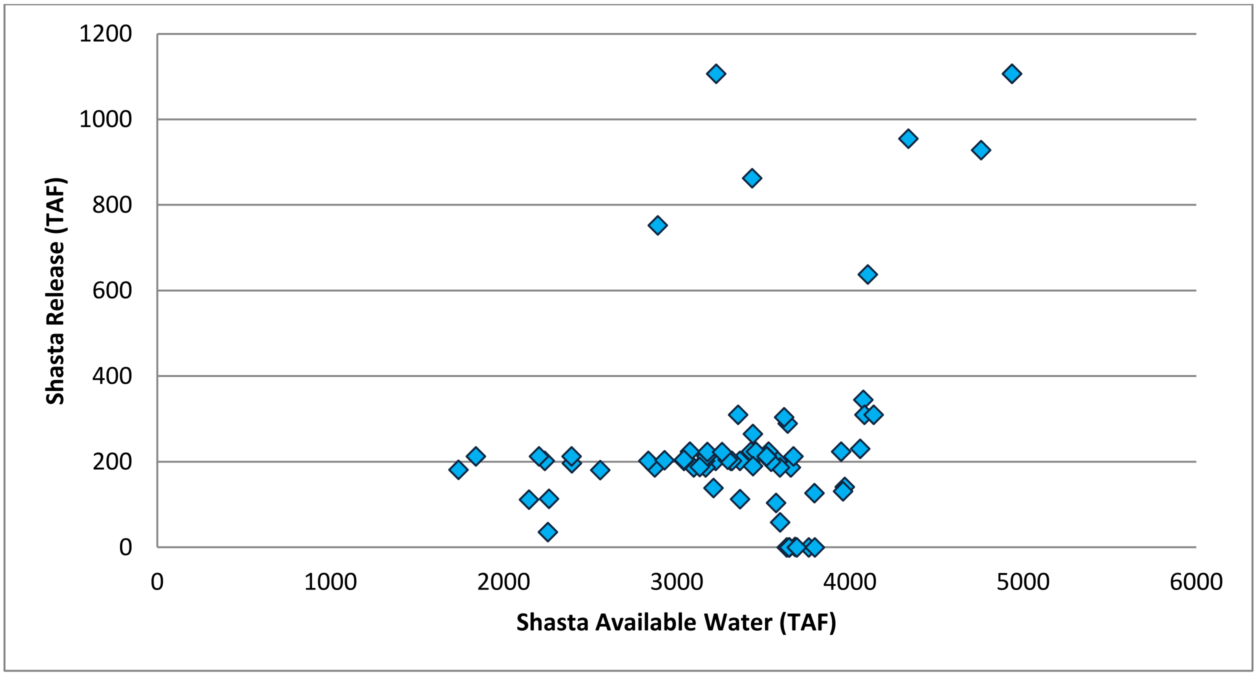
Table C-5: Monthly Folsom Release Rules Derived from CALVIN Results

	Folsom			
	Max Storage (TAF)	Min Storage (TAF)	Release Rule	Target Release (TAF)
January	575	251	if (AW) > 760 TAF then release = 1.28*(AW) - 763, else release the target	169
February	575	251	if (AW)> 673 TAF then release = 1.09*(AW) -583, else release the target	153
March	680	251	if (AW)>857 TAF then release = 1.02*(AW)-655, else release the target	if Folsom inflow (FI) < 200 then the target = 100, else the target = 218
April	800	251	if (AW) > 947 TAF then release = .98*(AW)-749, else release the target	if Folsom inflow (FI) < 171 then the target = 110, else the target = 175
May	975	251	if (AW) > 1061 TAF then release = .89*(AW)-814, else release the target	134
June	975	251	if (AW) > 1158 TAF then release = .97*(AW)-938, else release the target	220
July	950	251	if 1160 < (IOPY) < 2750 TAF then release = .20*(IOPY) -150, else if 3315 < (IOPY) < 3980 TAF then release = -.25*(IOPY) + 1202, else release the target	if (IOPY) <= 1160 then the target = 82, else if (IOPY) >= 3980 then the target = 207, else the target = 390
August	800	251	if (IOPY) < 2100 TAF then release = .11*(IOPY) - 44, else release the target	if (IOPY) < 3100 then the target = 188, else the target = 305
September	650	251	release the target	if (IOPY) < 3200 then the target =131, else the target = 244
October	720	251	if (IOPY) > 4400 TAF then the release = .17*(IOPY)-573, else release the target	if (IOPY) < 1330 then the target = 80, else if (IOPY) > 2700 then the target = 161, else the target = 140
November	575	251	release the target	if Folsom storage (FS) <350 then the target = 162, else the target = 111
December	575	251	if (AW) > 660 TAF then release = 1.27*(AW)-664, else release the target	174

Release Rule Graphs

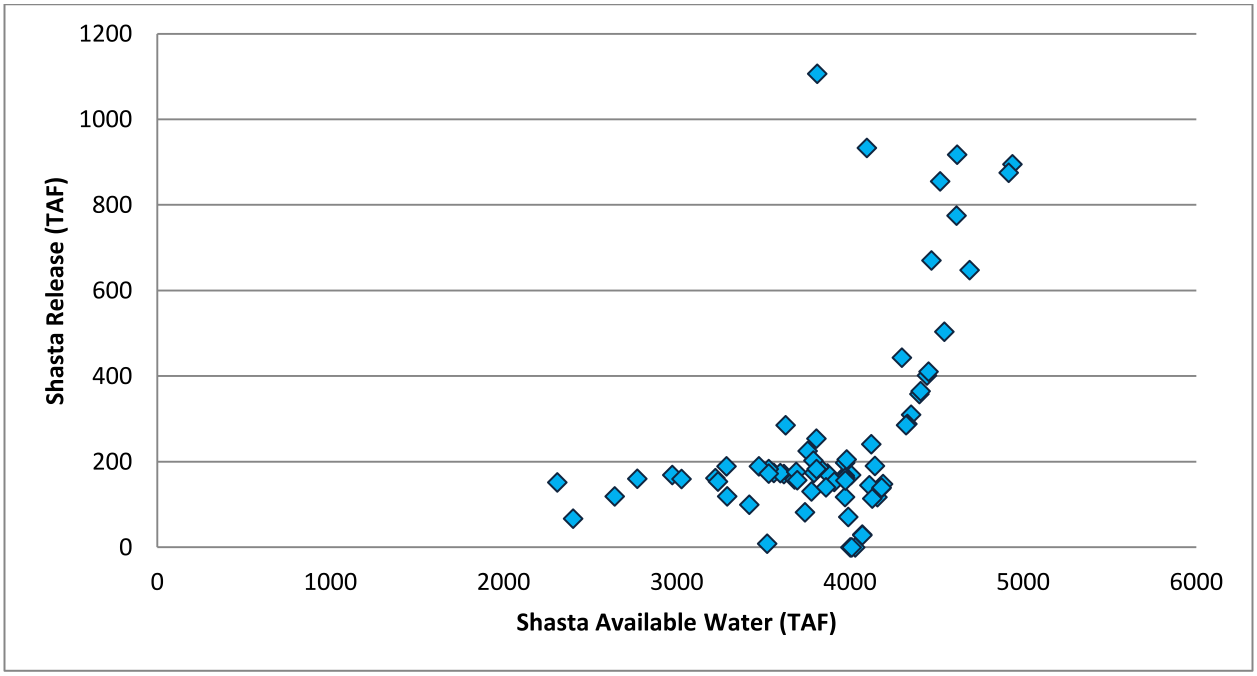
Shasta - January: Release target of 205 TAF.

Figure C-1: January Shasta Release vs. Shasta Available Water (Storage + Inflow)



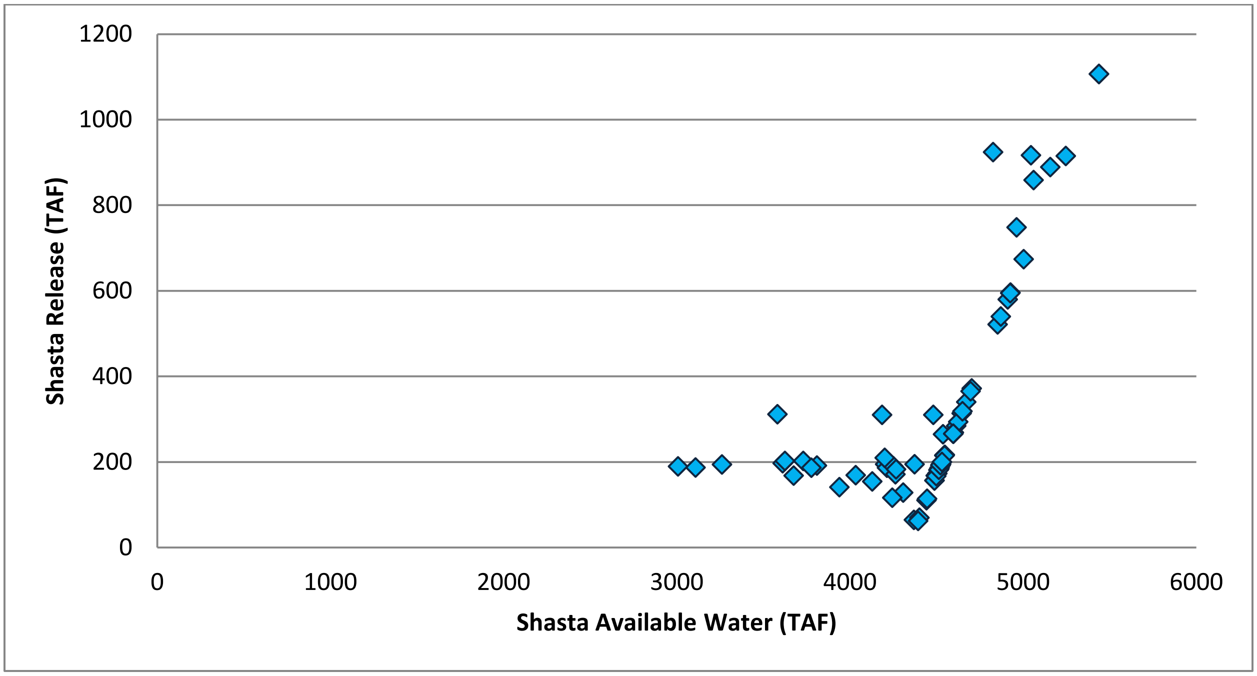
Shasta - February: Release target of 175 TAF.

Figure C-2: February Shasta Release vs. Shasta Available Water (Storage + Inflow)



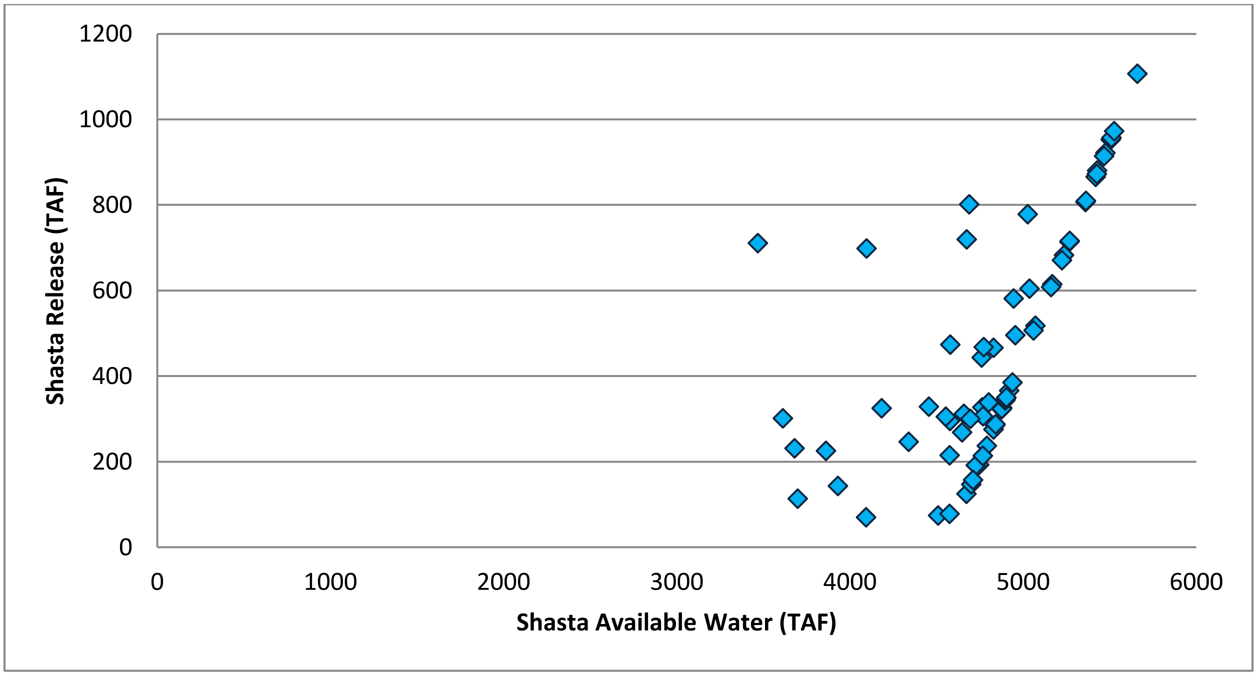
Shasta - March: Release target of 190 TAF.

Figure C-3: March Shasta Release vs. Shasta Available Water (Storage + Inflow)



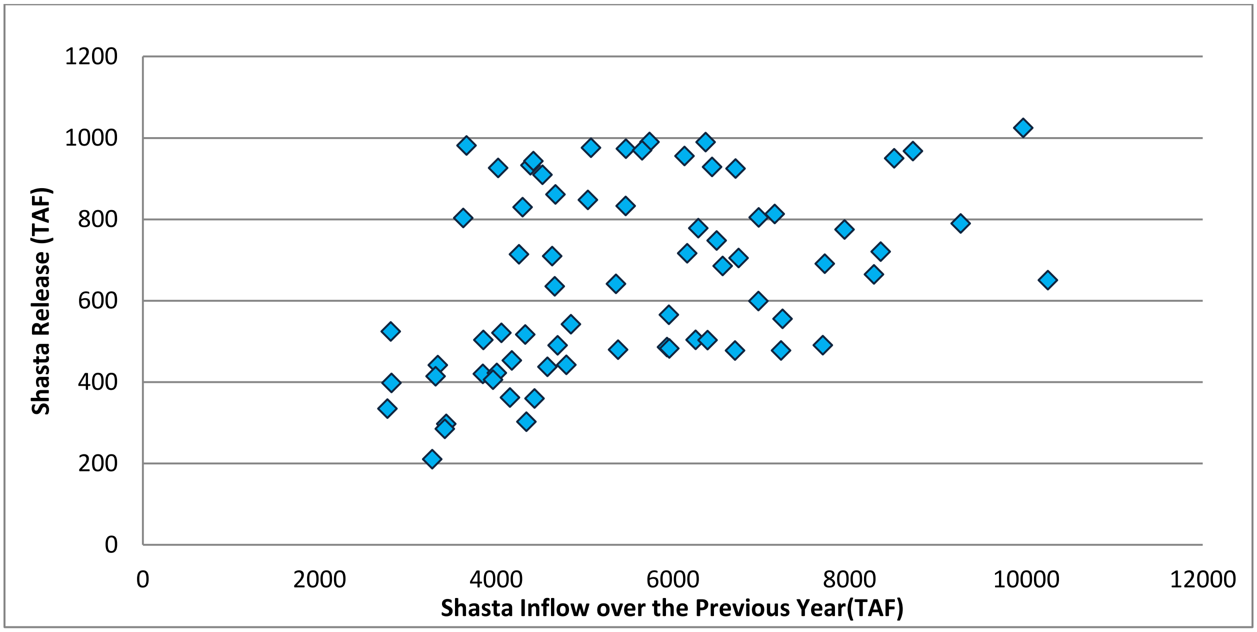
Shasta - April: If (AW) > 4677 TAF, then release = .8714*(AW)-3863, else release target of 213 TAF.

Figure C-4: April Shasta Release vs. Shasta Available Water (Storage + Inflow)



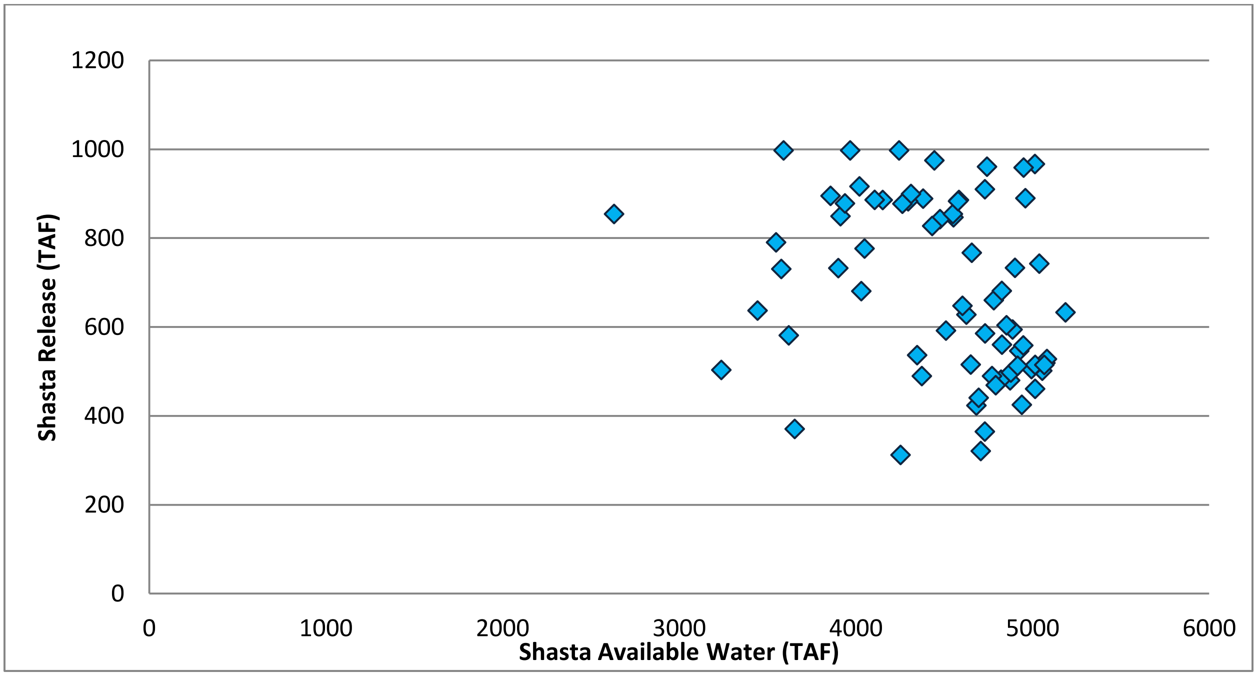
Shasta - May: Release the target. If (IOPY) < 4350 TAF then the target = 410 TAF, else the target = 850 TAF.

Figure C-5: May Shasta Release vs. Shasta Inflow over the Previous Year (IOPY)



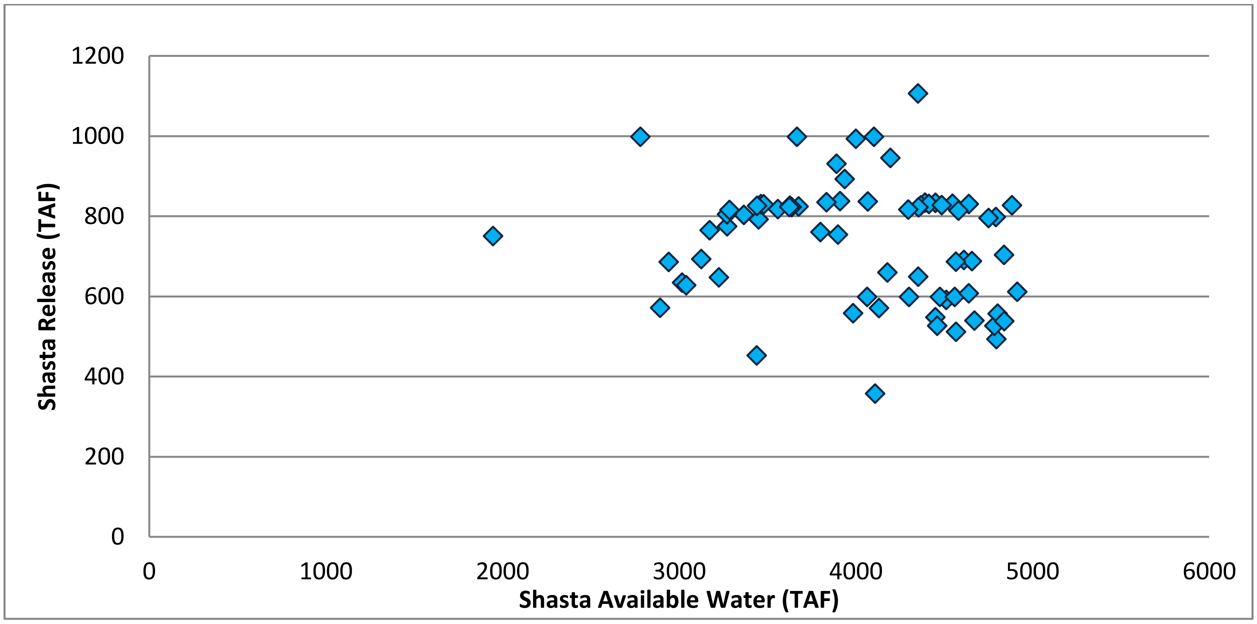
Shasta - June: If 3165<(AW)<3819 TAF then release = .63*(AW)-1494, else if 4466<(AW)<5000 TAF then release = -.75*(AW)+4263, else release the target. If (AW) >= 5000 TAF or if (AW) < 3165 TAF then the target = 500 TAF, else the target = 900 TAF.

Figure C-6: June Shasta Release vs. Shasta Available Water (Storage + Inflow)



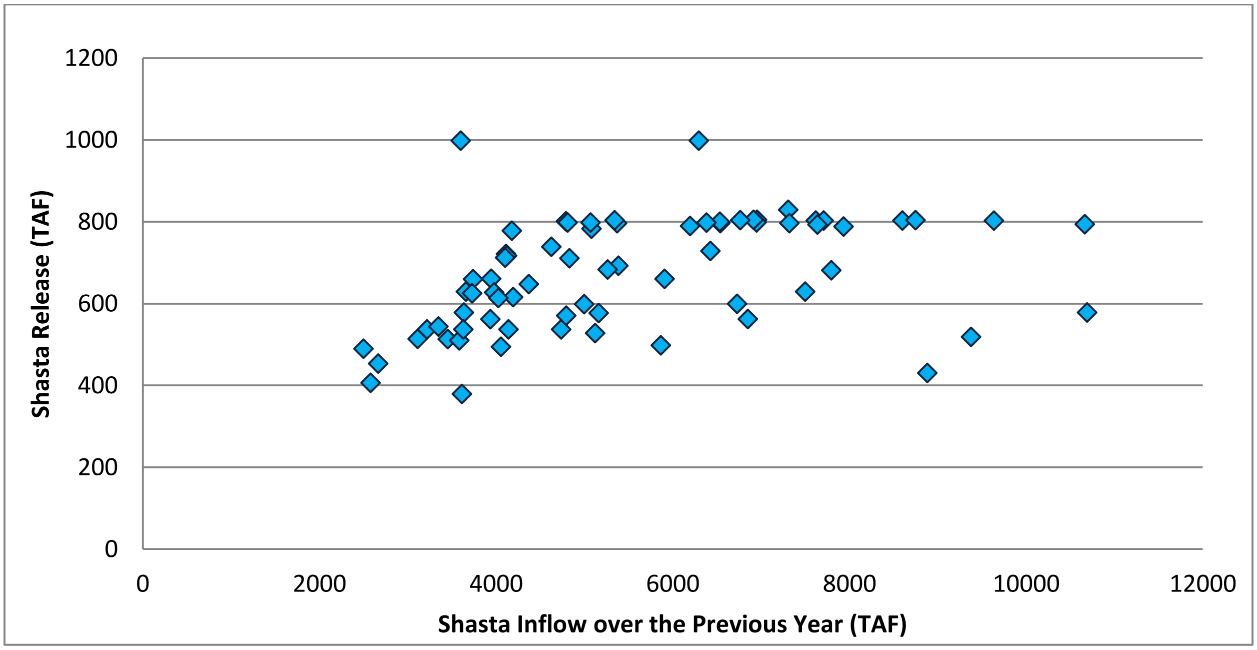
Shasta - July: If 2531 < (AW) < 3343 TAF then release = .46*(AW)-733, else if 4554<(AW)<4800 TAF then release = -1.12*(AW)+5894, else release the target. If (AW)<3000 TAF then target =429 TAF, else if (AW)>4600 TAF then target = 527 TAF, else the target = 802 TAF.

