Title
Channel Routing and Multi-Timestep Optimization in WRIMS2 for the Sacramento Valley: A Water Year 1997 Case Study

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Publication Date
2023

Peer reviewed|Thesis/dissertation

Channel Routing and Multi-Timestep Optimization in WRIMS2 for the Sacramento Valley: A Water Year 1997 Case Study

By

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2023

Abstract

This study couples the Muskingum routing method with multi-timestep optimization (MTO) to facilitate daily timestep mode in system operations planning models such as CalLite, CalSim II, and CalSim 3. The modeling framework used is the California Department of Water Resources' (CA DWR) Water Resources Integrated Modeling Software (WRIMS) using Water Resources Simulation Language (WRESL). In the report, Muskingum routing is implemented in a simplified modeling domain representing California's Sacramento Valley, North-of-Delta (NOD), based on the CalLite and HEC-FCLP schematics. The Muskingum method was chosen for its ease of implementation, relative accuracy, and parameter availability. Implementing channel routing involves introducing a storage node in between channel arcs to represent the accumulation and loss of storage as water travels from upstream to downstream. Models such as CalLite and CalSim mainly use single timestep optimization (STO). Unlike STO, MTO provides the capability to forecast and access future decision variables to optimize current timestep (e.g., one day) releases to meet future targets or objectives. Previous work demonstrated that using channel routing with STO where basin travel times (e.g., Shasta to the Delta) will exceed more than the timestep can generate unrealistic reservoir operations. As a result, a daily timestep model representing the NOD to Delta region requires both channel routing and MTO. Results during the simulation period of water year (WY) 1997 show reasonable reservoir releases at the major project reservoirs such as Shasta, Folsom, and Oroville. However, further work is needed in updating the weights and penalties to account for the MTO framework and to better represent the balancing of the NOD reservoirs. Overall, a daily timestep mode of the California Central Valley similar in scope with CalLite can be implemented using channel routing and MTO. One of the major areas of future work is performing a comprehensive recalibration and adjustment of weights, goal statements, and penalties to better represent real-time, daily-to-weekly coordinated operations among the major project reservoirs to meet obligations in the Delta and South-of-Delta.

Acknowledgements

"If I have seen further, it is by standing on the shoulders of giants." — Isaac Newton

Thank you to my thesis committee, Dr. Lund, Dr. Sandoval-Solis, and Dr. Herman. I appreciate the time and guidance you have provided to make my thesis better and force me to think deeply about my topic. Further thanks to my committee chair, Dr. Lund, for the invaluable feedback and advice you gave me during my time at UC Davis, even back when I was an undergraduate student.

Thank you to the members of the Water Systems Research Group. I enjoyed listening to you all share your research. I am grateful that you listened to my presentations, asked thoughtful questions, and provided feedback. From the pizza and beer outings, the sailing trips at the San Pablo Bay with Jay, I hope we have more opportunities to keep in touch.

Thank you to my mentors, Karandev and Nazrul. If not for them, I would not have been fascinated in CalSim and water system operations modeling. I would like to extend my deep thanks to Karandev for his guidance back when I was still a student assistant and a new engineer with DWR. If not for him, I would not have even considered graduate school to tackle this MS thesis topic. Thank you to Nazrul also for encouraging me to push forward. I learned so much not only about the technical side, but also about discipline and perseverance which helped me in graduate school but also in my professional life. Nazrul always gave me opportunities to keep learning new things and venture out of my comfort zone which helped me grow as a person.

Lastly, I would like to thank my dearest friends and family for their support. I appreciate the relentless encouragement to help me persevere. Words are not enough to express how grateful I am to have such a great support system. I would like to make a special mention to my high school best friends, Mira, Kristin, Nicole, for being there for me from the very beginning. Thank you for 13 years of friendship. I look forward to more.

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Abbreviations

AD	Accretion-depletion
AF	Acre-feet
ANN	Artificial neural network
BiOps/BOs	Biological Opinions
CAM	CalSim Allocation Module
CDFW	California Department of Fish and Wildlife
CFS	Cubic feet per second
CNRFC	California-Nevada River Forecast Center
COA	Coordinated Operation Agreement
CVP	Central Valley Project
CWF	California Water Fix
D-1641	Decision-1641 from the State Water Resources Control Board
DCP	Delta Conveyance Project
DCR	Delivery Capability Report
DWR	California Department of Water Resources
EIR	Environmental Impact Report
HEC	Hydrologic Engineering Center
ITP	Incidental Take Permit
LP	Linear Programming
MAF	Million acre-feet
MTO	Multi-timestep optimization
MIF	Minimum in-stream flow
MILP	Mixed-Integer Linear Programming
NMFS	National Marine Fisheries Service
NOD	North of Delta
ROC LTO	Reinitiation of Consultation on the Coordinated Long-Term Operations of the Central Valley Project and State Water Project
SACWAM	Sacramento Water Allocation Model
SAFCA	Sacramento Area Flood Control Agency
SGMA	Sustainable Groundwater Management Act
SOD	South of Delta
STO	Single timestep optimization
SWP	State Water Project
SWRCB	State Water Resource Control Board
TAF	thousand acre-feet
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
WCD	Water Control Diagram
WCM	Water Control Manual
WRESL	Water Resources Simulation Language
WRIMS	Water Resources Integrated Modeling System
WY	Water Year

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Chapter 1 Introduction

1.1 Problem

WRIMS-based models such as CalLite and CalSim have been run using a monthly timestep. Monthly simulations are sufficient for evaluating water supply planning (CA DWR and USBR, 2017; Draper et al., 2004; Munévar and Chung, 1999). However, a daily timestep model is needed to better simulate minimum in-stream flow requirements, flood control operations, weir spills, and Delta regulations. To accomplish this, a channel routing method will be required because travel times from the most upstream CVP reservoir, Shasta, exceed the one-day time step. General estimates of Shasta to Delta travel time are five days (USBR, 2020). Figure 1 shows the updated DWR travel time estimates during high flow ranges. According to these estimates, the total travel time from Shasta to Sacramento River at I St is approximately 78.5 hours or 3.3 days instead of the five-day estimate. Table 1 shows a tabular format of the California travel time estimates during high flow ranges.

The existing approach in the monthly models to estimate daily weir spills is through mapping of the monthly flows to historical daily patterns. The Freeport daily flow patterns were derived from DAYFLOW. This is used to estimate daily spills at Fremont and Sacramento Weirs. This method was needed because previous studies such as the Biological Assessment for the California Water Fix (CWF) needed estimates of daily flow variability to establish tunnel bypass flow criteria (ICF International, 2016). With a daily timestep model, such workarounds to determine weir spills will not be needed.