Figure C-7: July Shasta Release vs. Shasta Available Water (Storage + Inflow)



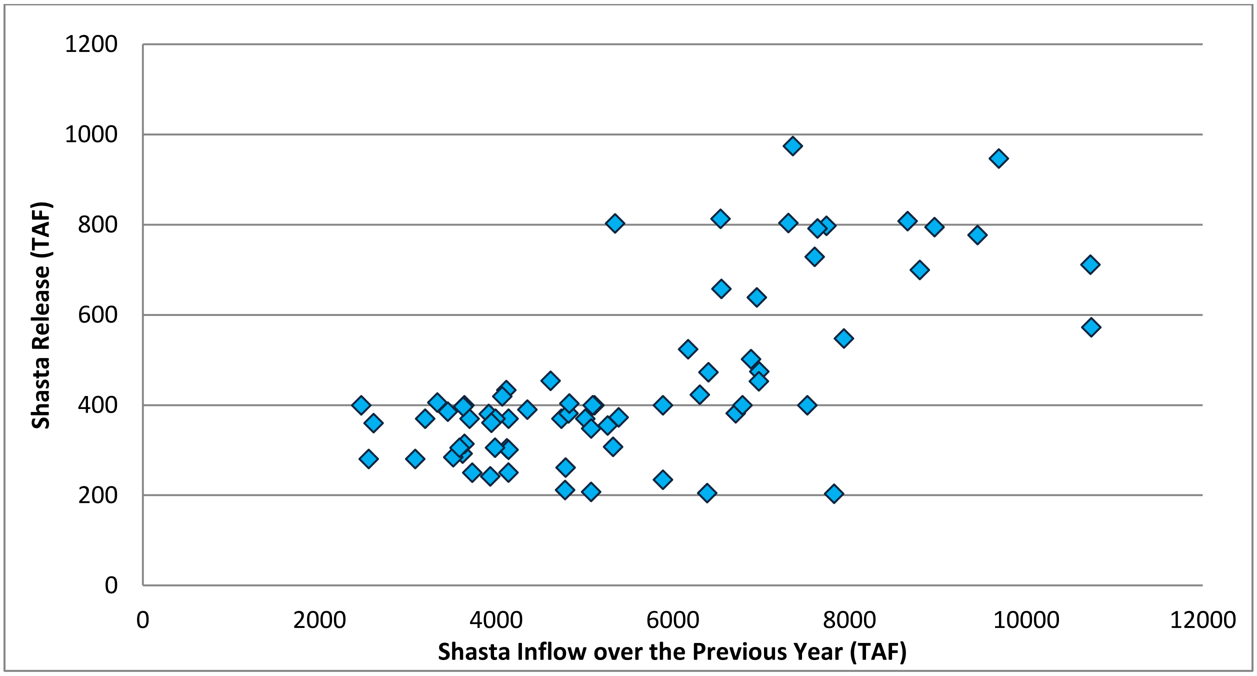
Shasta - August: If (IOPY) < 5625 TAF release = .12*(IOPY)+124, else release the target of 800 TAF.

Figure C-8: August Shasta Release vs. Shasta Inflow over the Previous Year (IOPY)



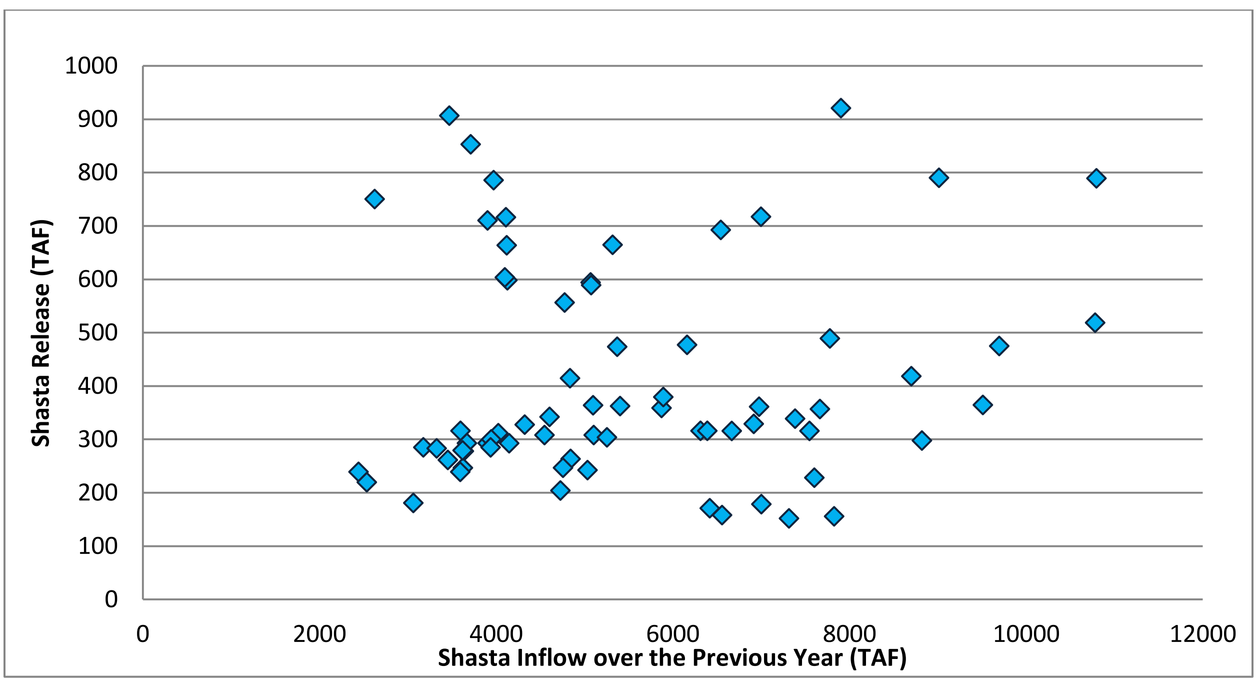
Shasta - September: If 6000 < (IOPY) < 7300 TAF then release = .28*(IOPY) - 1236, else release the target. If (IOPY) > 7300 then target = 800, else the target = 355

Figure C-9: September Shasta Release vs. Shasta Inflow over the Previous Year (IOPY)



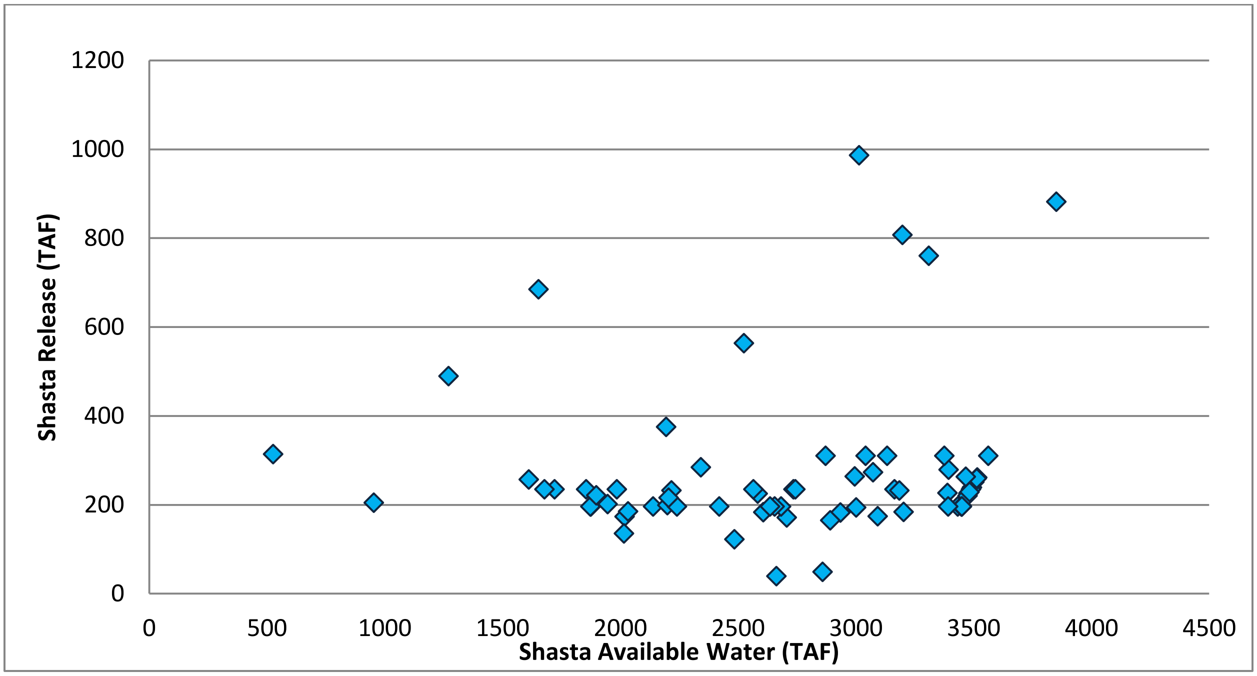
Shasta - October: If (IOPY) < 5023 TAF then release = .05*(IOPY)+89, else release the target of 350 TAF.

Figure C-10: October Shasta Release vs. Shasta Inflow over the Previous Year (IOPY)



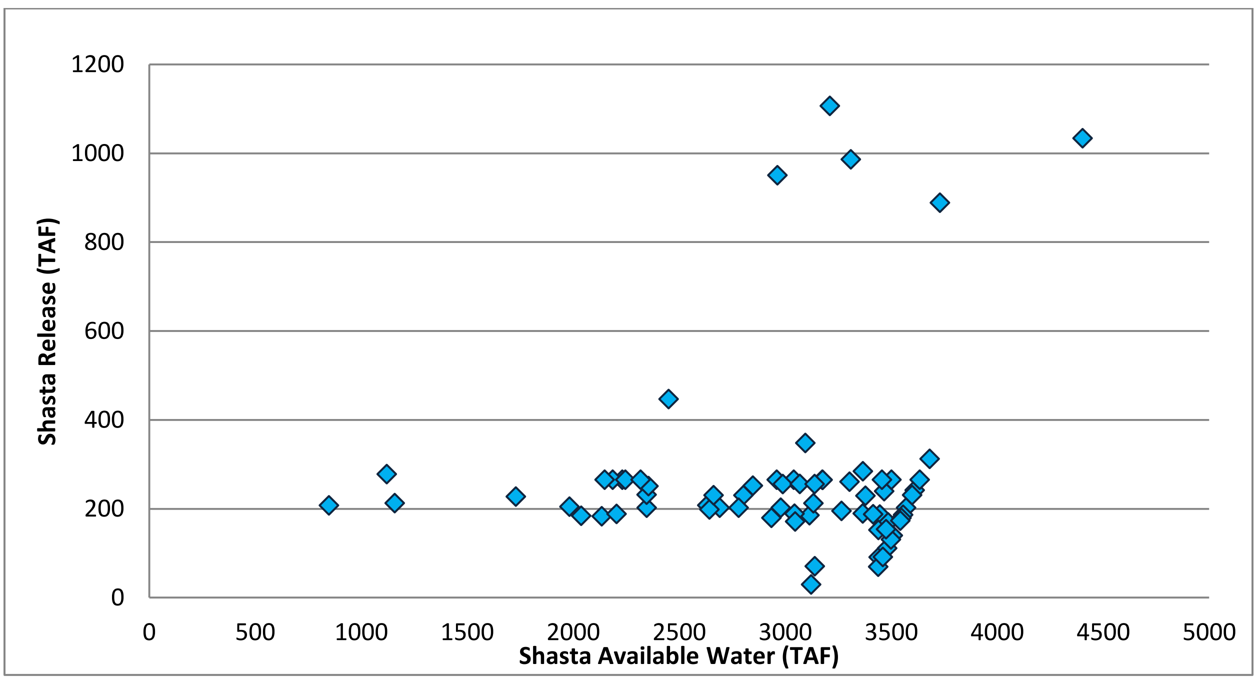
Shasta - November: Release target of 230 TAF.

Figure C-11: November Shasta Release vs. Shasta Available Water (Storage + Inflow)



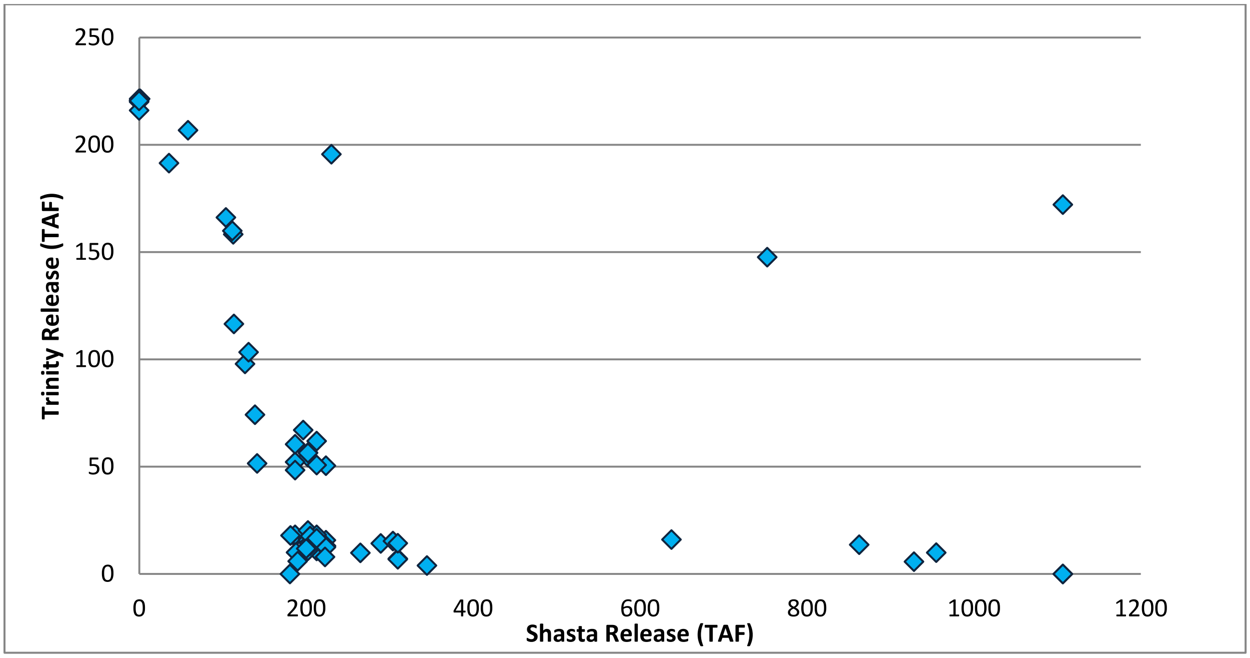
Shasta - December: Release target of 230 TAF.

Figure C-12: December Shasta Release vs. Shasta Available Water (Storage + Inflow)



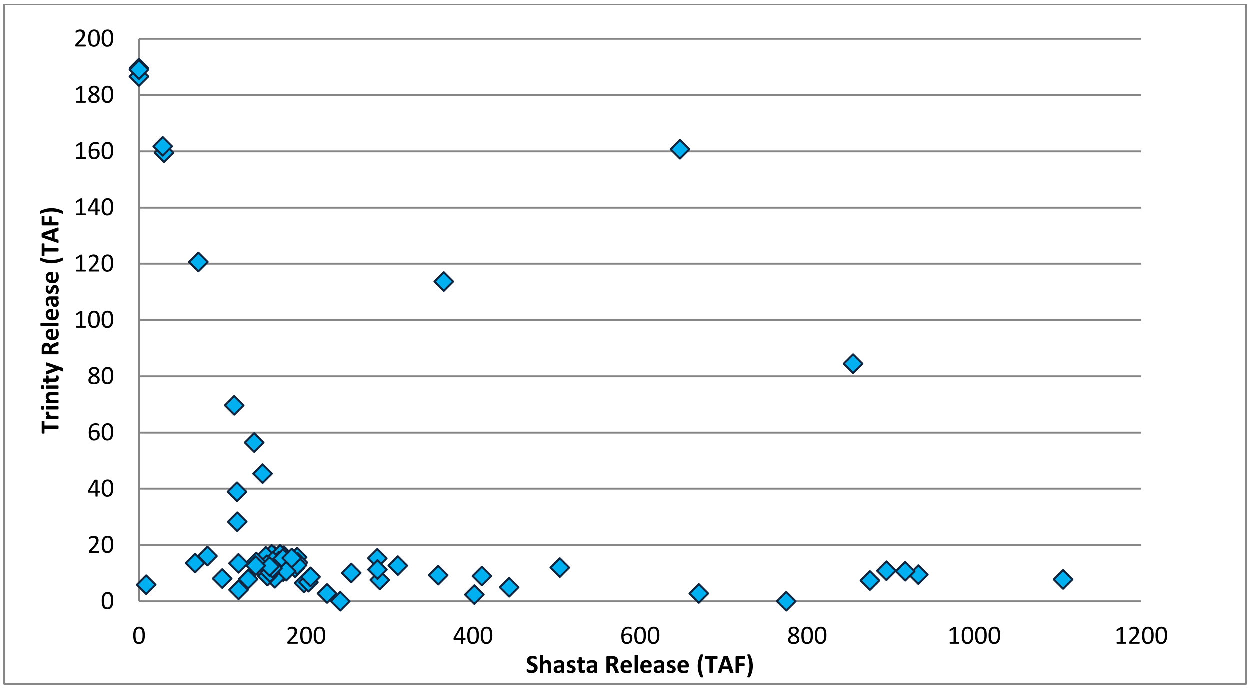
Trinity - January: If Shasta release (SR) < 209 TAF then release = -1.02*(SR)+230), else release the target of 15 TAF.

Figure C-13: January Trinity Release vs. Shasta Release



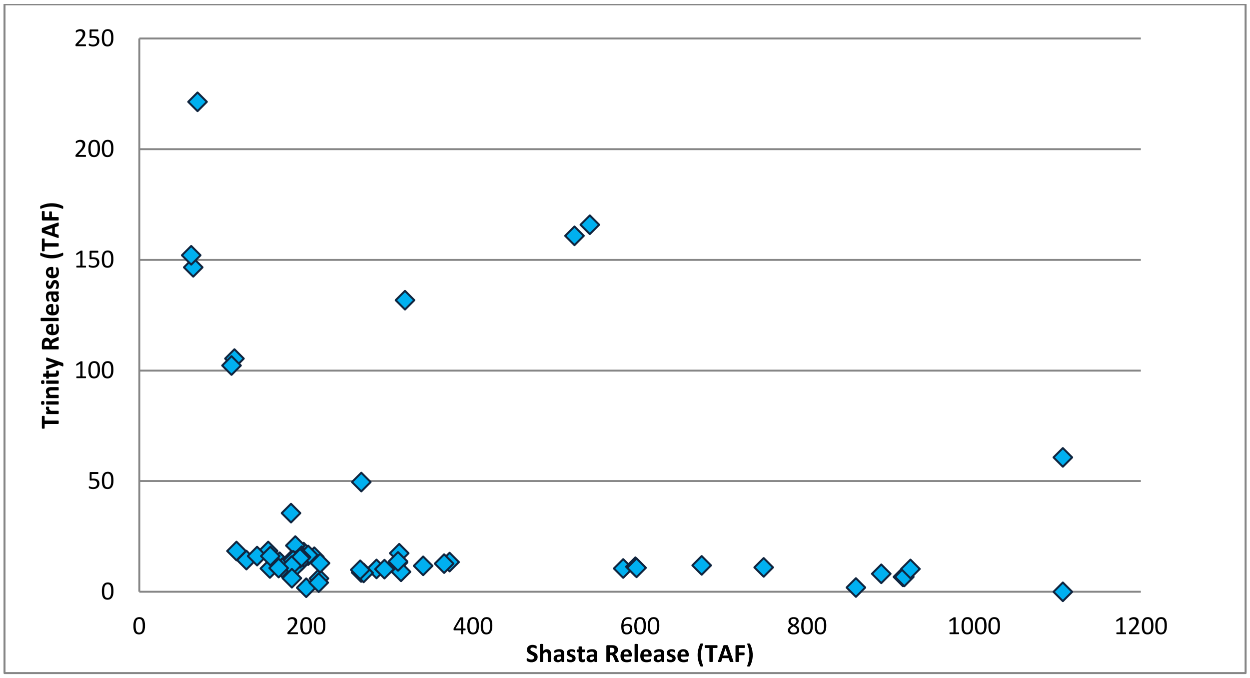
Trinity - February: If Shasta release (SR)< 154 TAF then release = -.81*(SR)+140), else release the target of 15 TAF.

Figure C-14: February Trinity Release vs. Shasta Release



Trinity - March: If Shasta release (SR)< 173 TAF then release = -1.22*(SR)+226), else release the target of 15 TAF.

Figure C-15: March Trinity Release vs. Shasta Release



Trinity - April: If Shasta release (SR)< 350 TAF, then release = -.93*(SR)+338), else release the target. If Shasta inflow (SI)< 700 TAF then the target = 230 TAF, else the target = 15 TAF.

Figure C-16: April Trinity Release vs. Shasta Release

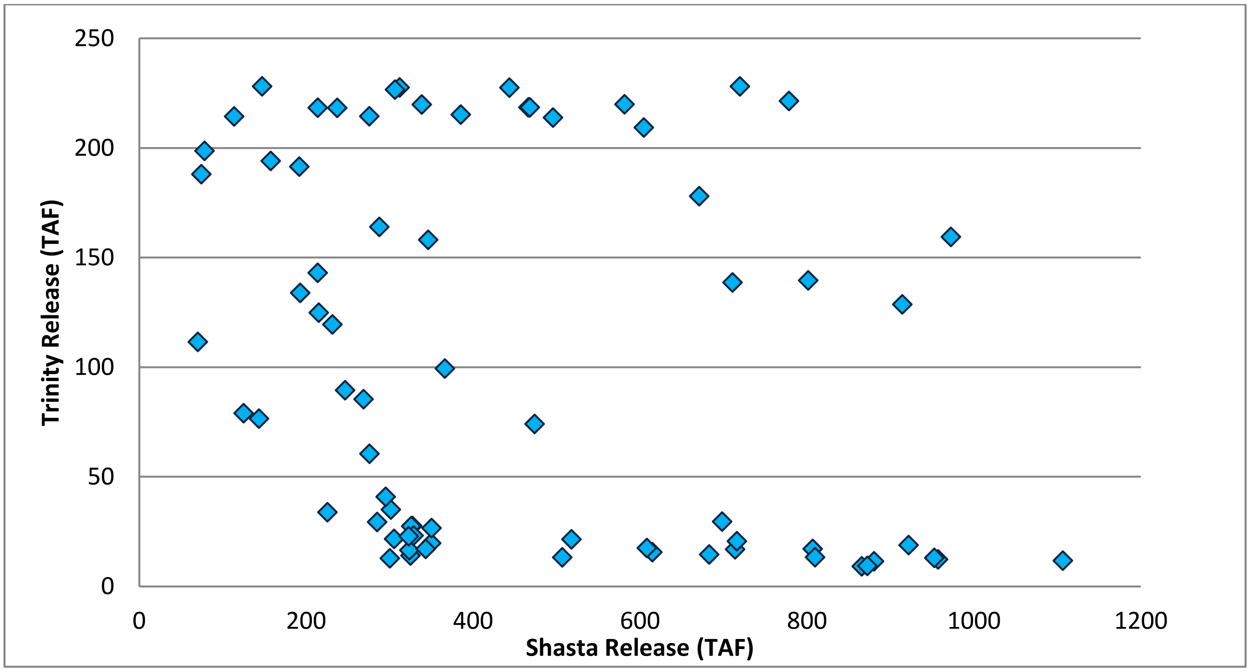
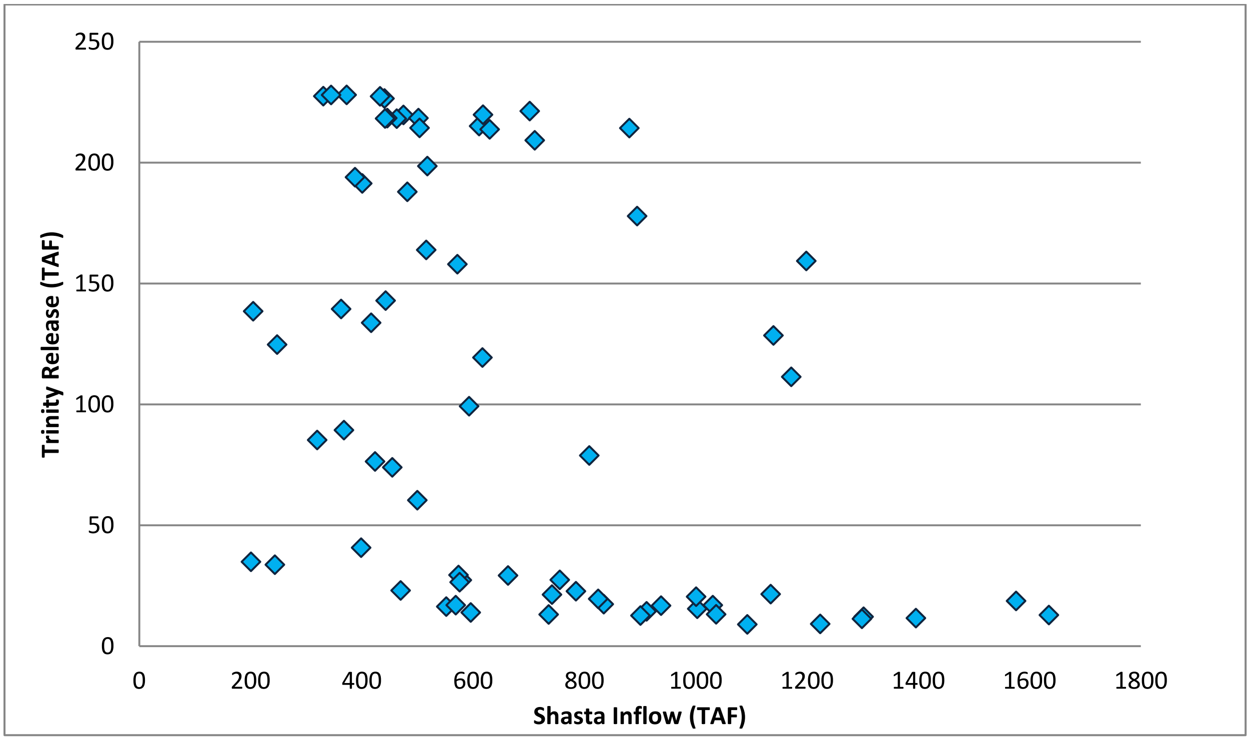
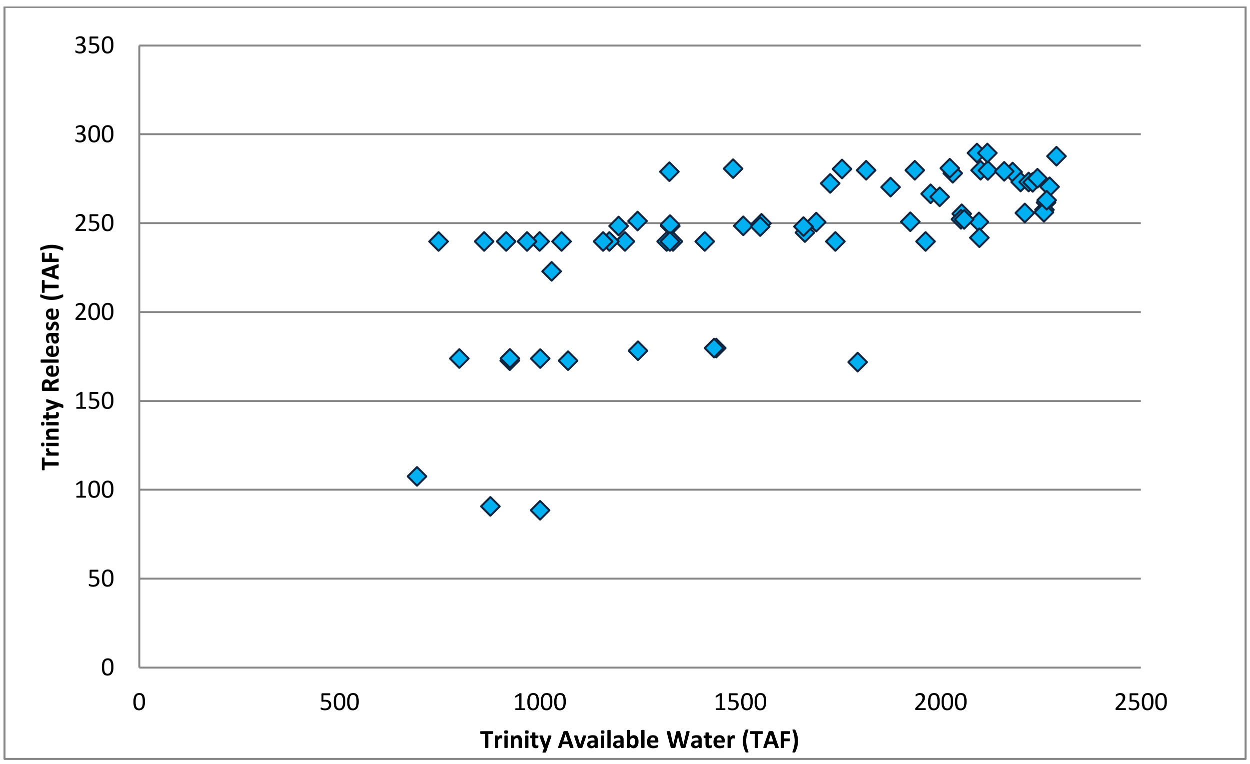