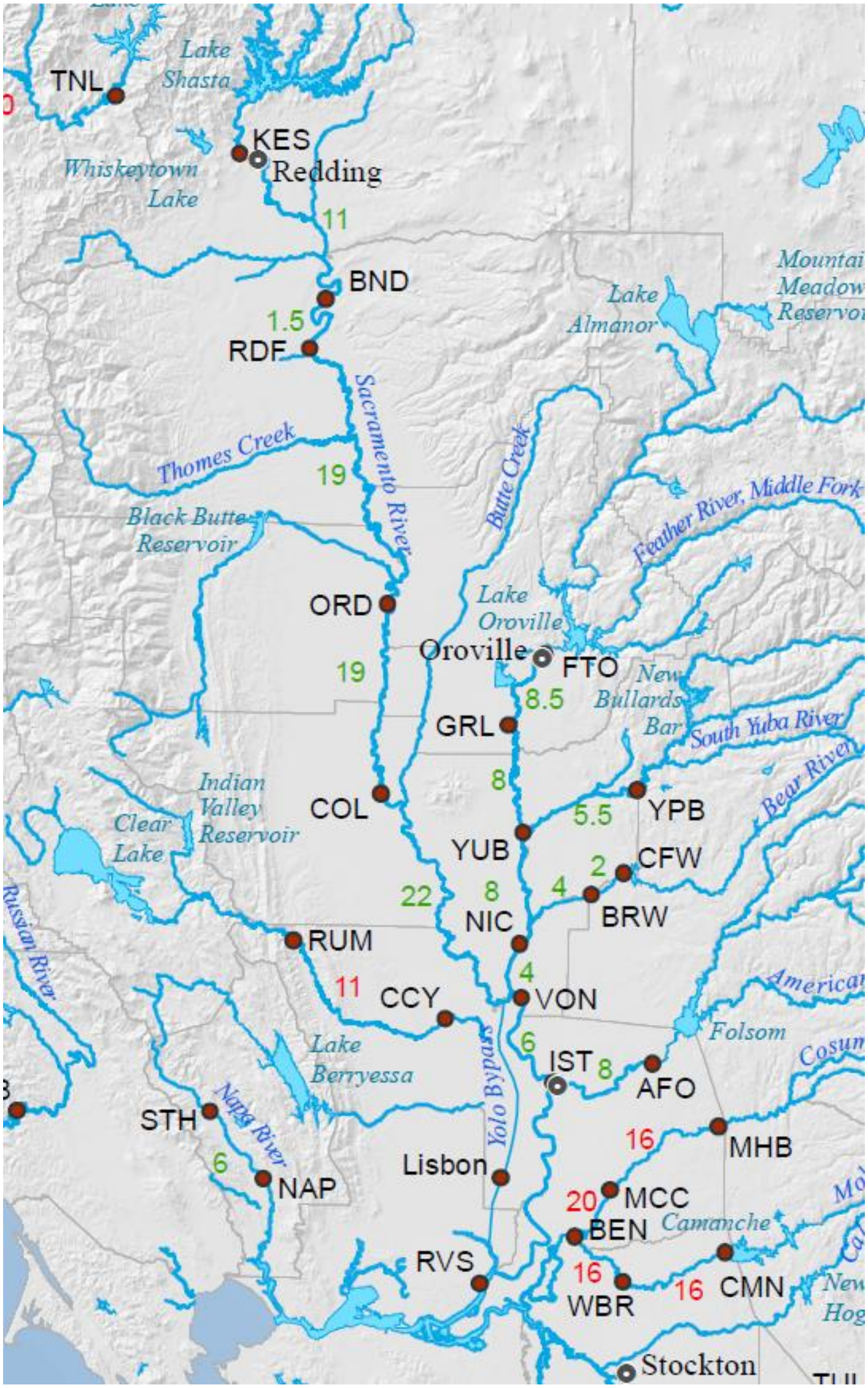


Figure 1. DWR Water Travel Times (Approximate Time in Hours) (CA DWR, 2016)

Table 1. California Sacramento Streams Reach Travel Time Estimates (CA DWR, 2016)

From Station Name (CDEC/USGS Gage ID)	To Station Name (CDEC/USGS Gage ID)	Length in River Miles (RMs)	Flow Range of Analysis (cfs)	Previous DWR Published Values (hrs)	Travel Time Estimates (hrs)
SACRAMENTO HYDROLOGIC REGION					
SACRAMENTO RIVER (MAINSTEM)					
SACRAMENTO RIVER AT KESWICK (KES/11370500)	SACRAMENTO RIVER AT BEND BRIDGE (BND)	44	36,000 - 112,000	10	11.0
SACRAMENTO RIVER AT BEND BRIDGE (BND)	SACARMENTO RIVER AT RED BLUFF	14	109,000 - 114,000	2	1.5
SACRAMENTO RIVER AT RED BLUFF	SACRAMENTO RIVER AT TEHAMA (TEH)	15	-	6	6.0
SACRAMENTO RIVER AT BEND BRIDGE (BND)	SACRAMENTO RIVER AT VINA-WOODSON BRIDGE (VIN)	38	120,000 - 140,000	8	9.0
SACRAMENTO RIVER AT TEHAMA (TEH)	SACRAMENTO RIVER AT VINA-WOODSON BRIDGE (VIN)	9	69,000 - 160,000	2	2.0
SACRAMENTO RIVER AT VINA-WOODSON BRIDGE (VIN)	SACRAMENTO RIVER AT HAMILTON CITY (HMC)	21	105,000 - 145,000	3	6.0
SACRAMENTO RIVER AT HAMILTON CITY (HMC)	SACRAMENTO RIVER AT ORD FERRY (ORD)	15	105,000 - 148,000	5	5.0
SACRAMENTO RIVER AT VINA-WOODSON BRIDGE (VIN)	SACRAMENTO RIVER AT ORD FERRY (ORD)	36	117,000 - 148,000	8	11.5
SACRAMENTO RIVER AT ORD FERRY (ORD)	SACRAMENTO RIVER AT COLUSA (COL/11389500)	41	43,000 - 140,000	19	19.0
SACRAMENTO RIVER AT ORD FERRY (ORD)	SACRAMENTO RIVER AT BUTTE CITY (BTC)	15	78,000 - 99,000	8	11.0
SACRAMENTO RIVER AT BUTTE CITY (BTC)	SACRAMENTO RIVER AT MOULTON WEIR (MLW)	11	98,000 - 99,000	8	5.0
SACRAMENTO RIVER AT BUTTE CITY (BTC)	SACRAMENTO RIVER AT COLUSA (COL/11389500)	26	46,000 - 134,000	11	8.5
SACRAMENTO RIVER AT COLUSA (COL/11389500)	SACRAMENTO RIVER AT TISDALE WEIR (TIS)	24	17,000 - 47,000	7	8.0
SACRAMENTO RIVER AT COLUSA (COL/11389500)	SACRAMENTO RIVER BL WILKINS SLOUGH NR GRIMES (WLK/11390500)	18	27,000 - 42,000	-	7.0
SACRAMENTO RIVER AT VERONA (VON)	SACRAMENTO RIVER AT I STREET BRIDGE (IST)	19.5	54,000 - 95,000	-	6.0
SACRAMENTO RIVER AT I STREET BRIDGE (IST)	SACRAMENTO RIVER AT FREEPORT (FPT/11447650)	19.5	92,000 - 116,000	-	4.0
AMERICAN RIVER					
AMERICAN RIVER AT FOLSOM (FOL)	AMERICAN RIVER AT FAIR OAKS (AFO/11446500)	7	116,000 - 117,000	-	1.0
AMERICAN RIVER AT FAIR OAKS (AFO/11446500)	AMERICAN RIVER AT H STREET (HST)	15.6	-	-	5.0
AMERICAN RIVER AT H STREET (HST)	SACRAMENTO RIVER AT I STREET BRIDGE (IST)	7.4	-	2	2.0
FEATHER, YUBA, AND BEAR RIVERS					
OROVILLE DAM (ORO)	FEATHER RIVER NR GRIDLEY (GRL/114007150)	20.7	80,000 - 160,000	8	8.5
FEATHER RIVER NR GRIDLEY (GRL/114007150)	FEATHER RIVER AT YUBA CITY (YUB)	22.4	-	8	8.0
YUBA RIVER NR SMARTVILLE (YRS/11418000)	YUBA RIVER NR MARYSVILLE (MRY/11421000)	16.8	99,000 - 113,000	-	3.0
YUBA RIVER NR MARYSVILLE (MRY/11421000)	FEATHER RIVER AT YUBA CITY (YUB)	5.2	-	-	2.5
FEATHER RIVER AT YUBA CITY (YUB)	FEATHER RIVER NR NICOLAUS (NIC)	19.3	-	10	8.0
FEATHER RIVER NR NICOLAUS (NIC)	SACRAMENTO RIVER AT VERONA (VON)	10.5	-	4	4.0
BEAR RIVER AT CAMP FAR WEST (CFW)	BEAR RIVER NR WHEATLAND (BRW/11424000)	5.3	28,000 - 36,000	-	2.0