Figure C-17: April Trinity Release vs. Shasta Inflow



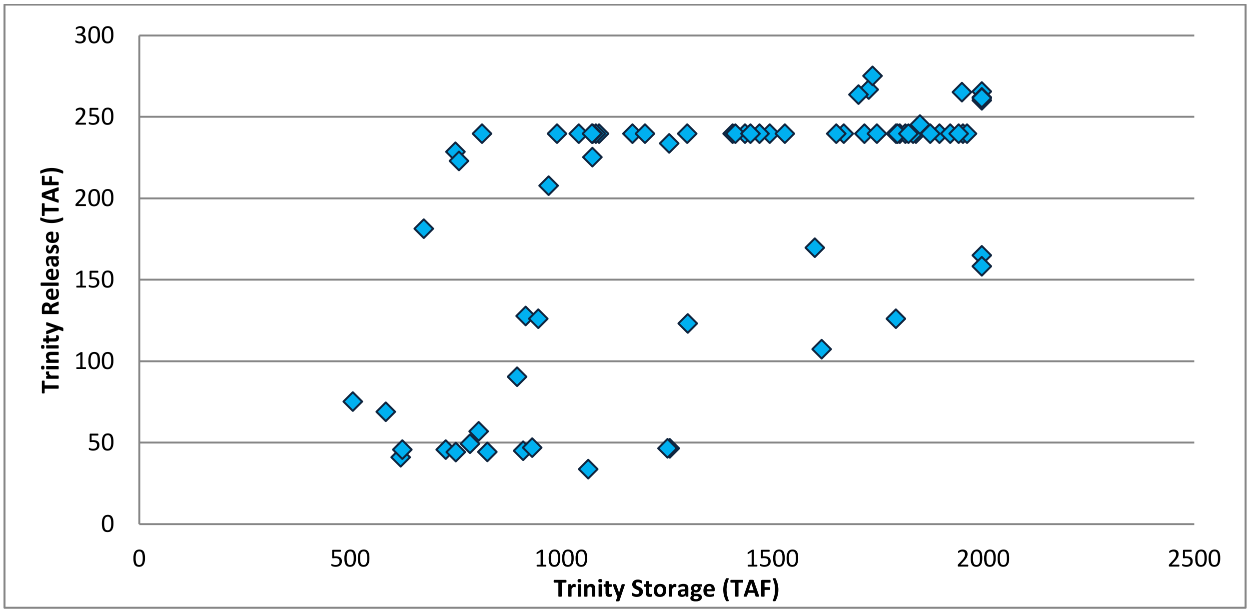
Trinity - May: Release target of 250 TAF.

Figure C-18: May Trinity Release vs. Trinity Available Water (Storage + Inflow)



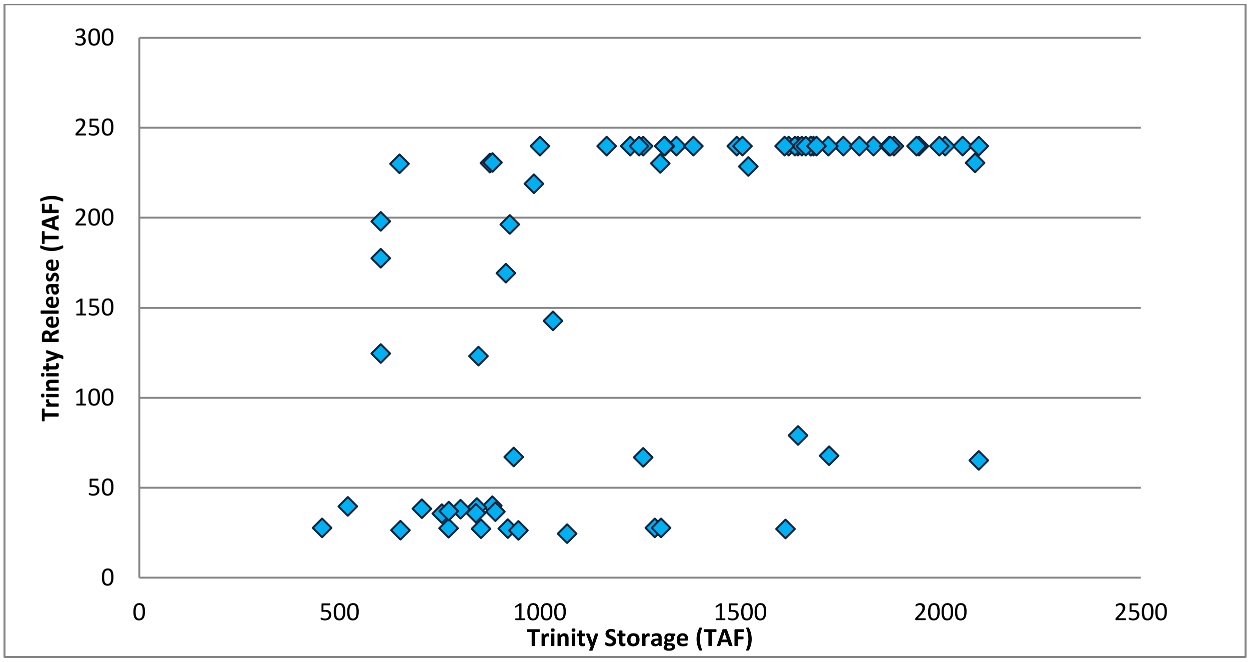
Trinity - June: If 720 <= Trinity storage (TS) < 1160 TAF then release = .62*(TS)-441, else release the target. If Trinity Storage (TS) < 720 TAF then the target = 45 TAF, else the target = 240 TAF.

Figure C-19: June Trinity Release vs. Trinity Storage



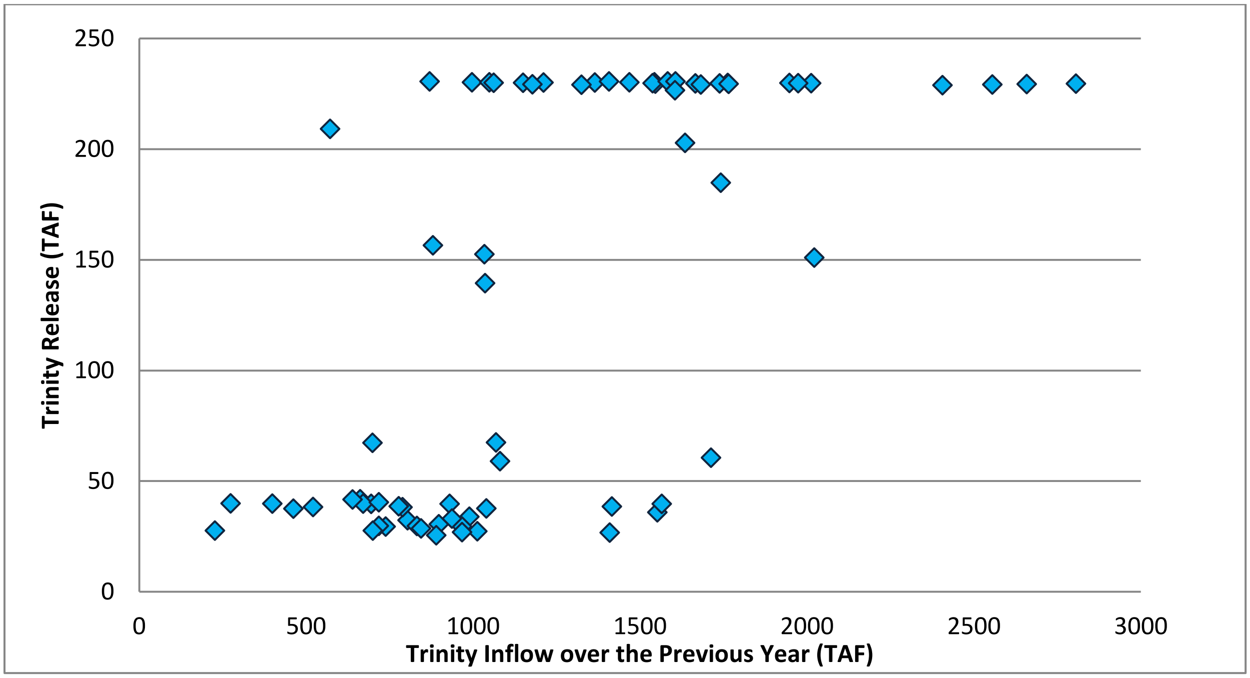
Trinity - July: If 800 < Trinity storage (TS) < 1000 TAF then release = 1.11*(TS)-858, else release the target. If Trinity storage (TS) < 800 TAF then the target = 32 TAF, else the target = 240 TAF.

Figure C-20: July Trinity Release vs. Trinity Storage



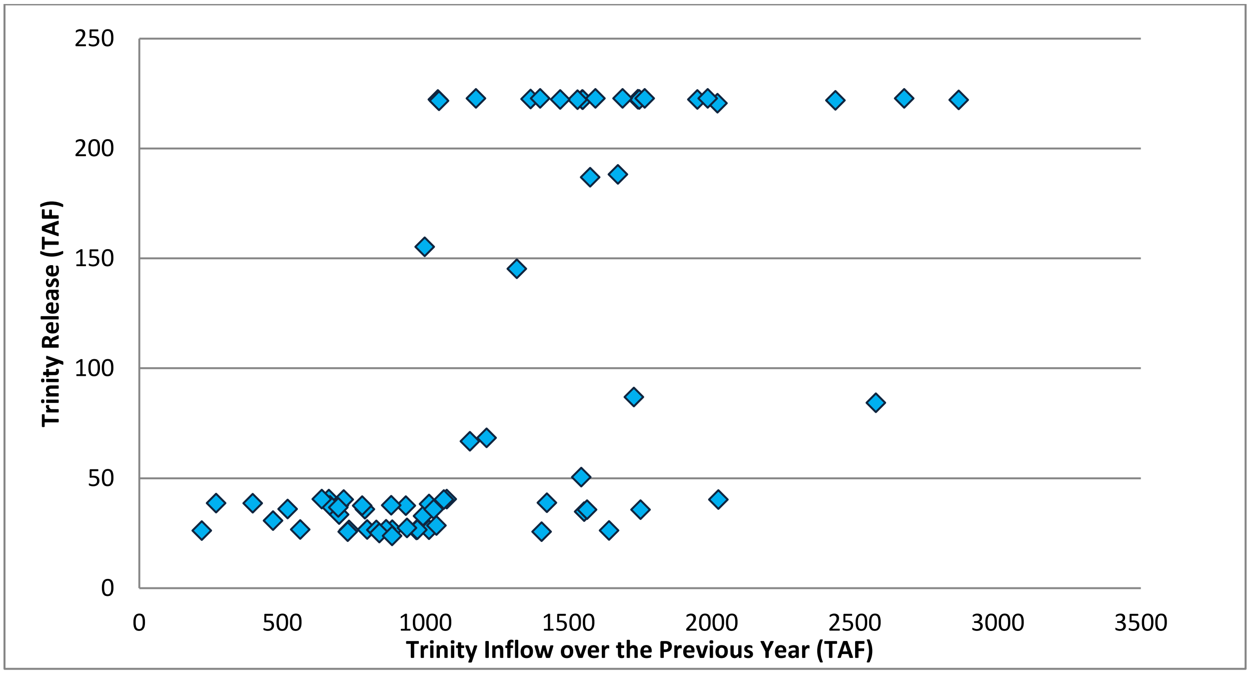
Trinity - August: Release the target. If (IOPY) < 1000 TAF then the target = 40 TAF, else the target = 230 TAF.

Figure C-21: August Trinity Release vs. Trinity Inflow over the Previous Year



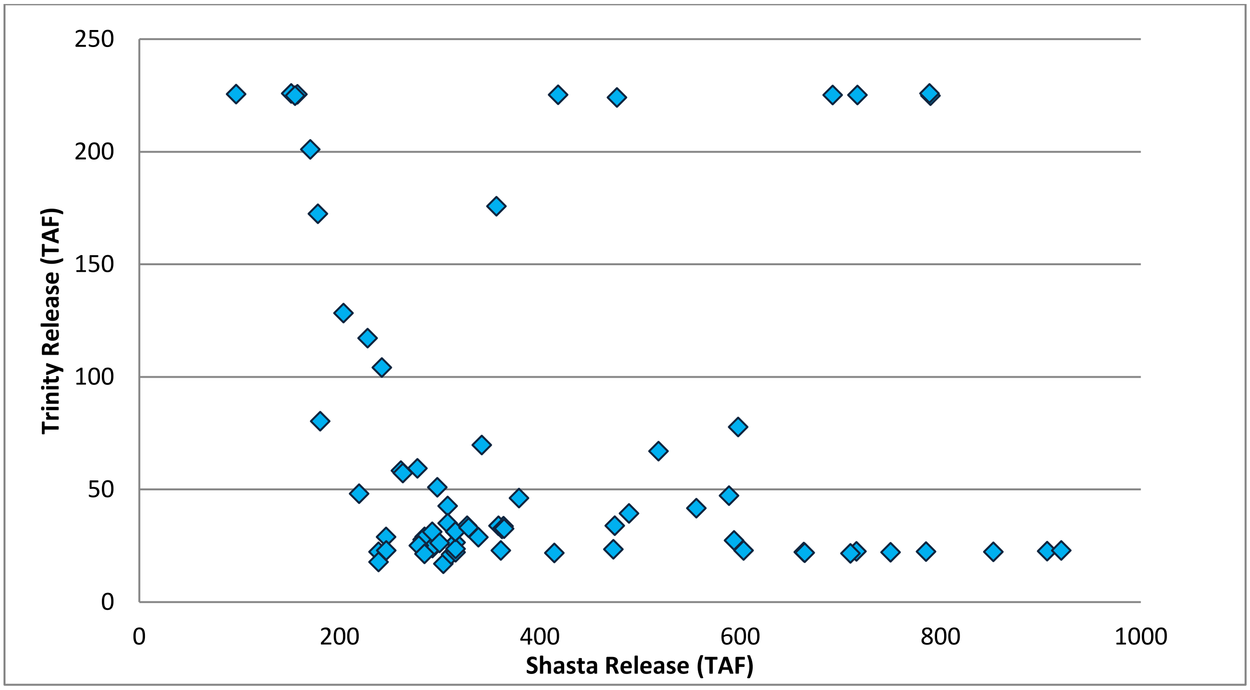
Trinity - September: Release the target. If (IOPY) < 1050 TAF then the target = 35 TAF, else the target = 220 TAF.

Figure C-22: September Trinity Release vs. Trinity Inflow over the Previous Year



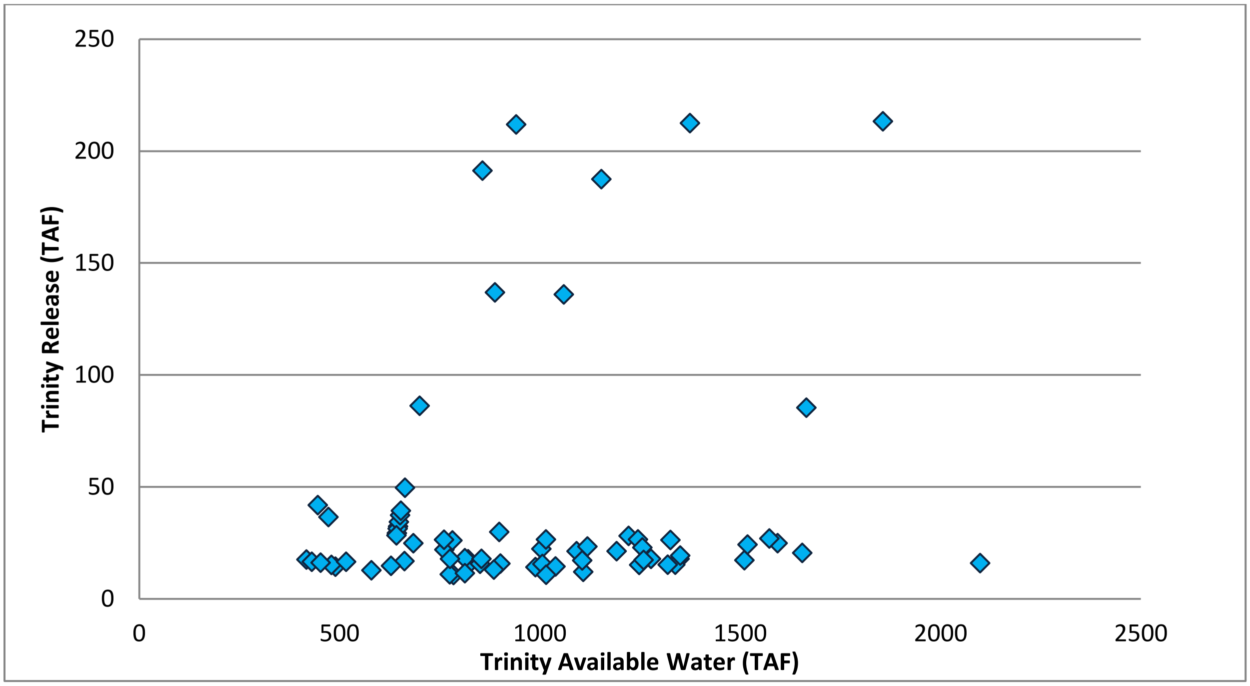
Trinity - October: If Shasta release (SR)< 292 TAF then release = -1.06*(SR)+340, else release the target of 30 TAF.

Figure C-23: October Trinity Release vs. Shasta Release



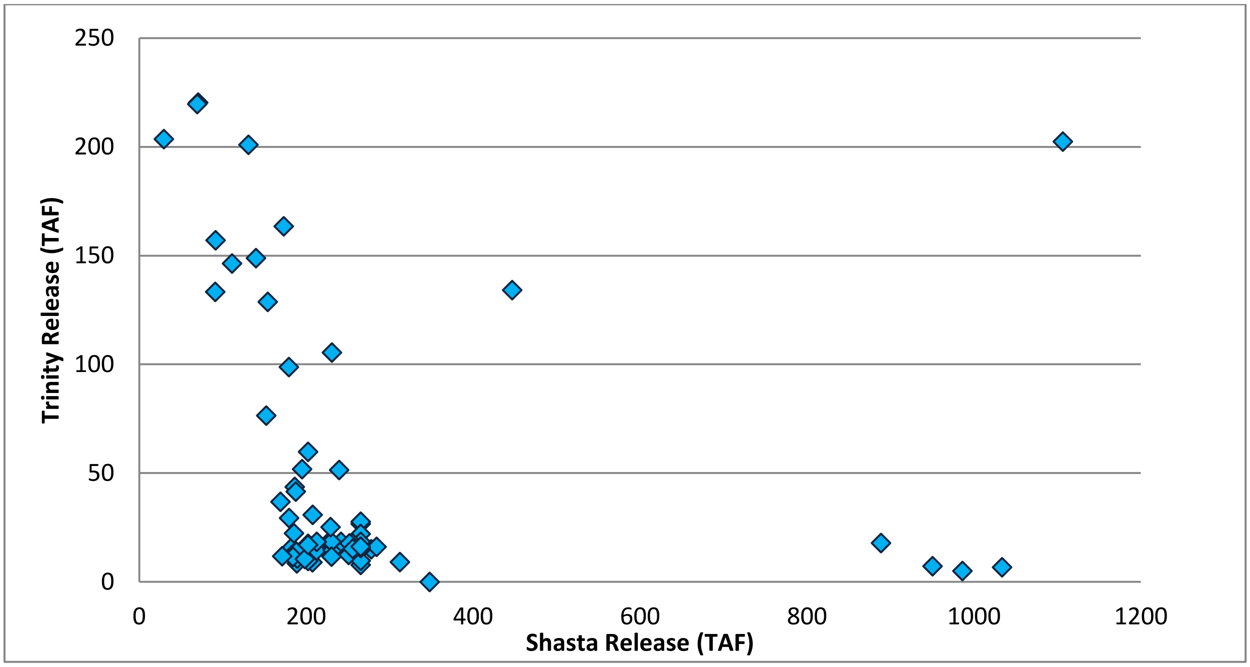
Trinity - November: Release target of 20 TAF.

Figure C-24: November Trinity Release vs. Trinity Available Water (Storage + Inflow)



Trinity - December: If Shasta release (SR)< 200 TAF then release = -1.34*(SR)+293, else release the target of 20 TAF.

Figure C-25: December Trinity Release vs. Shasta Release



Oroville - January: If (AW) > 3100 TAF then release = 1.28*(AW)-3870, else release the target. If Oroville Storage (AW)<2300 TAF and (IOPY)<3000 TAF then the target = 0 TAF, else if (AW)>=2300 TAF and (IOPY)<3000 TAF then the target = 39 TAF, else if the (IOPY) >= 3000 TAF then the target = 95 TAF.