1.2 Objectives

This study seeks to address shortcomings of linear programming with respect to channel routing noted by Ilich (2008, 2022). The first issue was that "channel routing cannot work within the LP framework using a single timestep solution unless the system is so small that the entire travel time is shorter than the length of the timestep required for routing." When channel routing is implemented in an LP-based model where travel times from the most upstream to downstream control points exceeded the timestep (one day), STO often fails to represent reasonable reservoir operations. As a result, multi timestep optimization (MTO) is needed. In a system such as the California North of Delta (NOD) region, travel time from Shasta to the Delta is assumed to be five days, Oroville three days, and Folsom one day in average conditions. Because travel time from Shasta or Oroville to the Delta usually exceeds one day, channel routing with MTO is needed. Otherwise, the LP model will most often "flood" the downstream channels to shorten the travel time so that the required flows at downstream demands will be available in the same timestep, even though for example, Shasta releases typically arrive at the Delta in five days on average.

The second issue identified was that implementing channel routing in an MTO framework may require nonlinear routing methods since routing coefficients should be updated when flow regimes shift from low to high (winter to summer). MTO requires automatically updating routing coefficients because the assumption of constant coefficients for large flow variations between wet and dry seasons is no longer appropriate. The problem then becomes non-linear. Ilich (2022) applied the SSARR routing method in an LP model iteratively to dynamically update the routing coefficients.

This study describes a WRIMS2 model application in which the NOD CVP/SWP system uses a daily timestep with channel routing and MTO. The concepts from this thesis supplement understanding to develop a larger-scale CVP/SWP simulation model with Delta and South of Delta (SOD) representation such as within CalLite (Islam et al., 2011). The model presented here simulates daily reservoir releases, weir operations, and flood control objectives in the NOD region based on the CalLite and CalSim II modeling logic. The second limitation of using fixed routing coefficients in an MTO model will not be part of this thesis. Future work will be to use routing methods (SSARR, variable Lag and K, etc.) which update coefficients based on channel flows. In summary, the research objectives are:

- Identify a channel routing method which fulfills criteria of "ease of implementation, quick run-time, and accuracy"
- Couple channel routing with multi-timestep optimization to prevent issues of excessive reservoir releases to decrease routing constraints travel times

The benefits of a daily WRIMS2-based model are:

- Prevent underestimation of flows in facilities like Fremont Weir, Sacramento Weir
- More direct coding of regulatory constraints which are usually daily requirements
- Facilitation of operations with short and medium-term forecasting.

1.3 California Water Resources Overview

California faces eternal challenges from hydrologic, temporal, and spatial water resources variability. Annual hydrology often varies greatly from year to year. Since 2000, a wet year has been followed by a multi-year dry period three times. Wet years are when the Sacramento Water Year (WY) Index exceeds 3.8. The 2000 water year (October 1999-September 2000) was followed by dry years from 2001 to 2005. 2006 was a wet year followed by dry years from 2007 to 2010. 2011 was another wet year followed by the 2012-2016 drought. Figure 2 shows that 2014-2015 and 2021 were the most critically dry years indicated by the Sacramento WY index below the threshold of 5.4. Figure 3 summarizes the interannual variability in California in which some periods are defined by historic flood events while others are historic drought periods. Overall, California has a lot of interannual variability where some years are dry from low precipitation while other years have record-high precipitation.