Figure C-26: January Oroville Release vs. Oroville Available Water (Storage + Inflow)

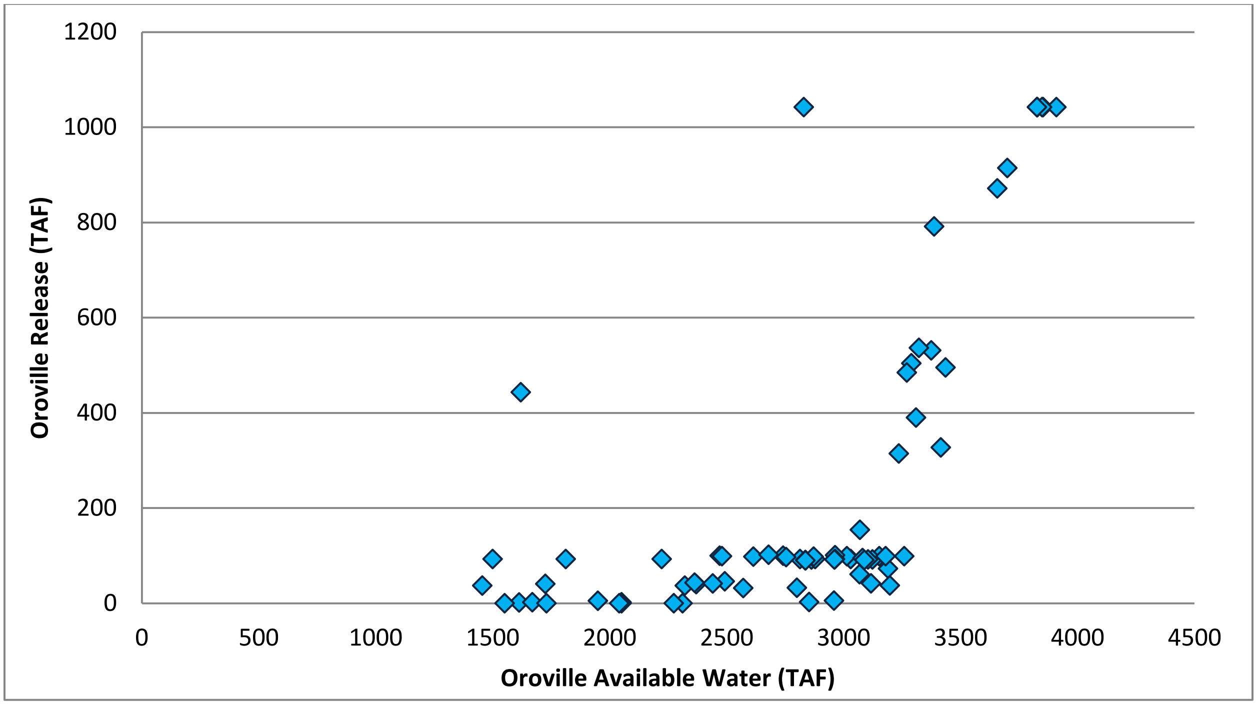
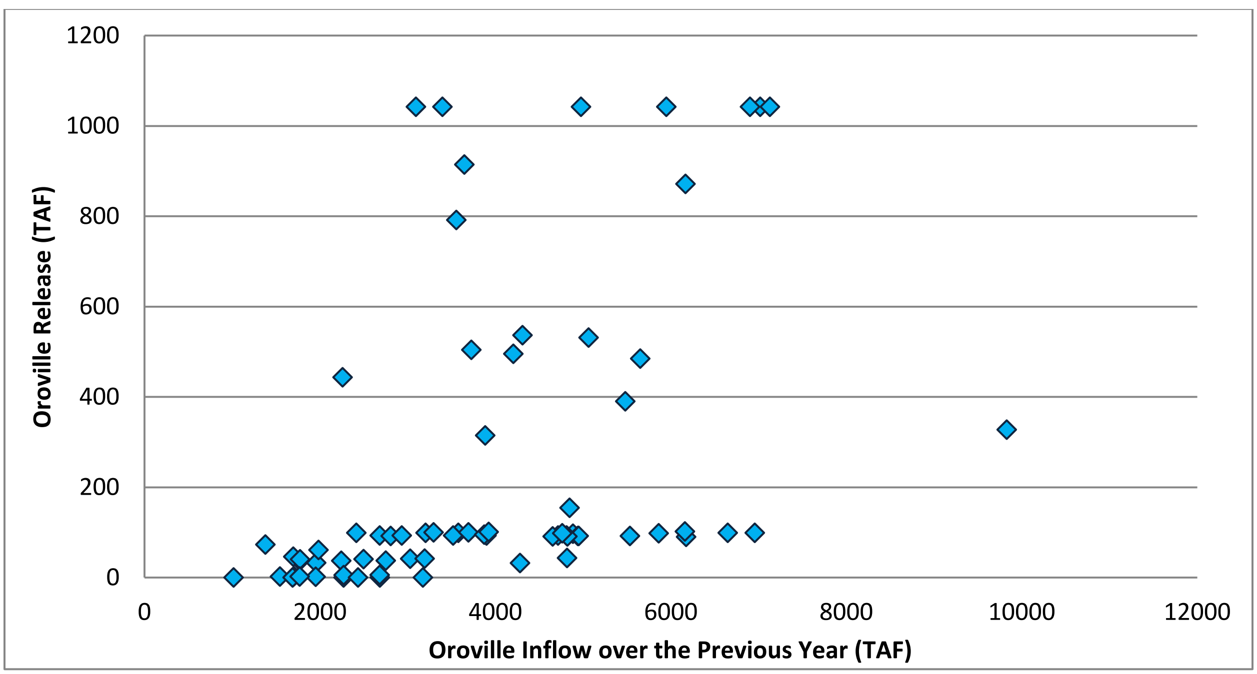


Figure C-27: January Oroville Release vs. Oroville Inflow over the Previous Year



Oroville - February: If (AW) > 3150 TAF then release = 1.41*(AW)-4338, else release the target. If (IOPY) < 2700 TAF then the target = 20 TAF, else the target = 90 TAF.

Figure C-28: February Oroville Release vs. Oroville Available Water (Storage + Inflow)

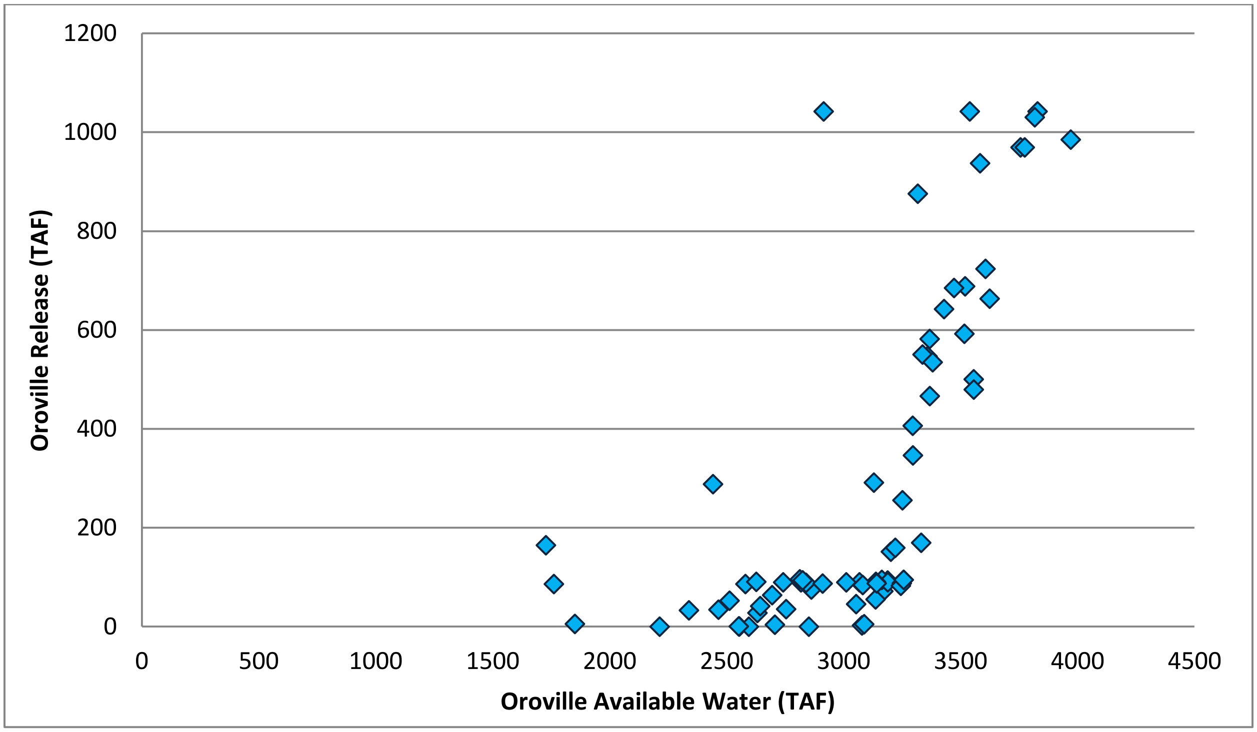
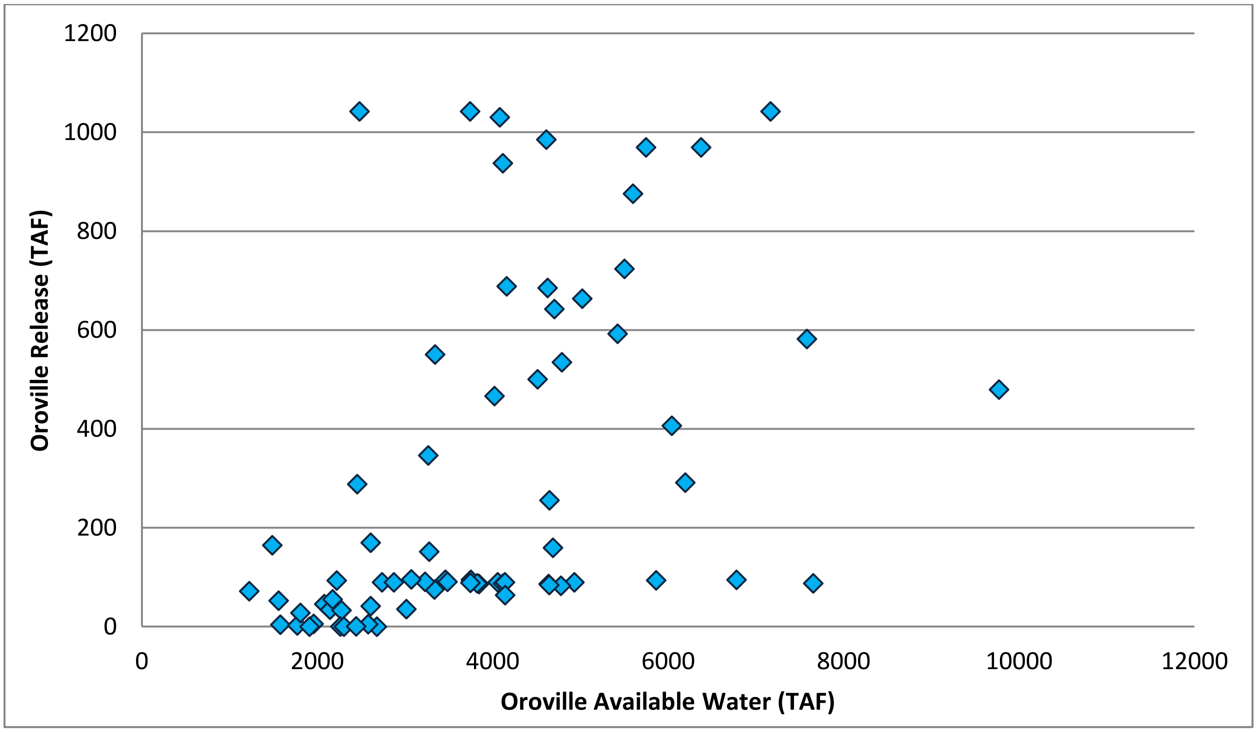


Figure C-29: February Oroville Release vs. Oroville Inflow over the Previous Year



Oroville - March: If (AW) > 3200 TAF then release = 1.39*(AW)-4375, else release the target. If (IOPY) < 2625 TAF then the target =12 TAF, else the target = 94 TAF.

Figure C-30: March Oroville Release vs. Oroville Available Water (Storage + Inflow)

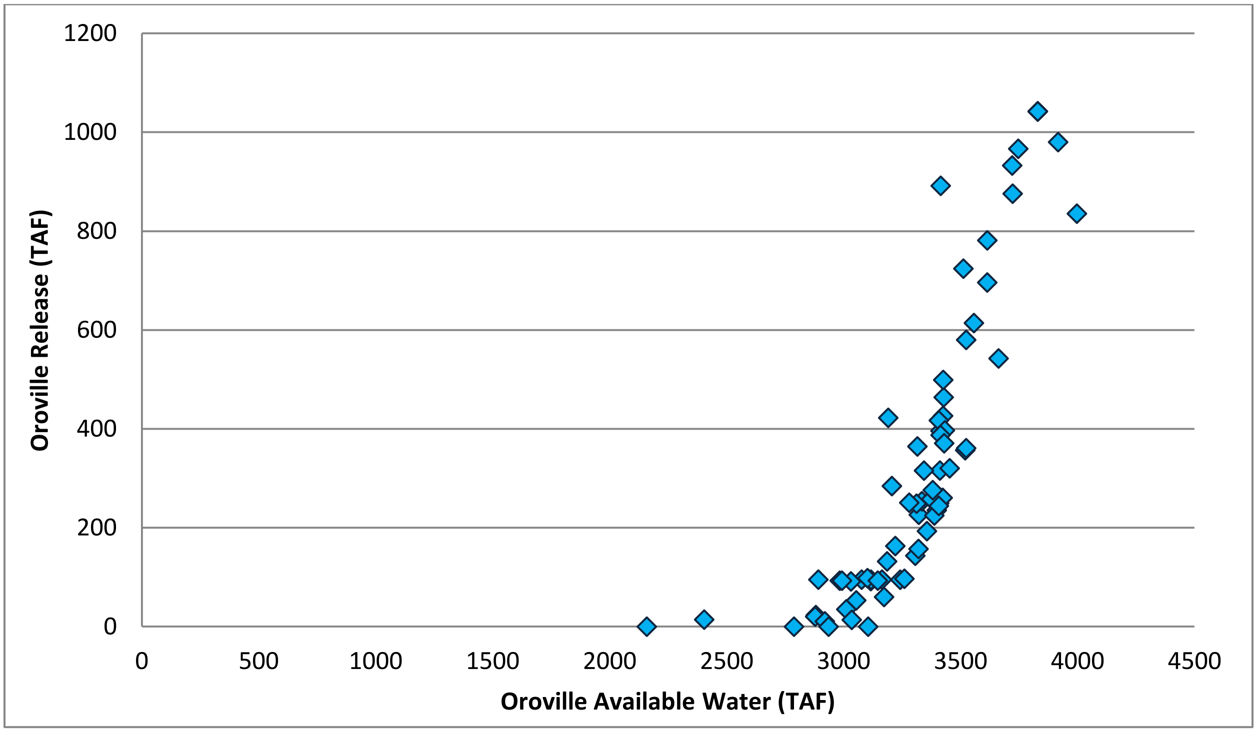
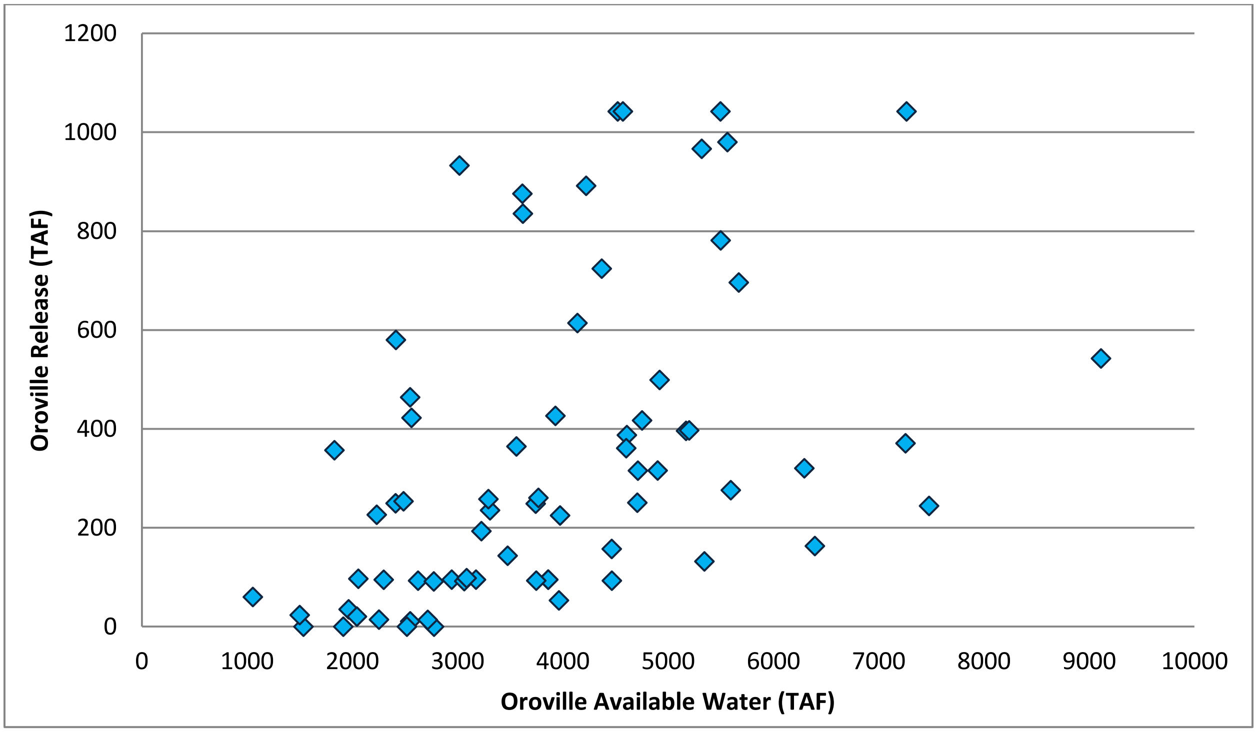
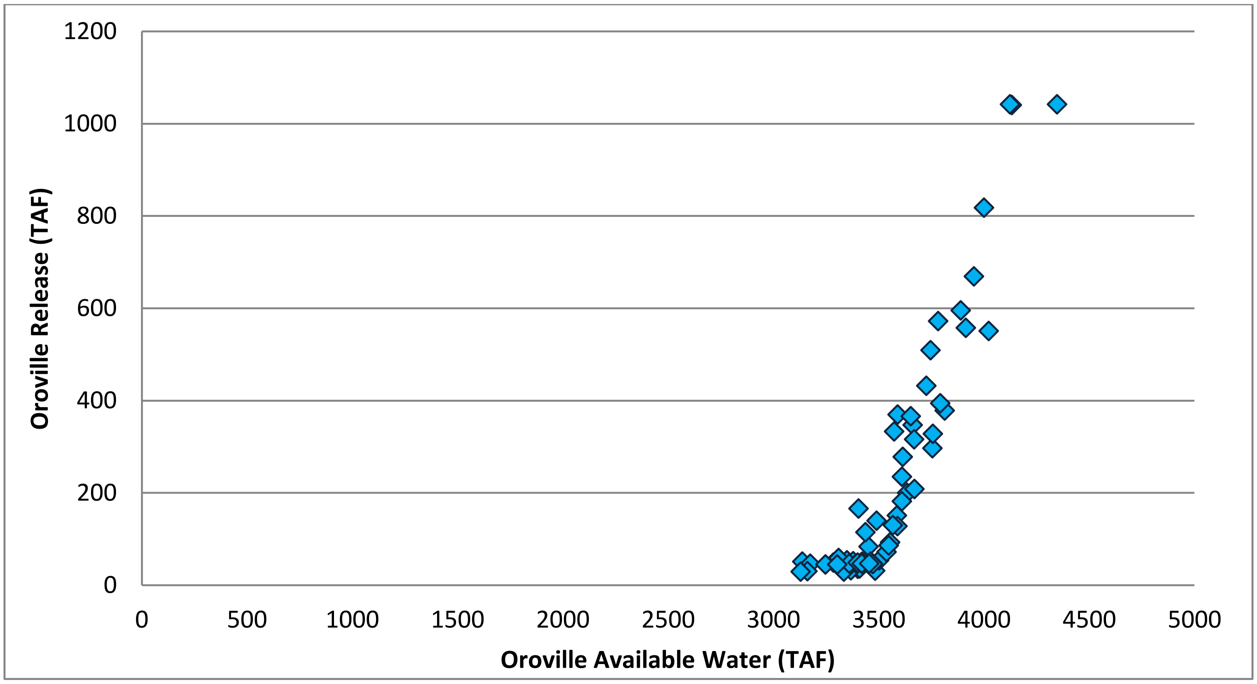


Figure C-31: March Oroville Release vs. Oroville Inflow over the Previous Year



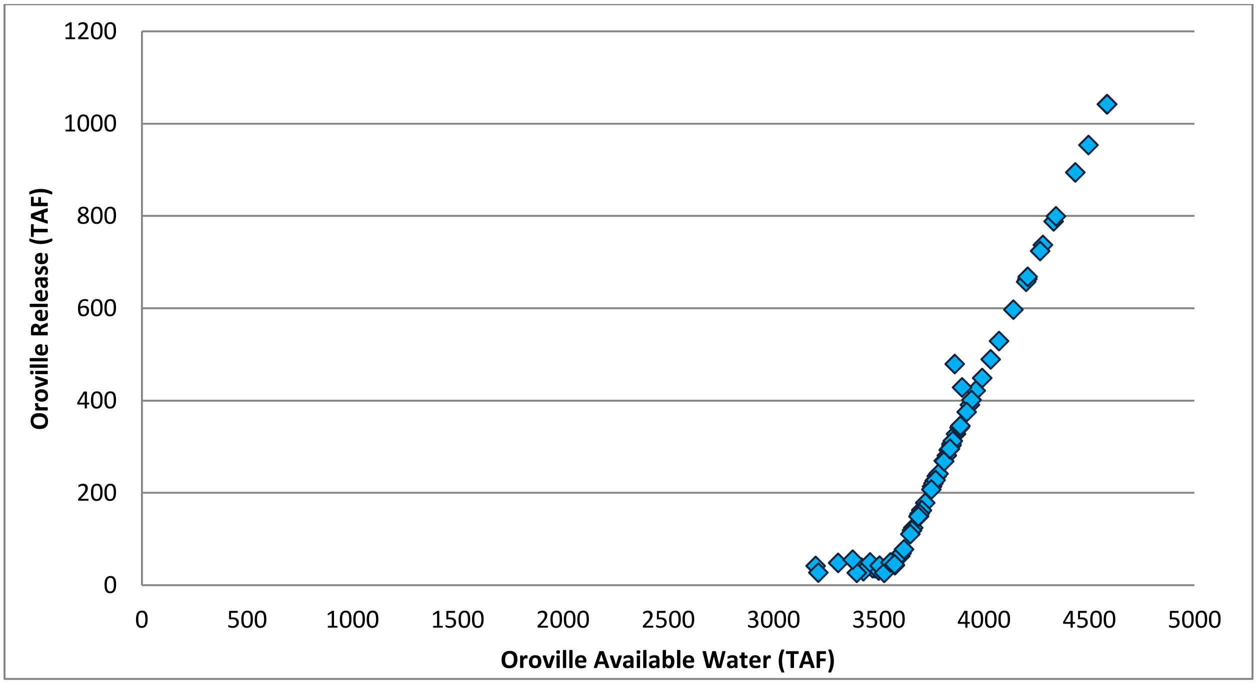
Oroville - April: If (AW) > 3470 TAF then release = 1.29*(AW)-4425, else release the target of 44 TAF.

Figure C-32: April Oroville Release vs. Oroville Available Water (Storage + Inflow)



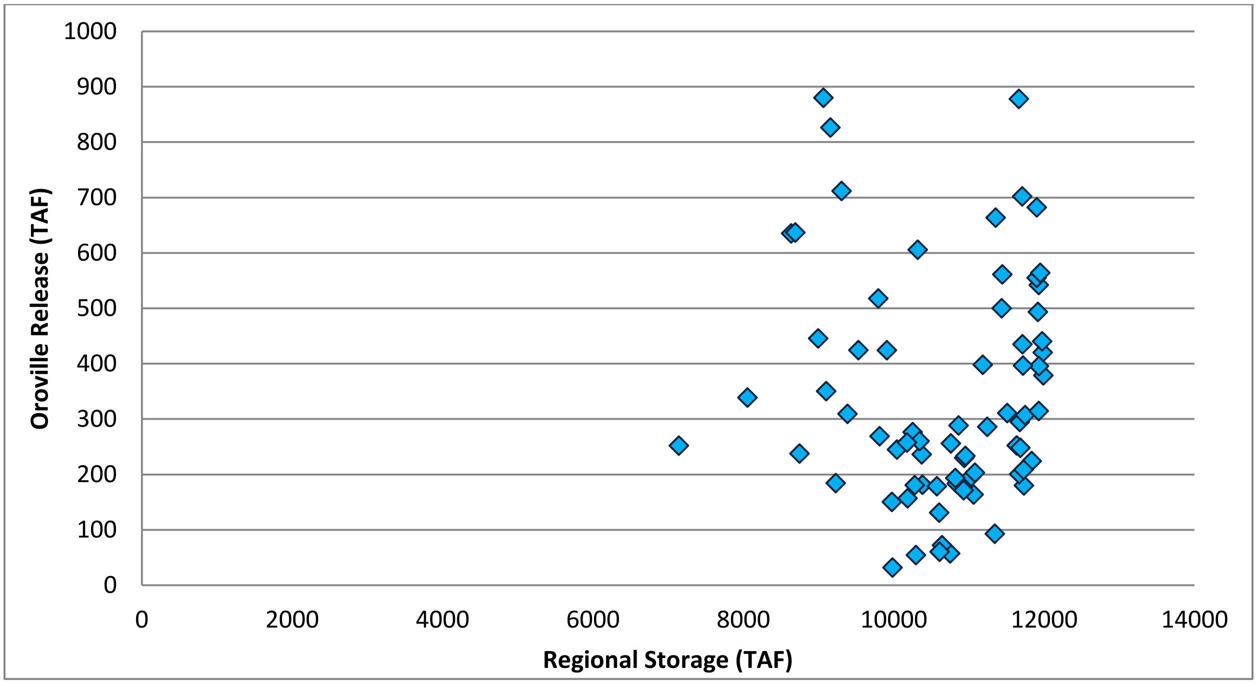
Oroville - May: Release the target of 39 TAF.