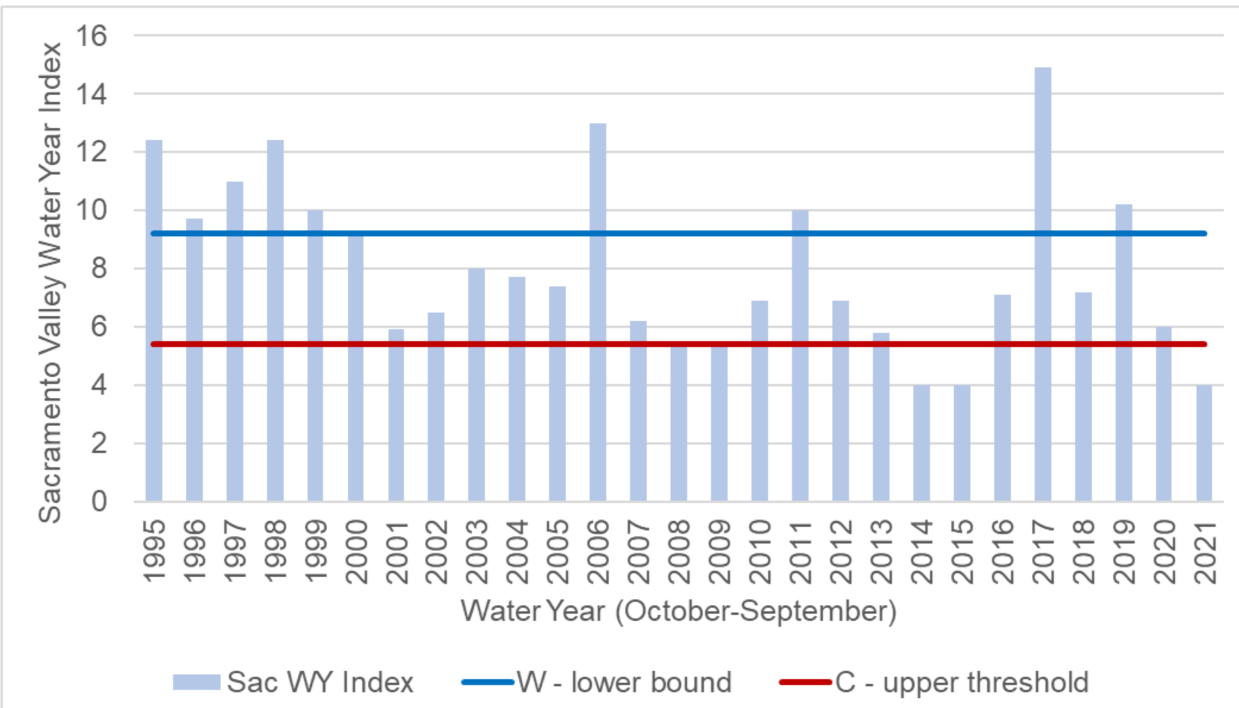


Figure 2. Official water year classifications based on May 1 Runoff forecasts from 1995-2021. Minimum index required to be considered a Wet year and the upper bound value before a year is considered Critical are shown as lines. (CA DWR, 2023)

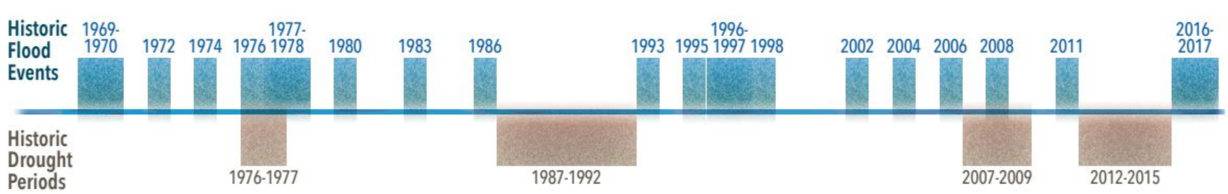


Figure 3. Historic flood and drought events from 1969 to 2017 (CADWR, 2018)

The hydrologic variability is due to the high interannual and intra-annual precipitation variability. Figure 4a and b show the coefficients of variation (standard deviation/mean) in a water year (October-September) for total precipitation and streamflow at long-term monitoring stations in the US. Precipitation and, to a lesser extent, streamflow in California are proportionally more variable from year to year compared to other West Coast regions and significantly more variable compared to most parts of the western and eastern states. Figure 4c shows that in much of California, the minimum number of wet days per year on average are 5-10 days to obtain half of the year's precipitation. California mainly relies on a few sizable storms. So it is important for water projects to be able to capture and store water in the few times that water is available.