Figure C-33: May Oroville Release vs. Oroville Available Water (Storage + Inflow)



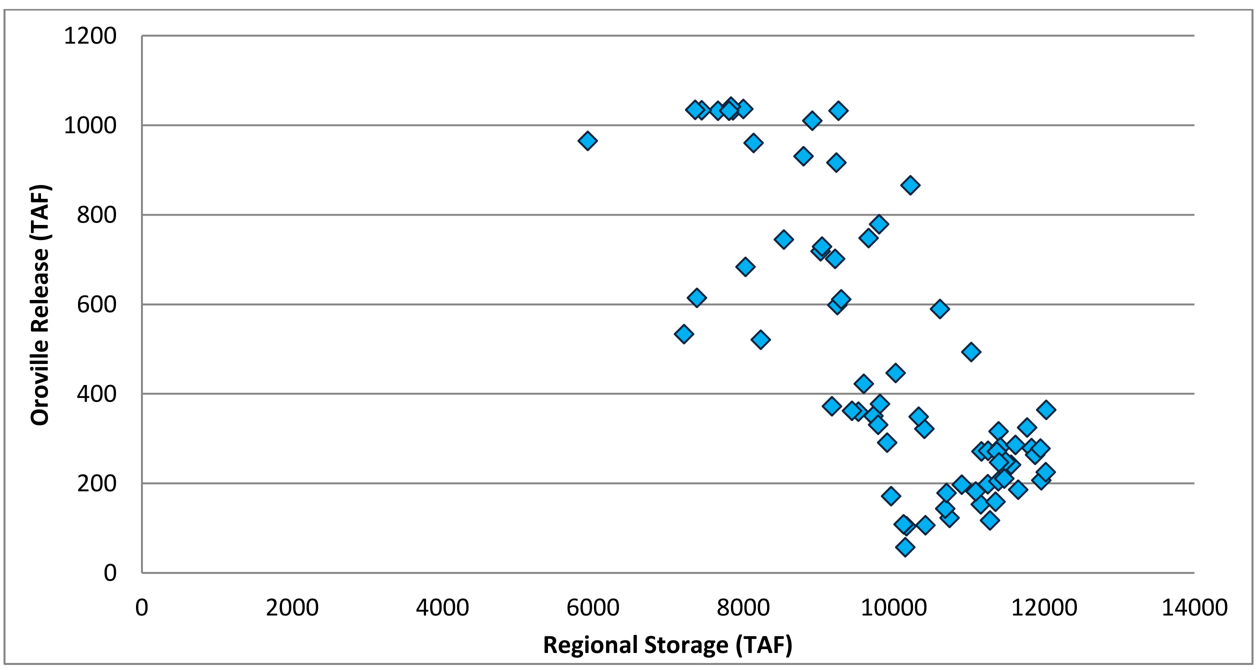
Oroville - June: If 8568 < (RS) < 10813 TAF then release = -.26*(RS)+2854, else release the target. If (RS) <= 8568 TAF then the target = 636 TAF, else the target = 55 TAF.

Figure C-34: June Oroville Release vs. Regional Storage



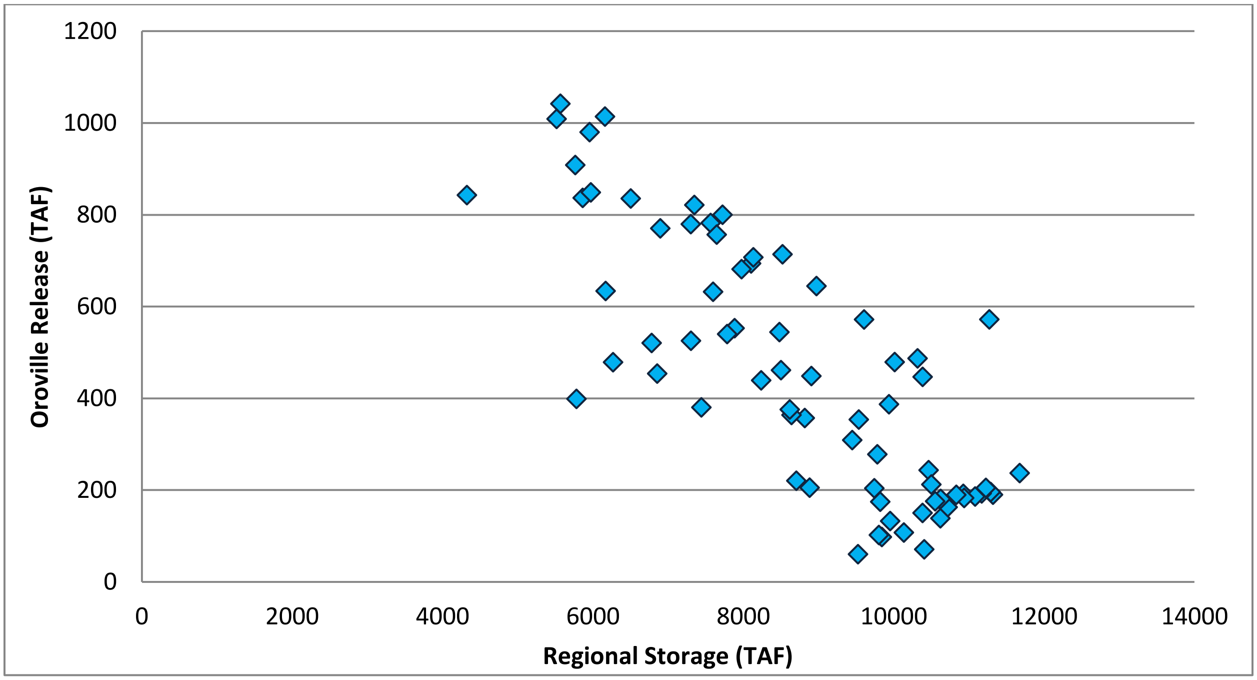
Oroville - July: If 8273 < (RS) < 10501 TAF then release = -.40*(RS) + 4370, else if (RS)>=10501 TAF then release = .1*(RS) - 940, else release the target of 1034 TAF.

Figure C-35: July Oroville Release vs. Regional Storage



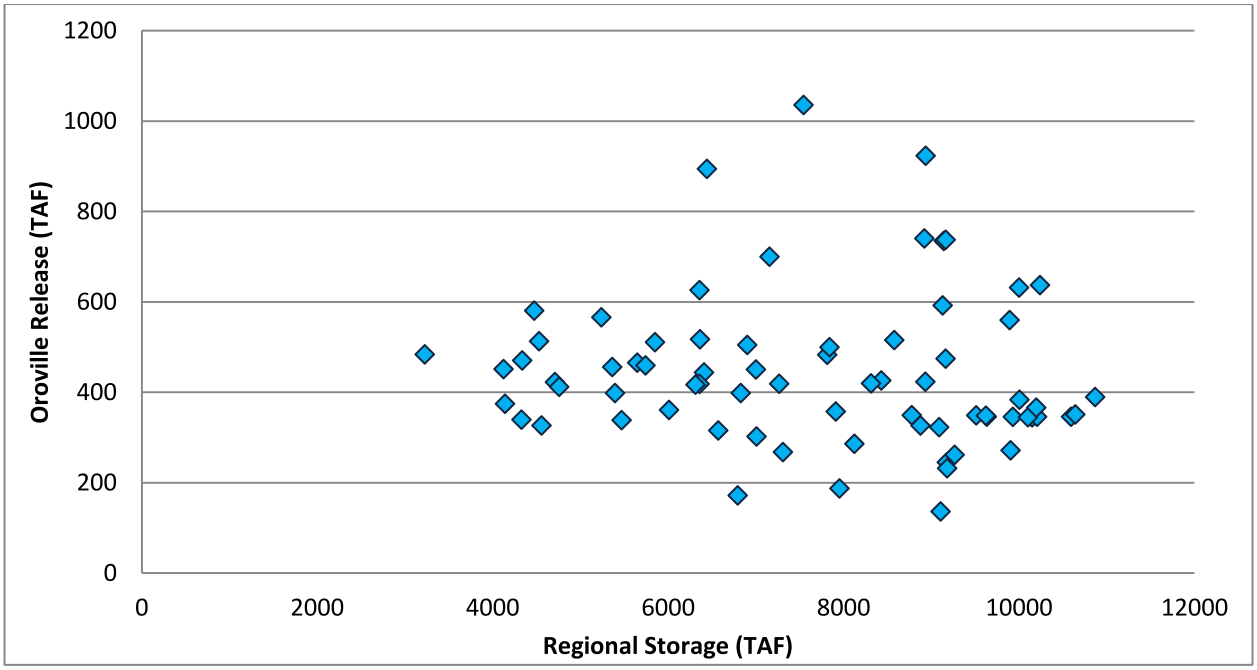
Oroville - August: If 4585 < (RS) < 9898 TAF then release = -.16*(RS) + 1719, else if (RS)>=9898 TAF then release = .06*(RS) +375, else release the target of 1034 TAF.

Figure C-36: August Oroville Release vs. Regional Storage



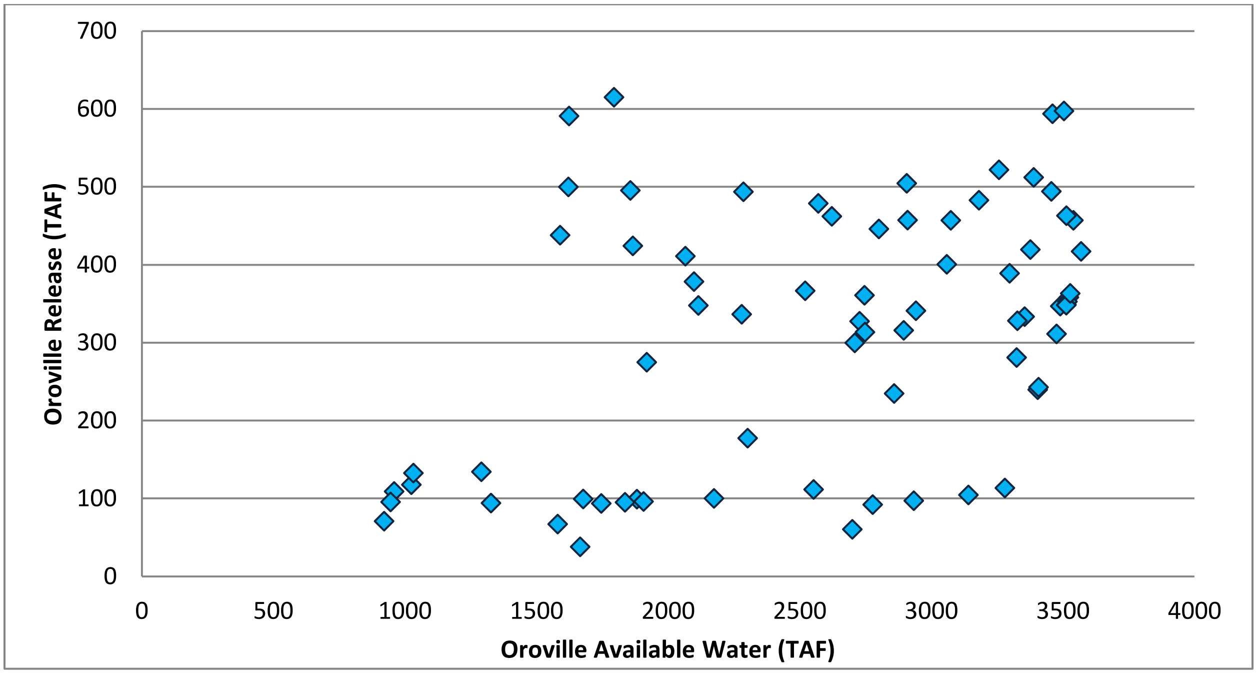
Oroville - September: Release the target. If (RS) < 8600 TAF then the target = 440 TAF, else the target = 350 TAF.

Figure C-37: September Oroville Release vs. Regional Storage



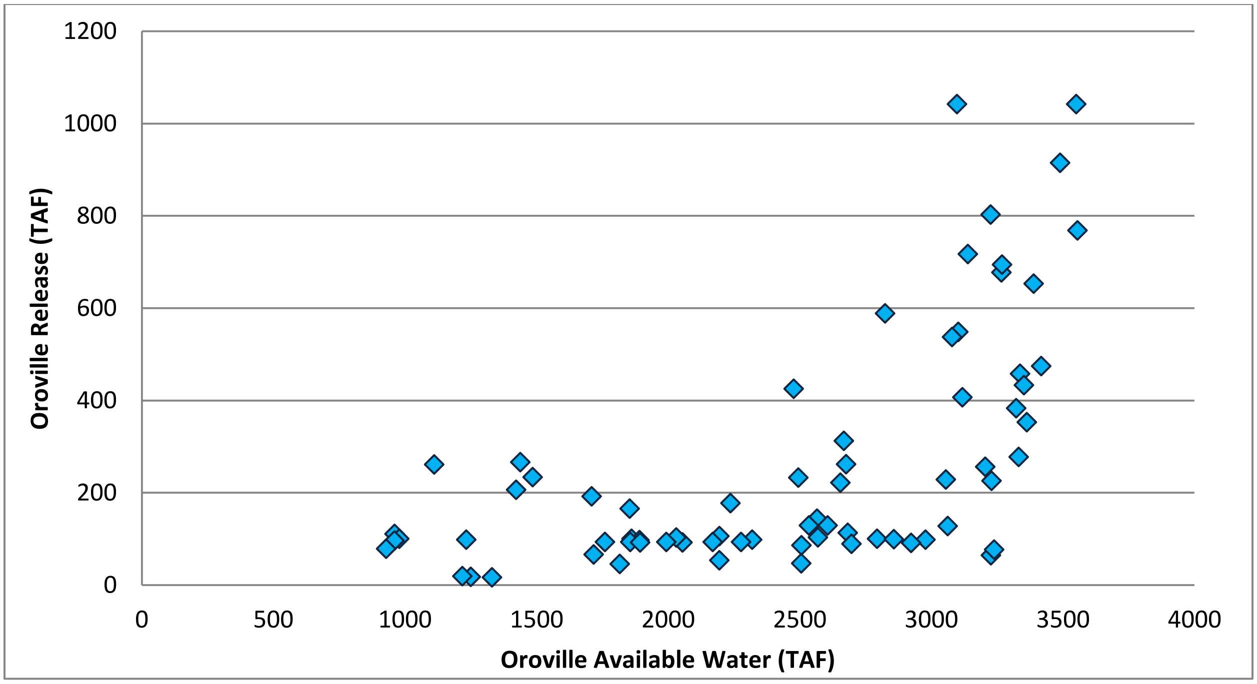
Oroville - October: Release the target. If (AW) < 2000 TAF then the target = 100 TAF, else the target = 400 TAF.

Figure C-38: October Oroville Release vs. Oroville Available Water (Storage + Inflow)



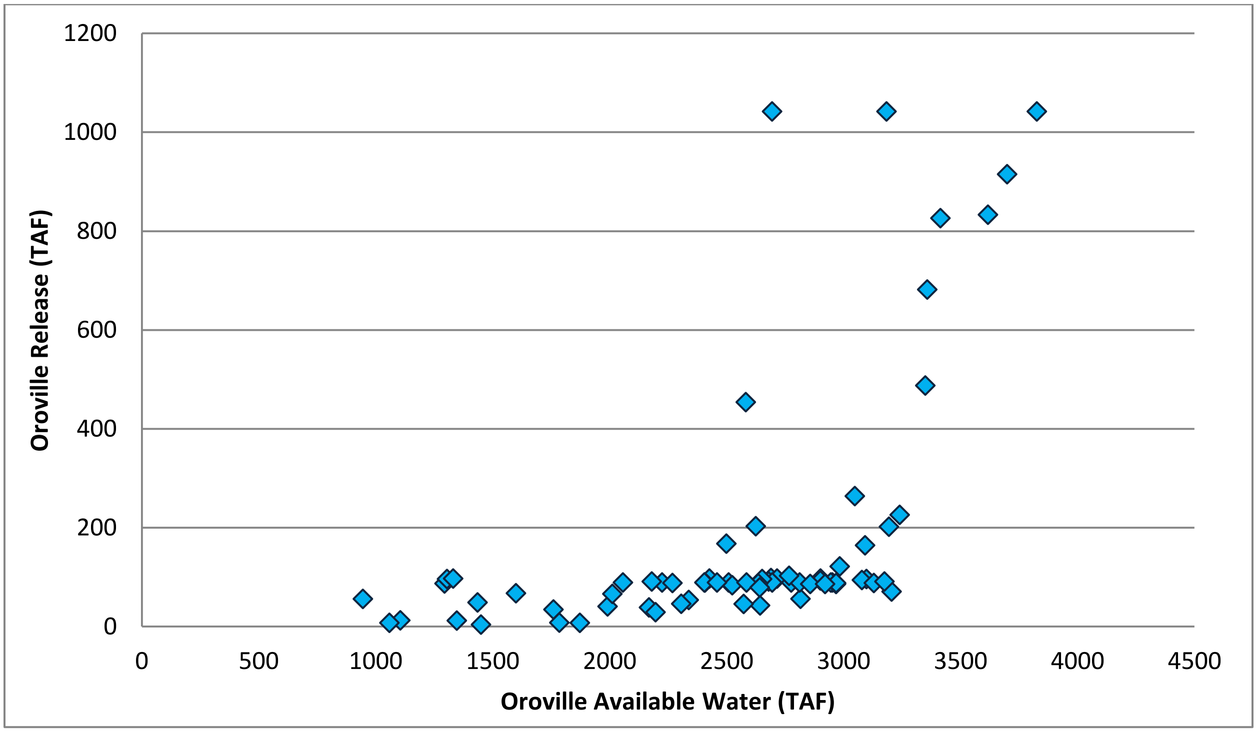
Oroville - November: If (AW) > 3200 TAF then release = 2.36*(AW) - 7472, else release the target of 99 TAF.

Figure C-39: November Oroville Release vs. Oroville Available Water (Storage + Inflow)



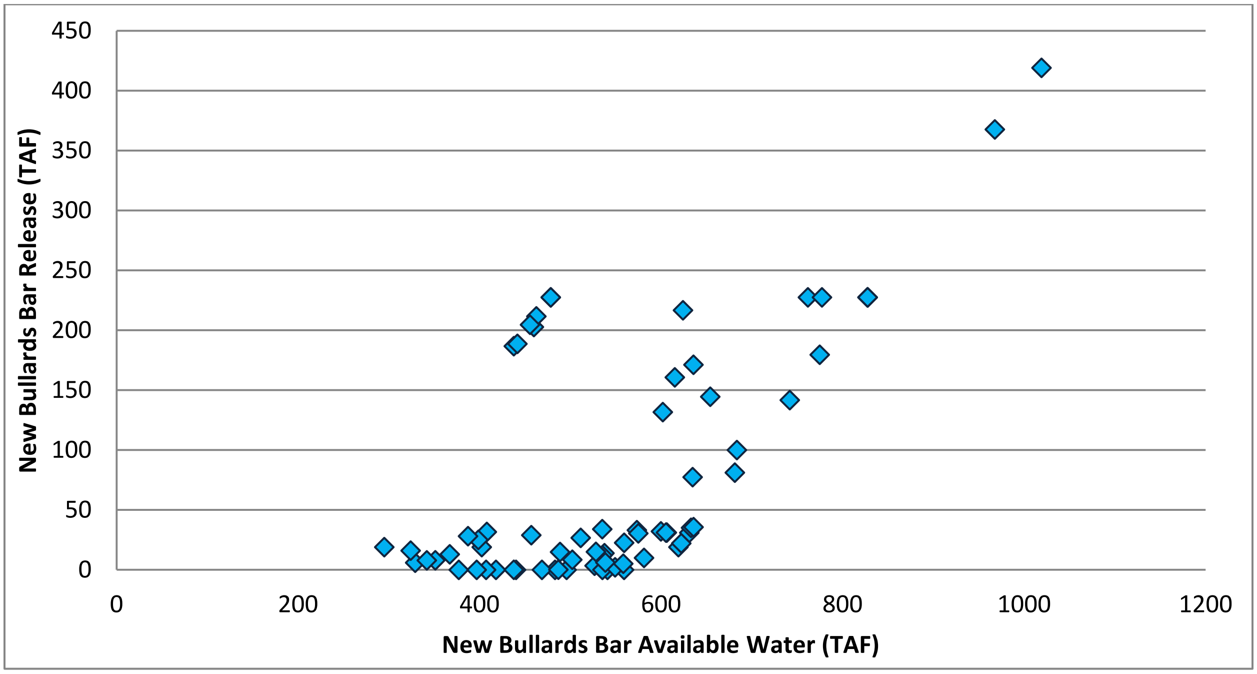
Oroville - December: If (AW) > 3110 TAF then release = 1.49*(AW) - 4532, else release the target of 91 TAF.

Figure C-40: December Oroville Release vs. Oroville Available Water (Storage + Inflow)



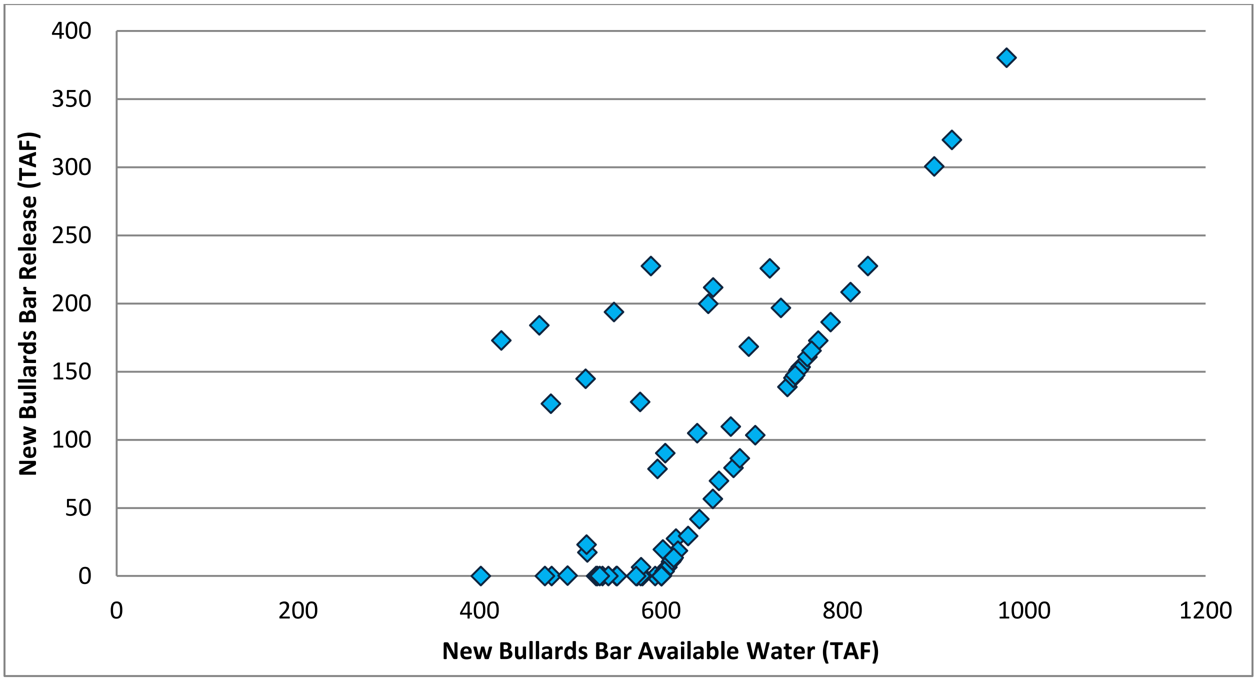
New Bullards Bar - January: If (AW) > 675 TAF then release = .94*(AW) - 538, else release the target of 11 TAF.

Figure C-41: January New Bullards Bar Release vs. Available Water (Storage + Inflow)



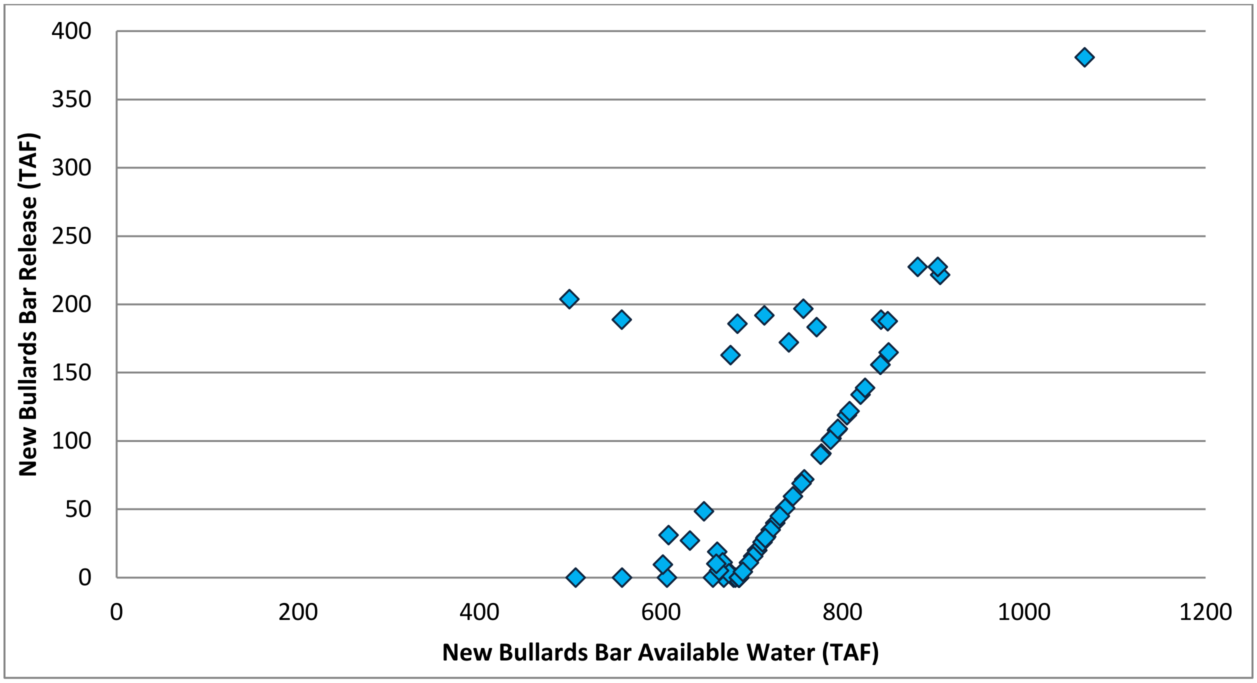
New Bullards Bar - February: If the storage + inflow is greater than the storage capacity release the excess, else release target of 0 TAF.

Figure C-42: February New Bullards Bar Release vs. Available Water (Storage + Inflow)



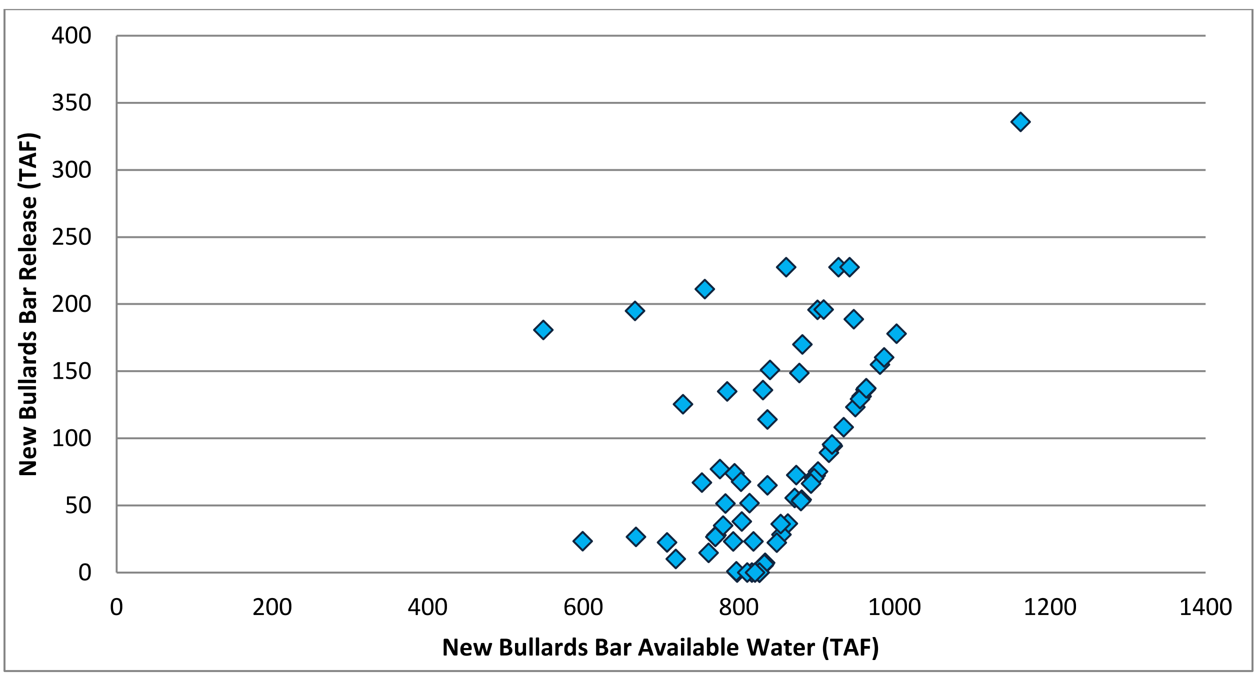
New Bullards Bar - March: If the storage + inflow is greater than the storage capacity release the excess, else release target of 0 TAF.

Figure C-43: March New Bullards Bar Release vs. Available Water (Storage + Inflow)



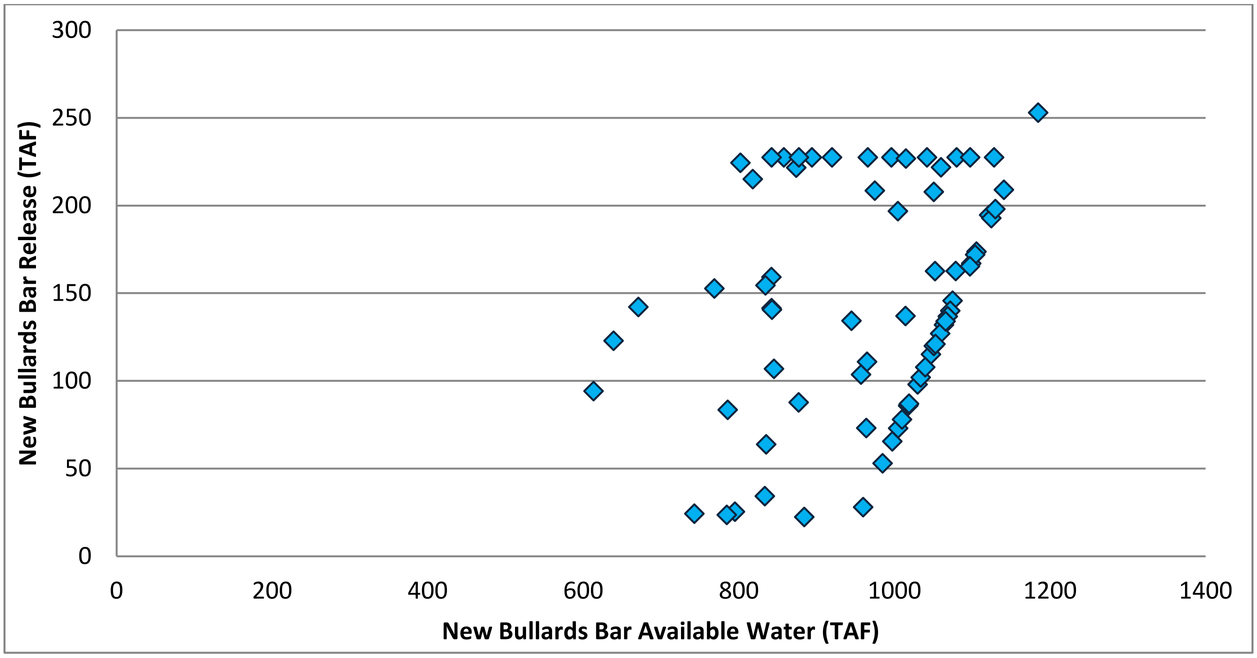
New Bullards Bar - April: If the storage + inflow is greater than the storage capacity release the excess and release the target of 32 TAF.

Figure C-44: April New Bullards Bar Release vs. Available Water (Storage + Inflow)



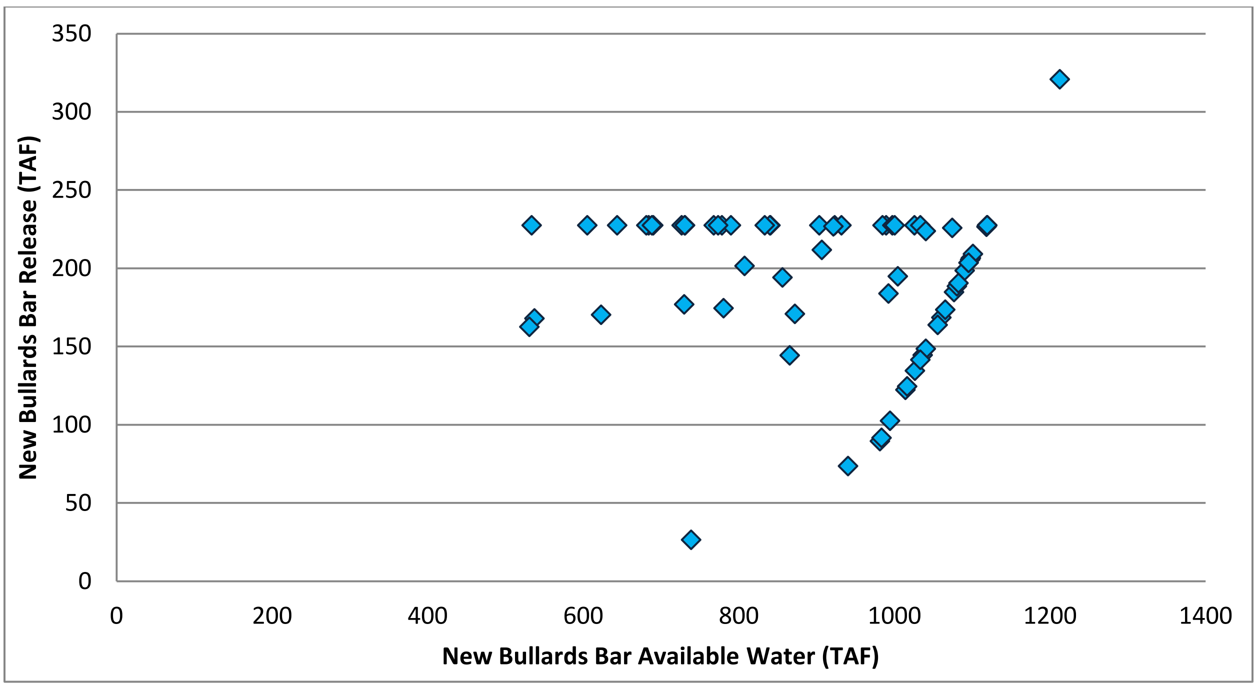
New Bullards Bar - May: If the storage + inflow is greater than the storage capacity release the excess, and release the target. If (AW) >= 1000 TAF then target = 71 TAF, else target = 227 TAF.

Figure C-45: May New Bullards Bar Release vs. Available Water (Storage + Inflow)



New Bullards Bar - June: If the storage + inflow is greater than the storage capacity release the excess, and release the target. If (AW) >= 1000 TAF then target = 108 TAF, else target = 228 TAF.

Figure C-46: June New Bullards Bar Release vs. Available Water (Storage + Inflow)



New Bullards Bar - July: Release the target. If (AW) >= 900 TAF then the target = 71 TAF, else if (AW) < 900 TAF and (IOPY)< 400 TAF then the target = 17 TAF, else if (AW)< 900 TAF and 400<=(IOPY)< 650 TAF then the target = 151 TAF, else the target = 227 TAF.

Figure C-47: July New Bullards Bar Release vs. Available Water (Storage + Inflow)

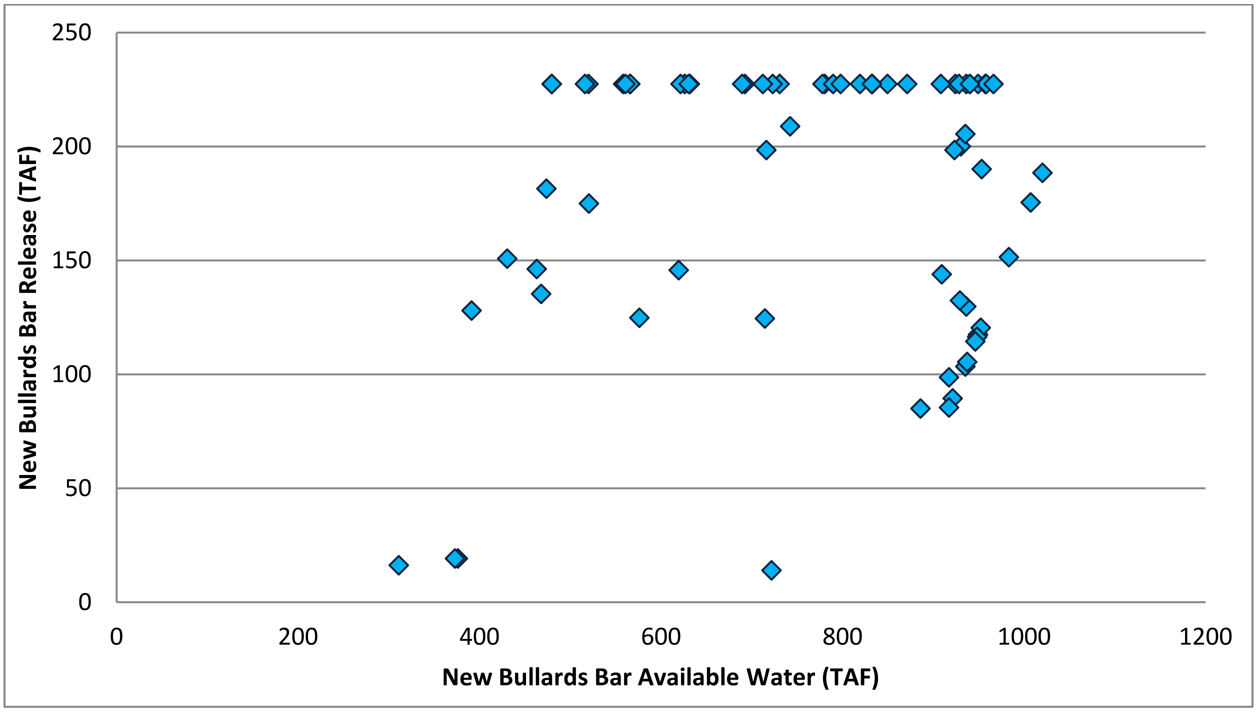
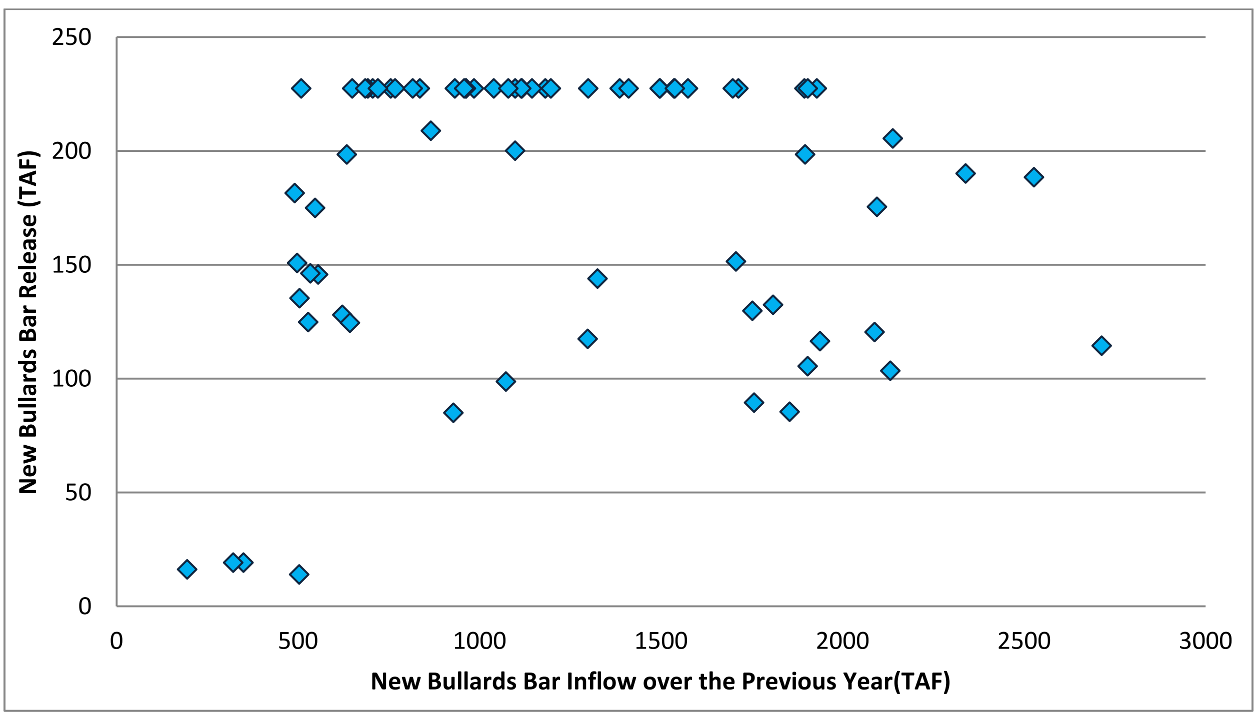
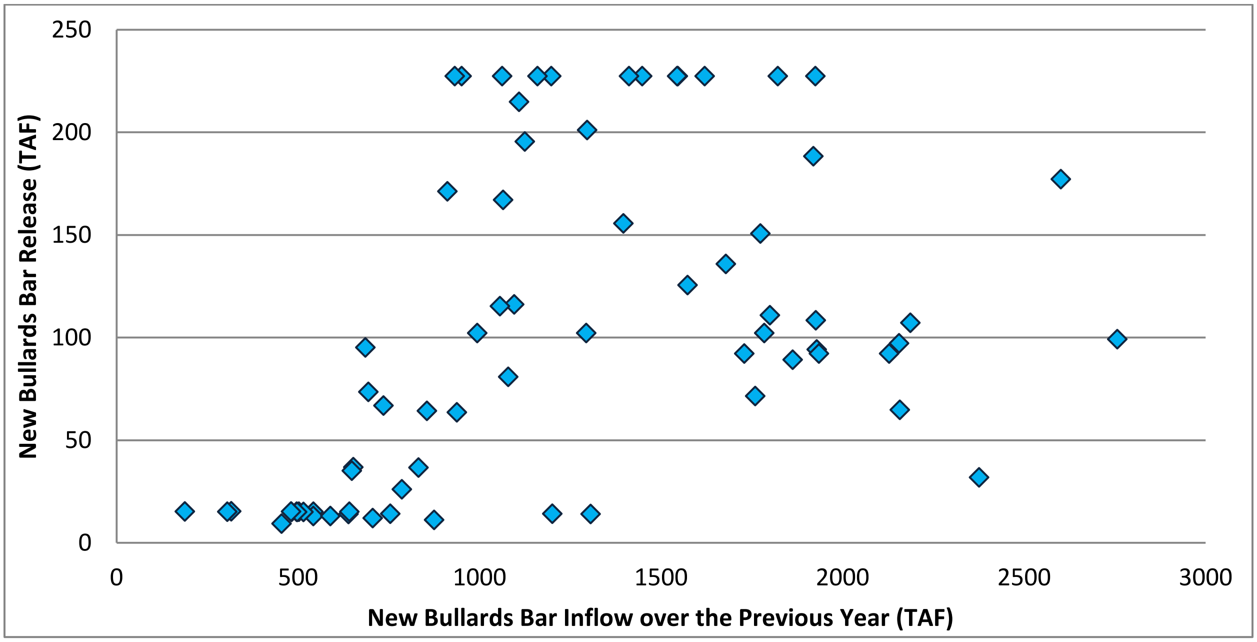


Figure C-48: July New Bullards Bar Release vs. Inflow over the Previous Year



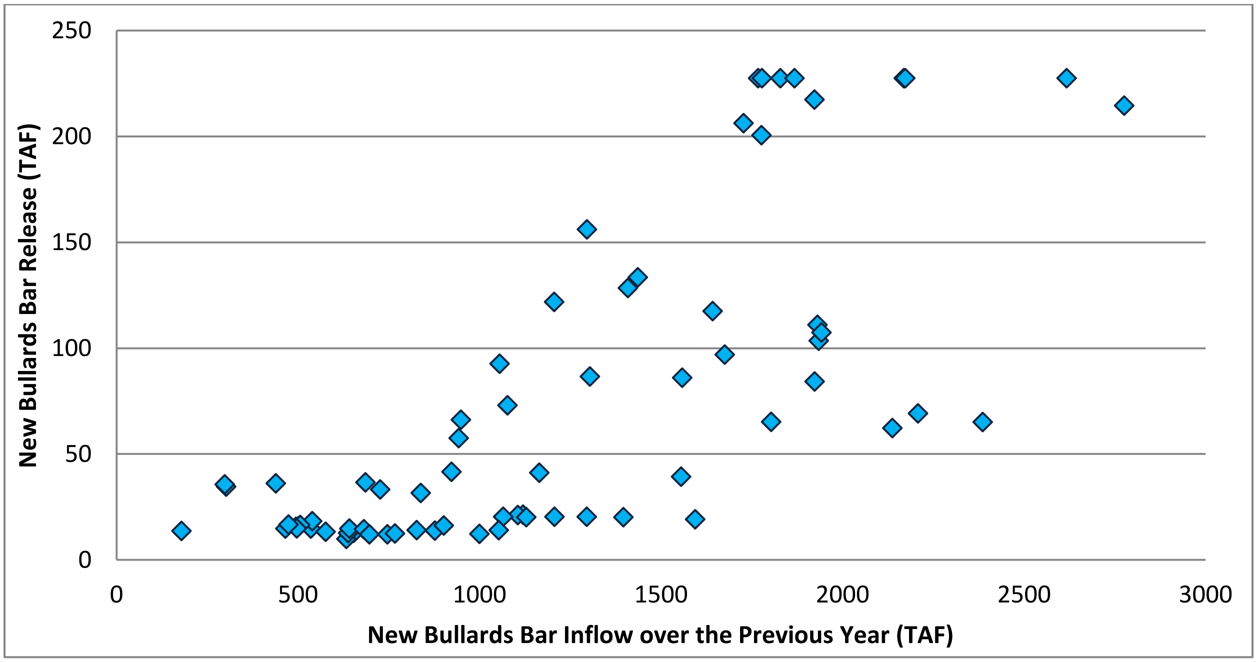
New Bullards Bar - August: If 630 < (IOPY) < 1250 TAF then release = .34*(IOPY)-200, else release the target. If (IOPY) < 600 TAF then the target = 15 TAF, else if (IOPY)>1700 TAF then the target = 99 TAF, else the target = 227 TAF.

Figure C-49: August New Bullards Bar Release vs. Inflow over the Previous Year



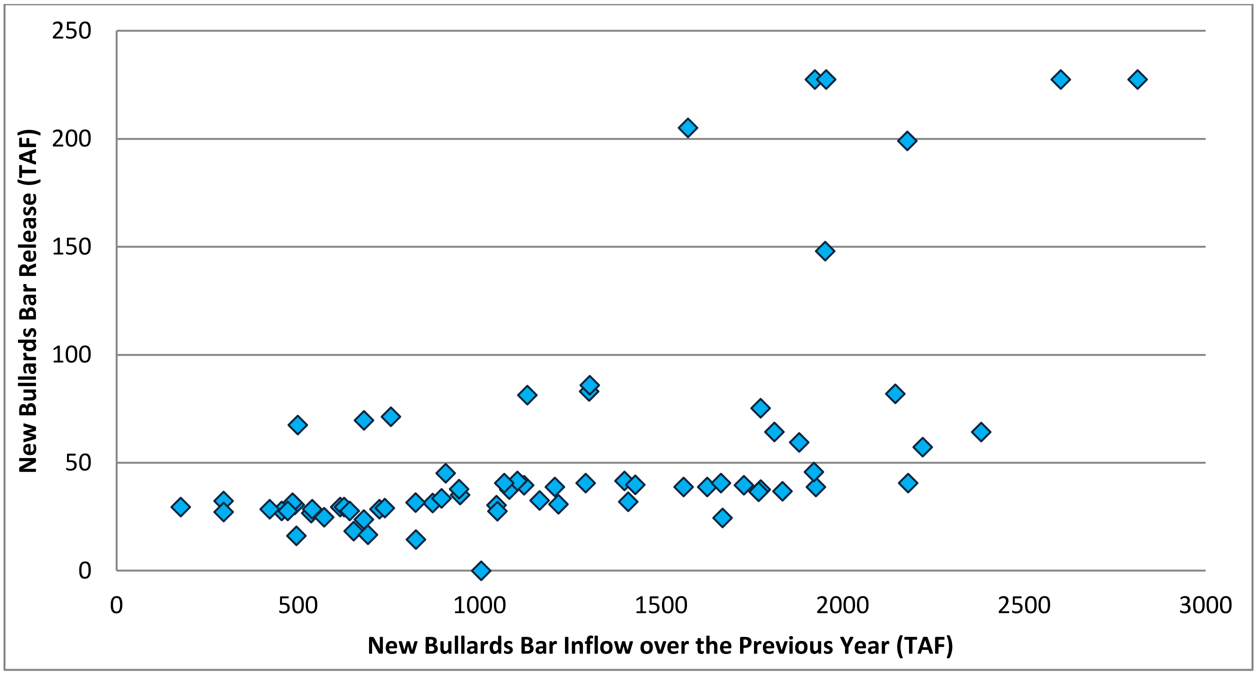
New Bullards Bar - September: If 1160 < (IOPY) < 1950 TAF then release = .26*(IOPY)-287, else release the target. If (IOPY) <=1160 TAF then the target = 19 TAF, else the target = 227 TAF.

Figure C-50: September New Bullards Bar Release vs. Inflow over the Previous Year



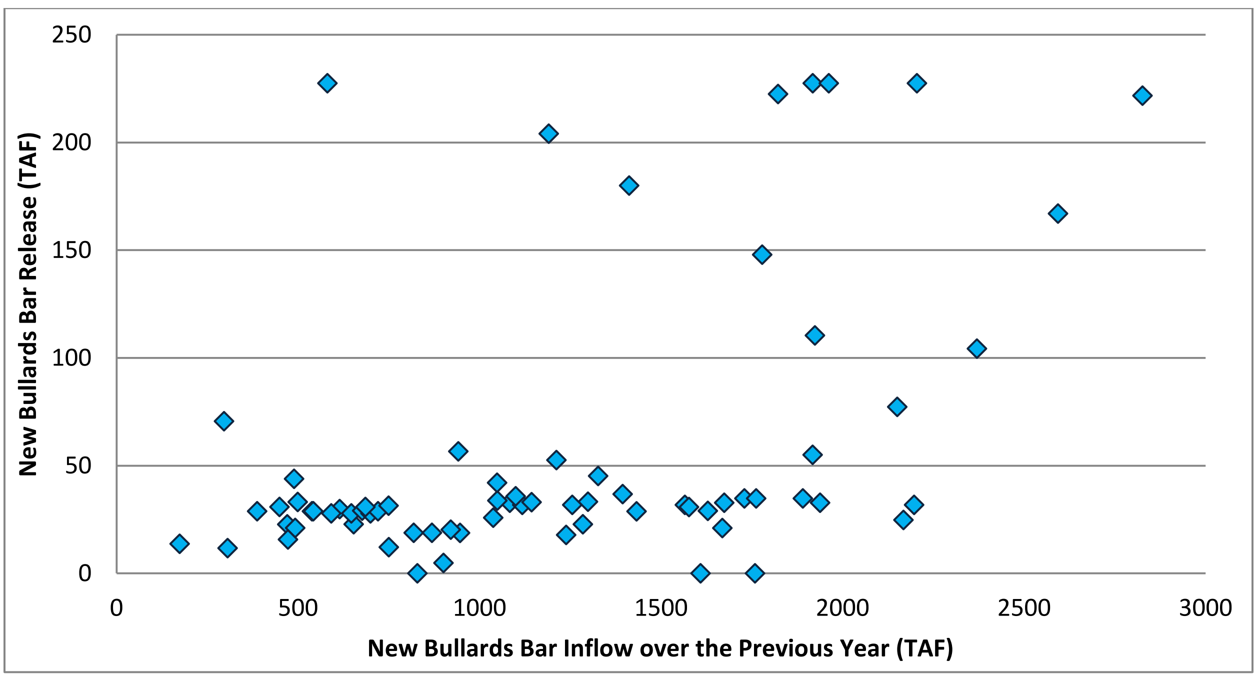
New Bullards Bar - October: Release the target. If (IOPY) < 1900 TAF then the target = 38 TAF, else the target = 227 TAF.

Figure C-51: October New Bullards Bar Release vs. Inflow over the Previous Year



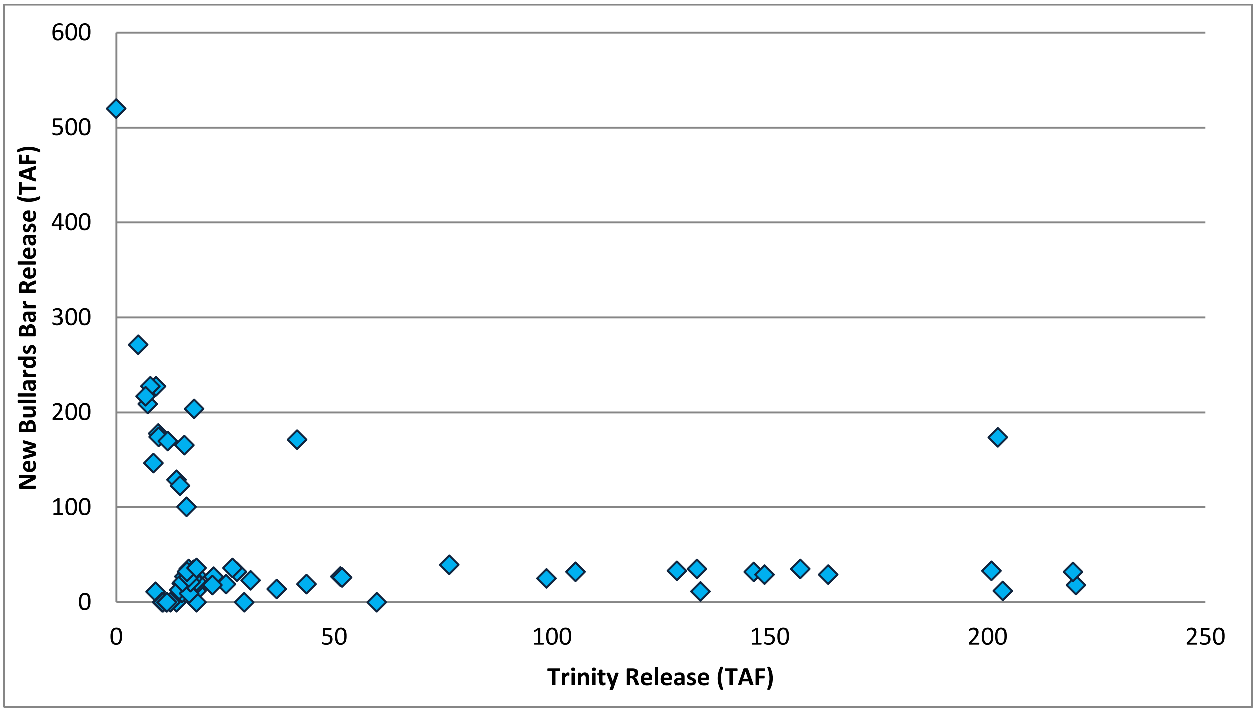
New Bullards Bar - November: Release the target. If (IOPY) < 1800 TAF then the target = 29 TAF, else the target = 227 TAF.

Figure C-52: November New Bullards Bar Release vs. Inflow over the Previous Year



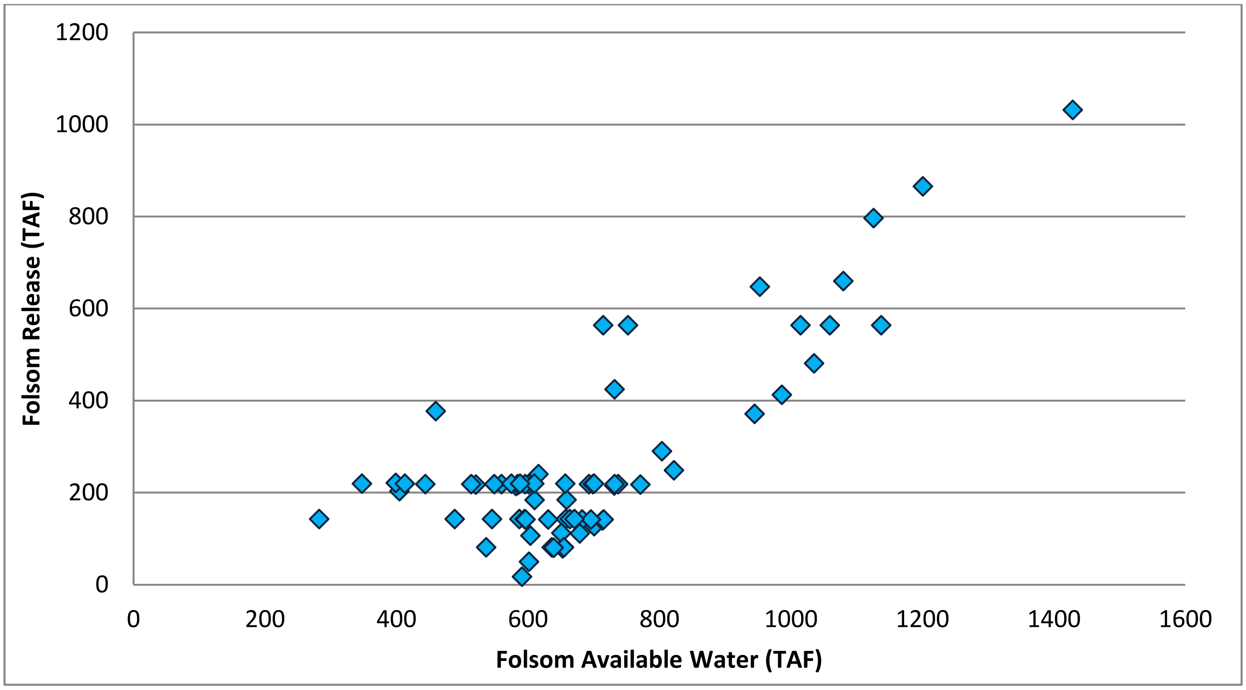
New Bullards Bar - December: If Trinity release (TR) < 16 TAF then release = -21.7951*(TR) + 382, else release the target of 24 TAF.

Figure C-53: December New Bullards Bar Release vs. Trinity Release



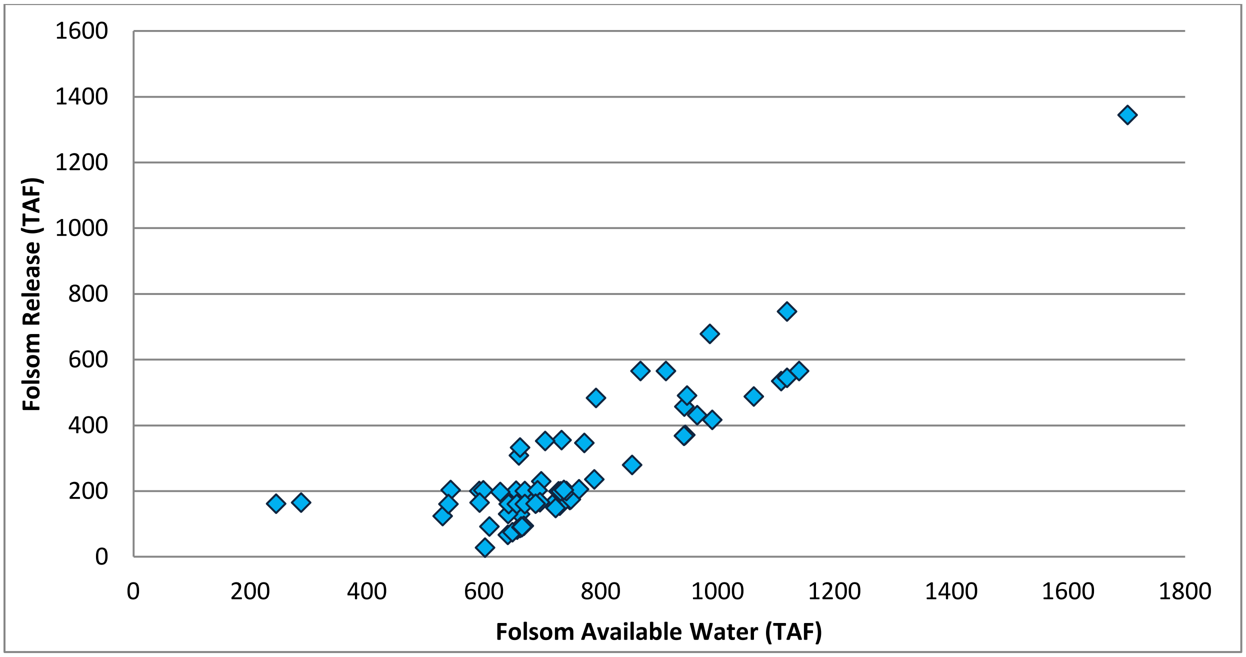
Folsom - January: If (AW) > 760 TAF then release = 1.28*(AW) - 763, else release the target of 169 TAF.

Figure C-54: January Folsom Release vs. Available Water (Storage + Inflow)



Folsom - February: If (AW) > 673 TAF then release = 1.09*(AW) - 583, else release the target of 153 TAF.

Figure C-55: February Folsom Release vs. Available Water (Storage + Inflow)



Folsom - March: If (AW) > 857 TAF then release = 1.02*(AW) - 655, else release the target. If Folsom inflow (FI) < 200 TAF then the target = 100 TAF, else the target = 218 TAF.

Figure C-56: March Folsom Release vs. Folsom Available Water (Storage + Inflow)

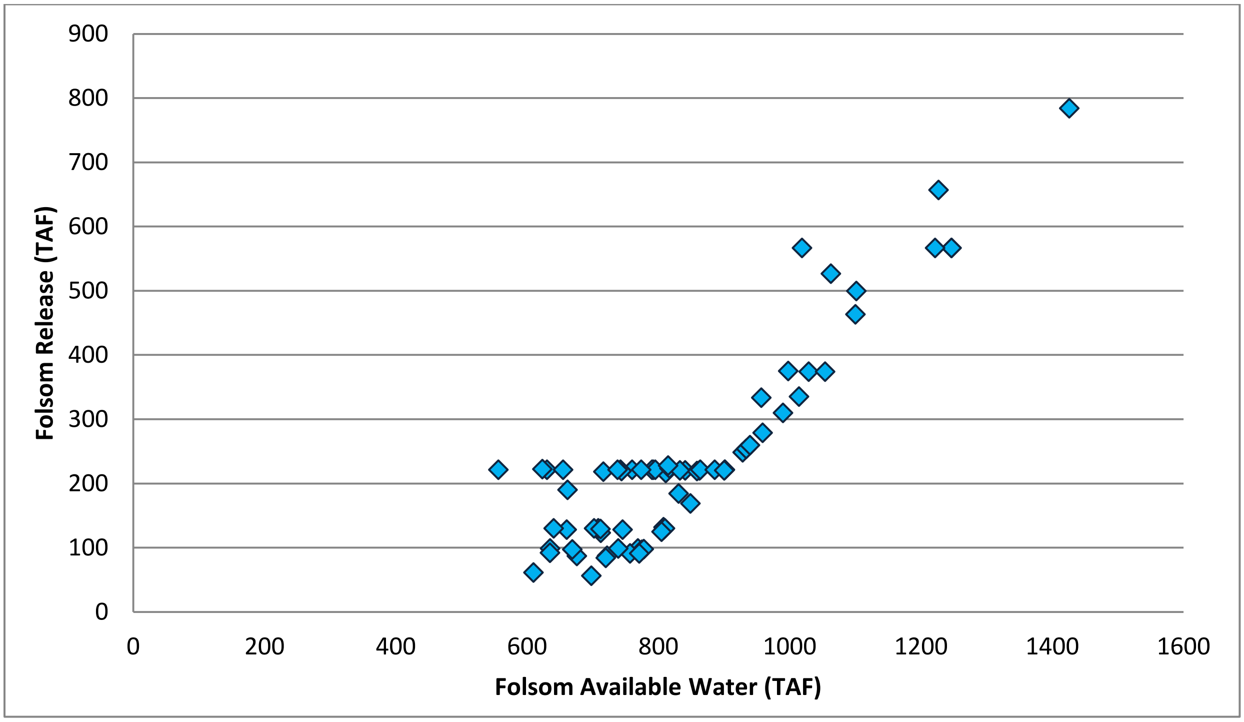
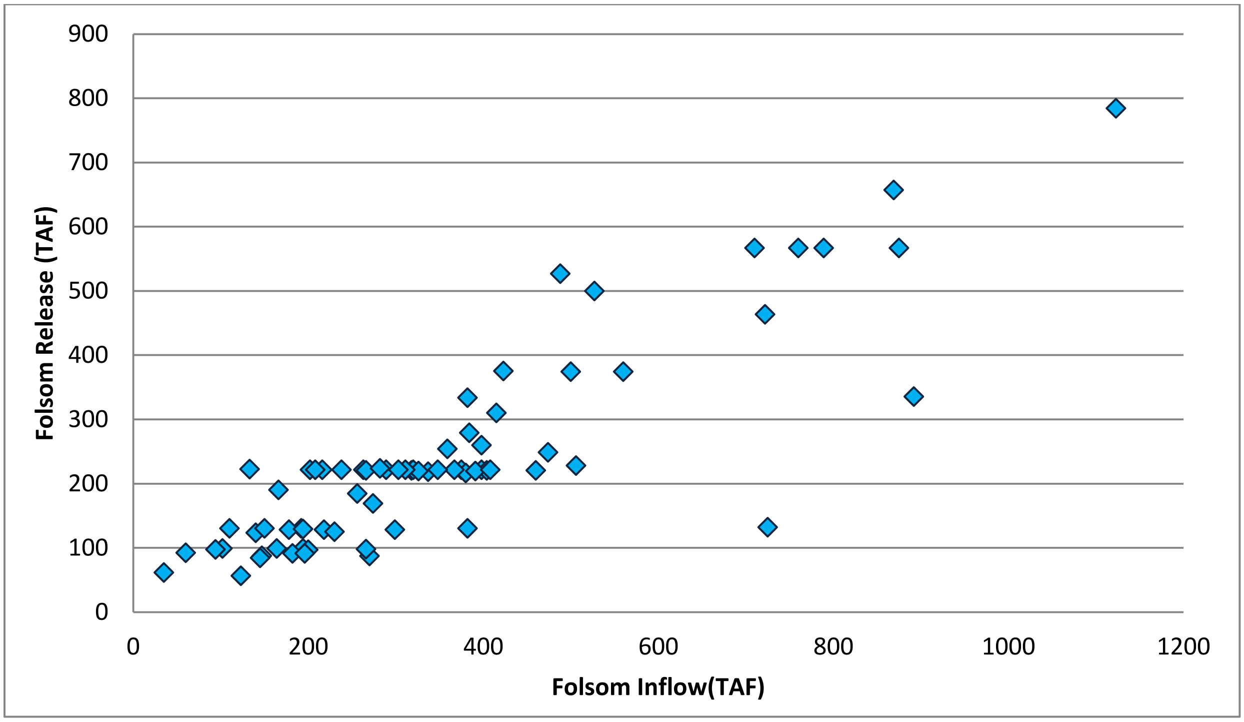


Figure C-57: March Folsom Release vs. Folsom inflow



Folsom - April: If (AW) > 947 TAF then release = .98*(AW) - 749, else release the target. If Folsom inflow (FI) < 171 TAF then the target = 110 TAF, else the target = 175 TAF.

Figure C-58: April Folsom Release vs. Folsom Available Water (Storage + Inflow)

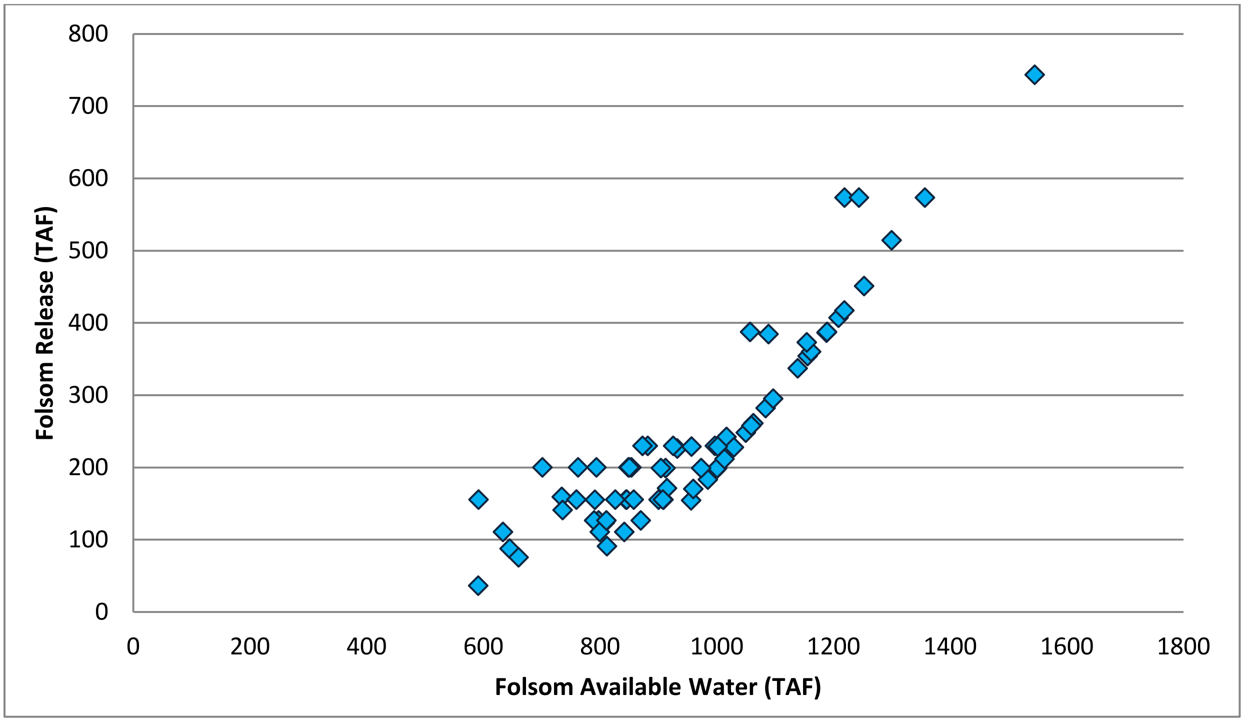
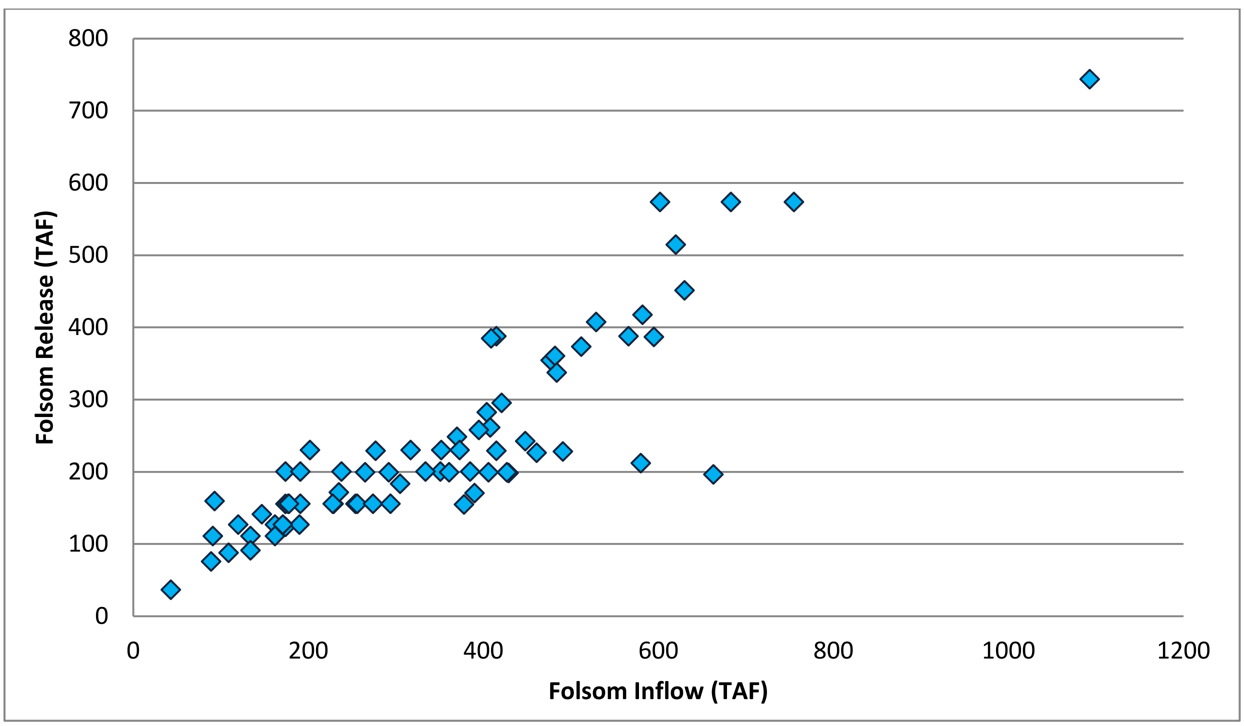
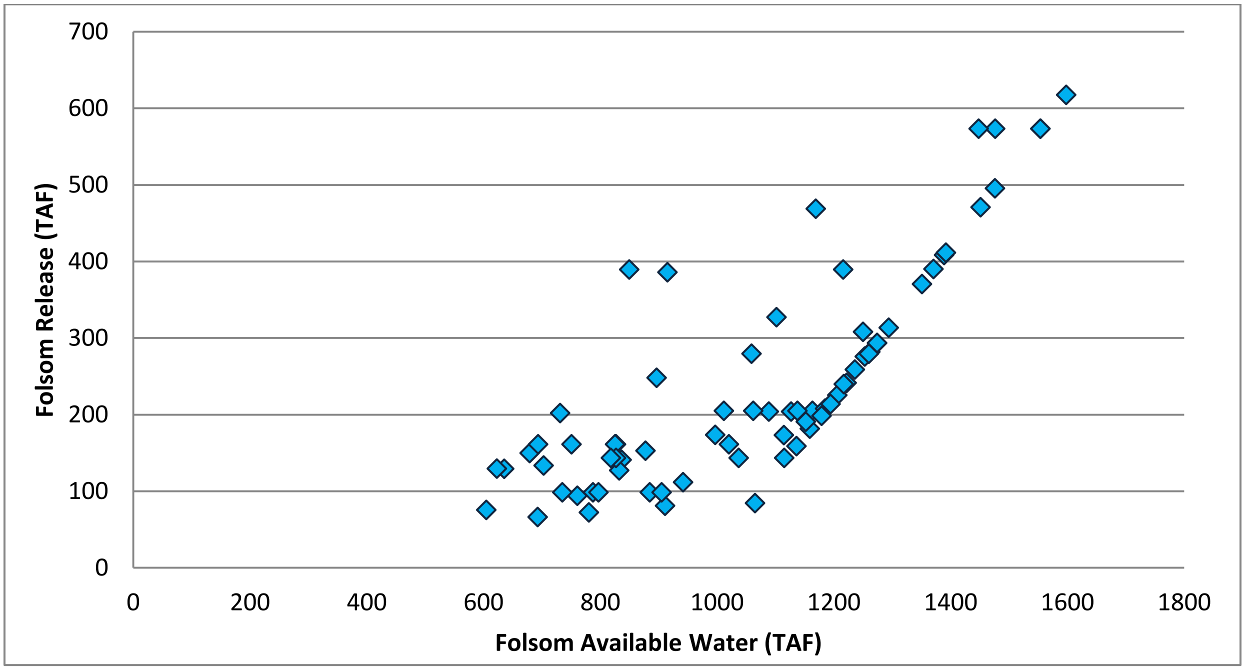


Figure C-59: April Folsom Release vs. Folsom inflow



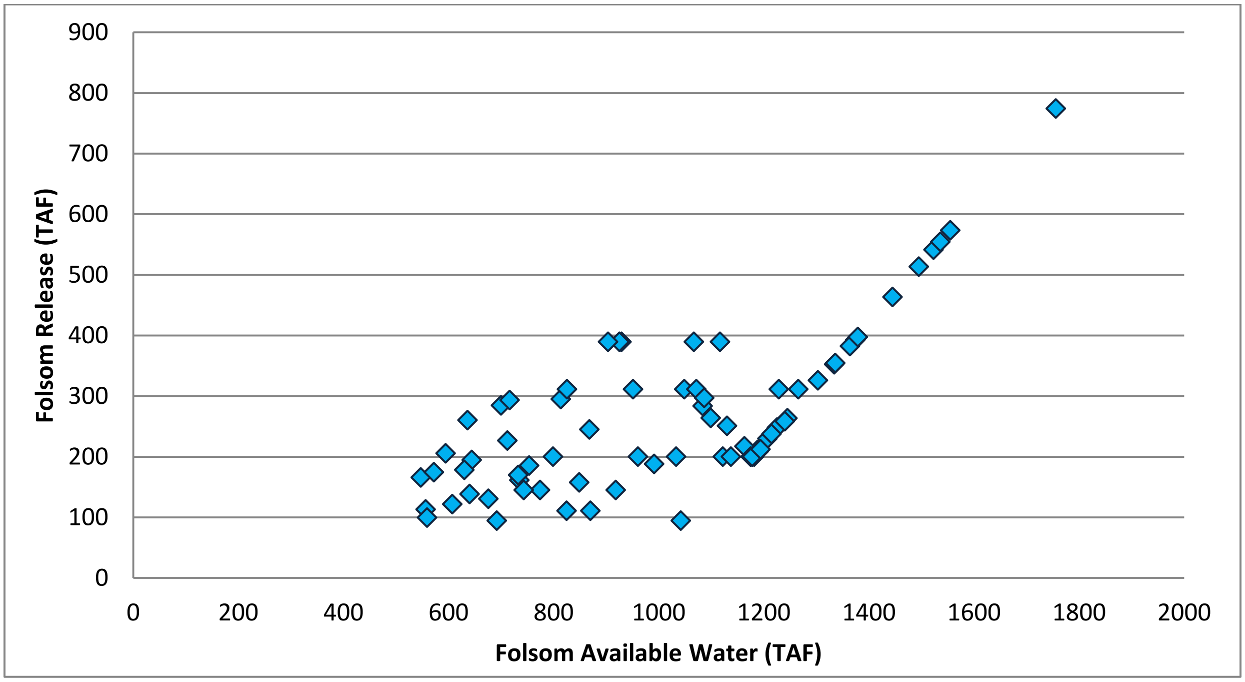
Folsom - May: If (AW) > 1061 TAF then release = .89*(AW) - 814, else release the target of 134 TAF.

Figure C-60: May Folsom Release vs. Folsom Available Water (Storage + Inflow)



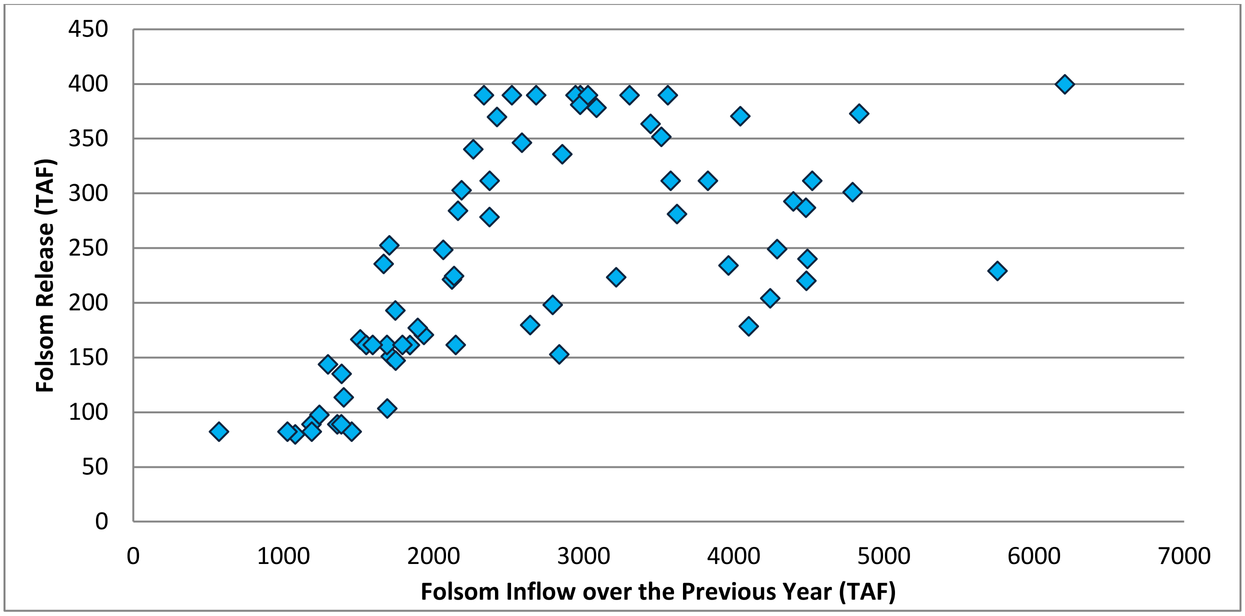
Folsom - June: If (AW) > 1158 TAF then release = .97*(AW) - 938, else release the target of 220 TAF.

Figure C-61: June Folsom Release vs. Folsom Available Water (Storage + Inflow)



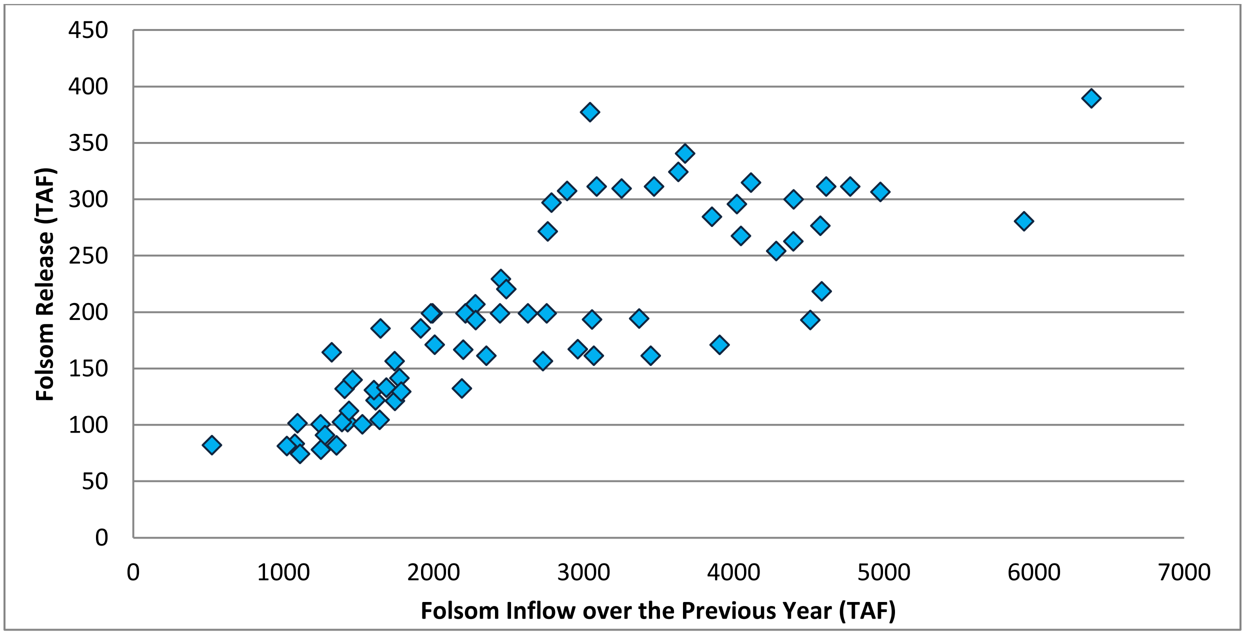
Folsom - July: If 1160 < (IOPY) < 2750 TAF then release = .20*(IOPY) -150, else if 3315 < (IOPY) < 3980 TAF then release = -.25*(IOPY) + 1202, else release the target. If (IOPY) <= 1160 TAF then the target = 82 TAF, else if (IOPY) >= 3980 TAF then the target = 207 TAF, else the target = 390 TAF.

Figure C-62: July Folsom Release vs. Folsom Inflow over the Previous Year



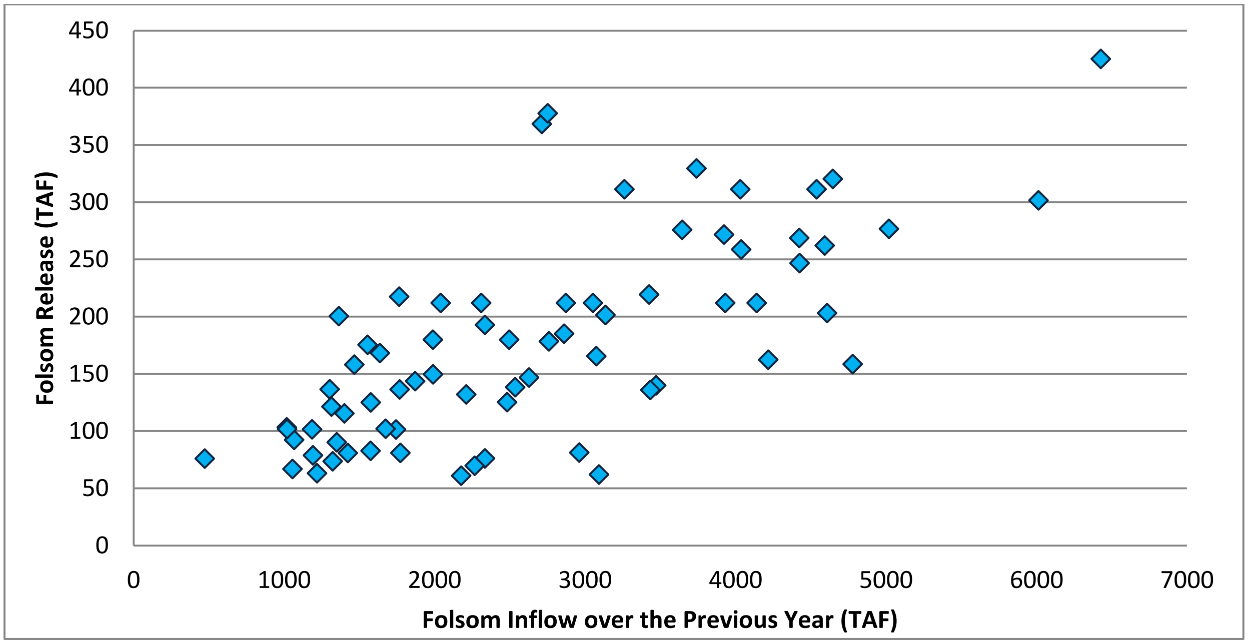
Folsom - August: If (IOPY) < 2100 TAF then release = .11*(IOPY) - 44, else release the target. If (IOPY) < 3100 TAF then the target = 188 TAF, else the target = 305 TAF.

Figure C-63: August Folsom Release vs. Folsom Inflow over the Previous Year



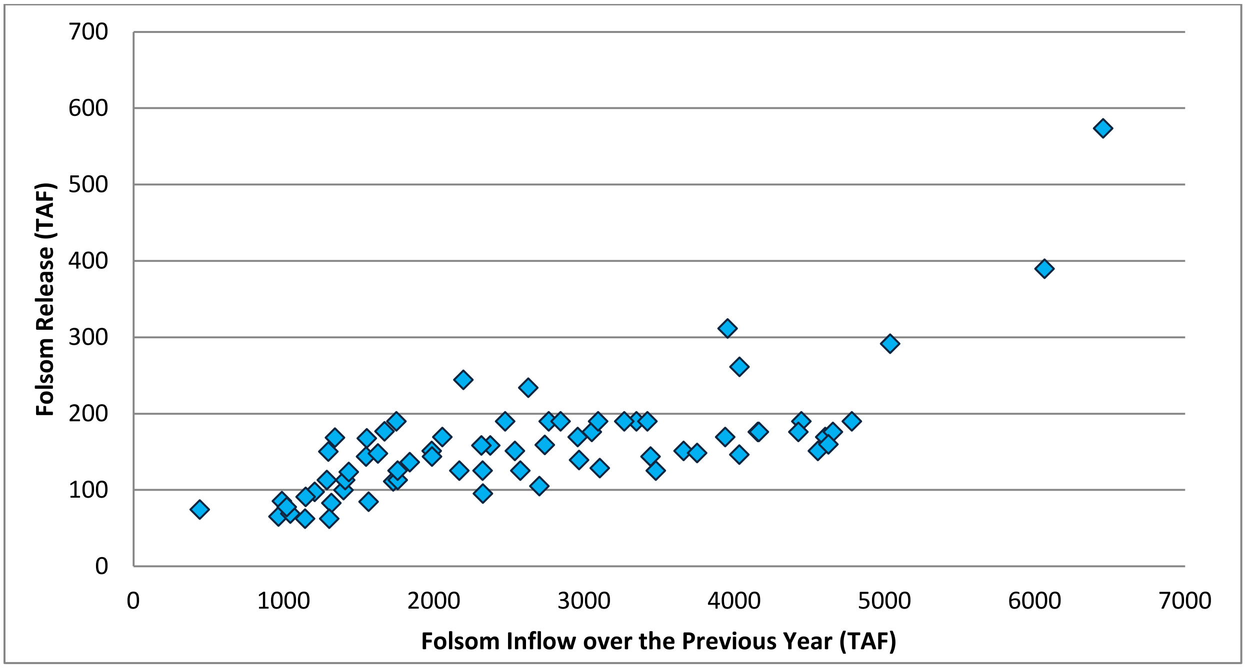
Folsom - September: Release the target. If (IOPY) < 3200 TAF then the target =131 TAF, else the target = 244 TAF.

Figure C-64: September Folsom Release vs. Folsom Inflow over the Previous Year



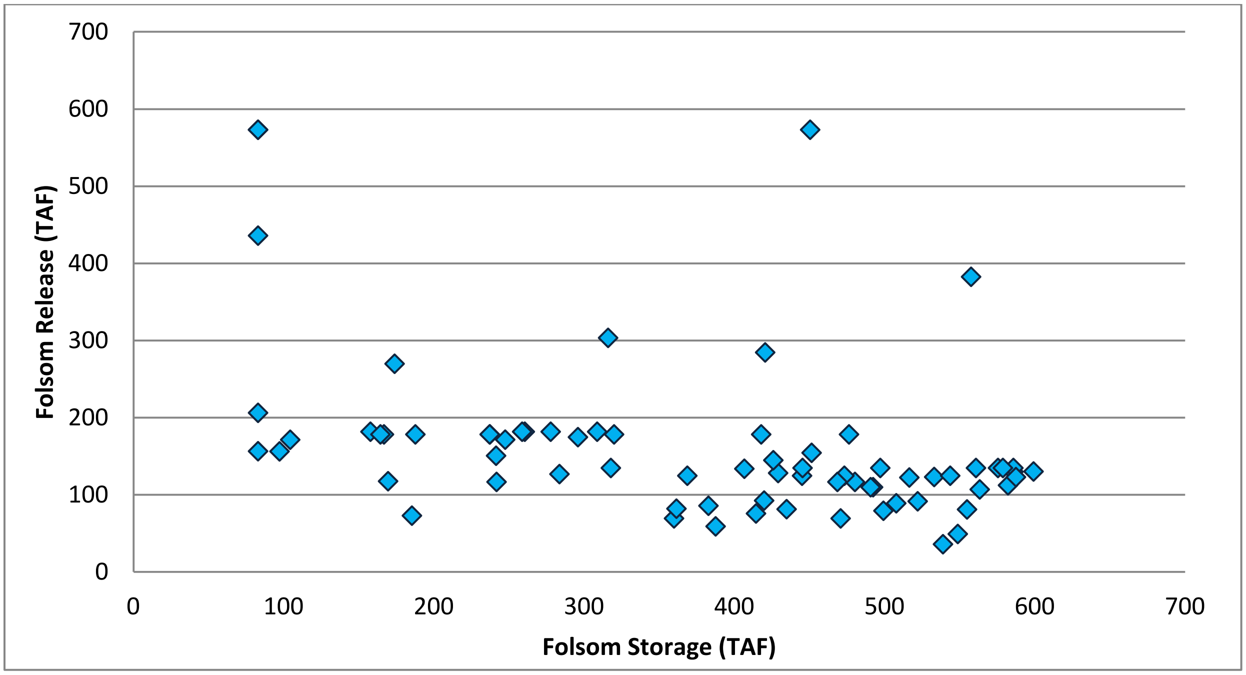
Folsom - October: If (IOPY) > 4400 TAF then the release = .17*(IOPY)-573, else release the target. If (IOPY) < 1330 TAF then the target = 80 TAF, else if (IOPY) > 2700 TAF then the target = 161 TAF, else the target = 140 TAF.

Figure C-65: October Folsom Release vs. Folsom Inflow over the Previous Year



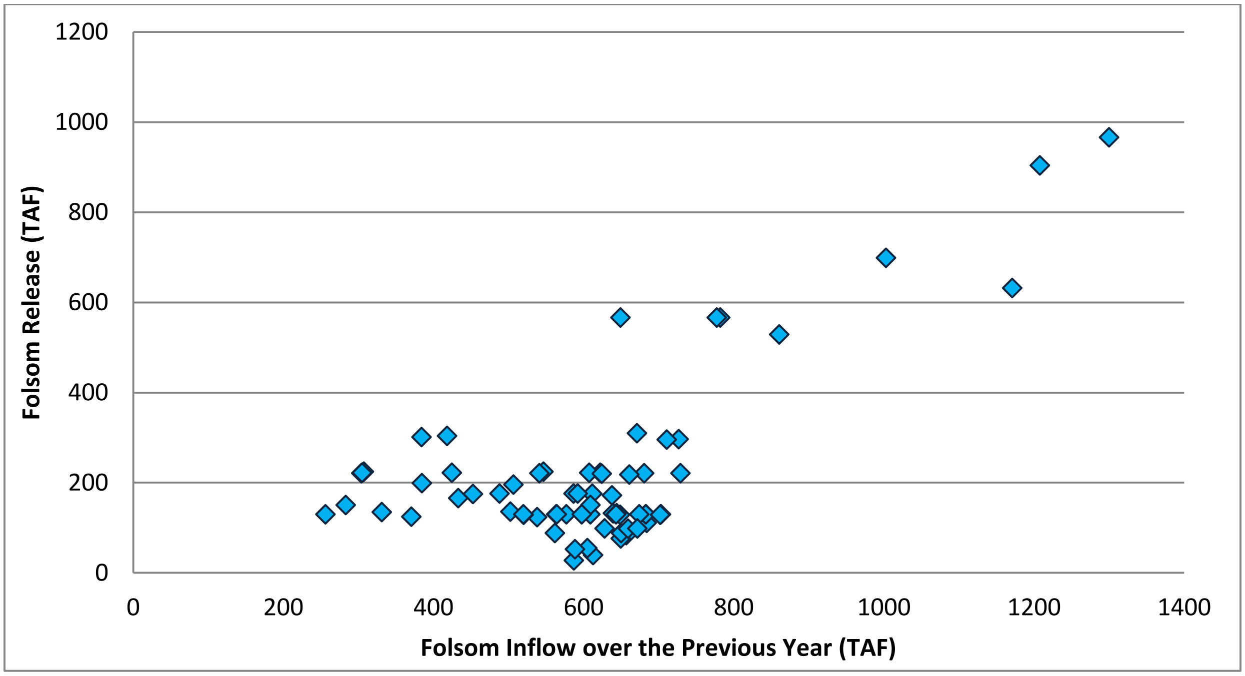
Folsom - November: Release the target. If Folsom storage (FS) < 350 TAF then the target = 162 TAF, else the target = 111 TAF.

Figure C-66: November Folsom Release vs. Folsom Storage



Folsom - December: If (AW) > 660 TAF then release = 1.27*(AW)-664, else release the target of 174 TAF.

Figure C-67: December Folsom Release vs. Folsom Available Water (Storage + Inflow)



Appendix D

Tables 1 through 5 below present the Depletion penalties for Shasta, Trinity, Oroville, New Bullards Bar, and Folsom. These penalties represent the opportunity cost of removing storage from each reservoir along with a small persuasion penalty. If it is equally valuable to release to preserve storage then the persuasion penalty encourages the model to keep the storage which would be a more realistic operation. The left most column of each table represents the reservoir storage and the rest of the table is the penalties associated with each storage level separated by month. As storage decreases the penalty increases linearly from one indicated value to the next in each column. For example, if Shasta storage is at 3830 TAF in January the penalty is $928,000, and if the storage fell to 2325 TAF then the penalty would linearly increase to $1,563,000. Overall, Oroville has the highest penalties, approaching $1.00/AF, while Trinity has the lowest penalties, at about $0.20/AF.

Unfortunately, these penalties have very little documentation. For the example mentioned above the penalty increases by about $0.42/AF. All the documentation says that the persuasion penalty should account for $0.02/AF, which leaves $0.40/AF unaccounted for. Some of this cost will come from lost hydropower generation, but it should not account for that much. In addition, there is no information on why the penalties are so high even when the reservoirs are near full. It may be valuable to reexamine these penalties and update them in the near future.

Table D-1: Shasta Storage Depletion Penalty Breakdown for each month

	Shasta Depletion Penalty											
Storage	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(TAF)	(1000 $)											
4554				888	921	888						
4332			961									
4302							1434					
4044		839										
4002								1408				
3830	928											
3702									1318			
3402										1199		
3370												1194
3254											1158	
2818			1439									
2806					1415							
2800							2153					
2758				1389		1389						
2669								2128				
2523		1354										
2325	1563											
1664									2768			
1527										2480		
1424											2409	
1421												2551
931			2615									
930								3781				
927							3911					
909					2490							
907				2414		2414						
895	2531											
888		2330										
762									3914			
756										3401		
729											3270	
706												3489
212	3898	3572	4034	3635	3757	3635	6034	5894	5664	4942	4709	4943
116	18037	16480	18565	16486	17035	16486	27790	27307	25990	22798	21790	22740

Table D-2: Trinity Storage Depletion Penalty Breakdown for each month

	Trinity Depletion Penalty											
Storage	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(TAF)	(1000 $)											
2449									319.4			
2422								324.5				
2302							312.3					
2272										256.9		
2152											252	
2102						175.3						
2002					181.4							
1977												261.8
1902				173.5								
1880								430.4				
1871									430.6			
1866							400.4					
1852	196.6	177.8	196.6									
993										559.7		
945											537.8	
928						370						
914		342.5										
913												529.6
907				342								
898					373.9							
894	383.7		383.7									
754							738.7		759.4			
751								774.3				
636										709.3		
614											681.8	
605		442.7				470.1						
604												674.6
594				442.2								
586					479.8							
584	501.1		501.1									
212	732.9	661.1	732.9	648.5	689.3	681.1	1201.4	1236.3	1207.3	1043.4	992.1	988.3
400	3741	3379	3741	3289	3457	3394	5986	6090	5924	5170	4934	4974

Table D-3: Oroville Storage Depletion Penalty Breakdown for each month

	Oroville Depletion Penalty											
Storage	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(TAF)	(1000 $)											
3540					1109	1075	1848	1848				
3472				1025								
3353									1640			
3165	1094	988	1094							1423	1377	1423
2271						1978						
2245				1905								
2244					2068		3446	3446				
2186									3066			
2125	2000	1807	2000							2600	2517	2600
1190						3037						
1188					3142		5237	5237				
1183				2951								
1179											3883	
1178	3088	2789	3088							4014		4014
1171									4751			
850	3777	3411	3777	3562	3778	3657	6297	6297	5746	4910	4751	4910
29.6	24956	22541	24956	22526	23531	22772	39218	39218	36998	32442	31396	32442

Table D-4: New Bullards Bar Storage Depletion Penalty Breakdown for each month

	New Bullards Bar Depletion Penalty											
Storage	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(TAF)	(1000 $)											
932					211							
892						194.3						
832							307					
827				177.3								
757								265				
707									260			
687			180									
662										235		
647											227	235
606						308.4						
605							461					
603				265.6	351							
602	177	159.3										
342								693				
313									676			
302			465									
296										594		
293											567	585
287	421											
284		382.7										
258					596							
256						550.5						
252							885					
251				512.3								
240								870				
234									829			
231			569									
229										727		
228											694	718
224	527											
223		478.4										
178	688	622	747	709.9	804	750.9	1227	1167	1098	952	910	940
251	10546	9525.4	10735	9558	10084	9680.6	16476	16278	15634	13892	13404	13851

Table D-5: Folsom Storage Depletion Penalty Breakdown for each month

	Folsom Depletion Penalty											
Storage	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(TAF)	(1000 $)											
977					200.5	193.6						
952							339.4					
802				190.2				327.5				
723										270.1		
682			202									
652									286.7			
602		172.2										
577	187.8										235.8	243.6
529					379.4							
524							629.8					
514						374						
441				350.7				604				
422										479.8		
409			353.1									
394									501.3			
378		295										
376	312											
370											398.6	
368												413.5
280					543.8							
276							904.5					
268						537.5						
243				500.1				861.4				
236										696.8		
228			520.6									
222		432.4										
221									741.7			
218	467											
217											589.6	
211												618.9
81	674.9	623.9	741.3	707.4	793.1	769.1	1315.1	1218.3	1049.7	995.4	849.1	878.4
80	5920	5394	6130	5533	5939	5747	9862	9528	8813	8070	7447	7696