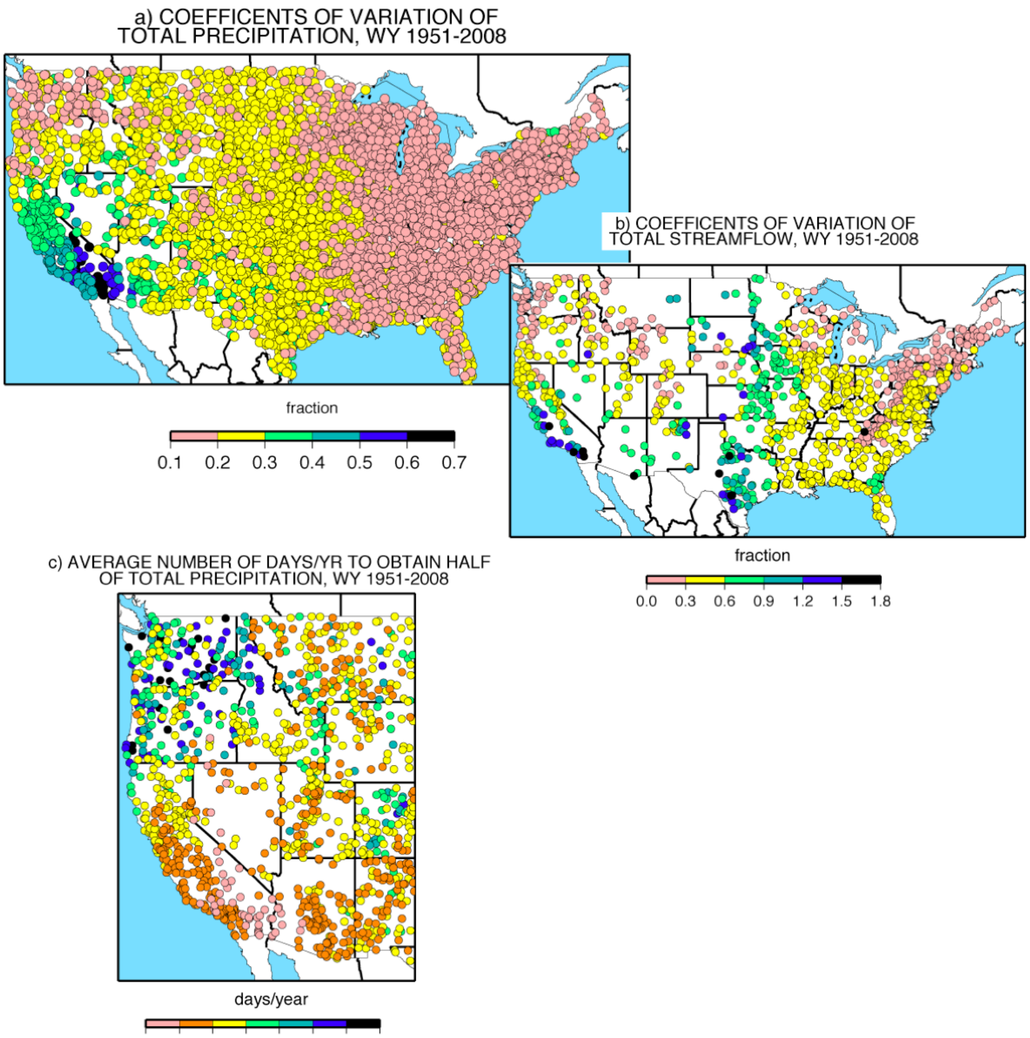


Figure 4. Coefficients of variation of water-year (a) precipitation and (b) streamflow totals at long-term monitoring stations across the conterminous US, from water year 1951–2008, along with (c) tallies of the minimum number of wet days per year, on average, that provide half of the year's precipitation in the western States (Dettinger et al., 2011)

Temporal imbalance exists between seasons when water availability exceeds demand, and seasons with more water demand than availability. For example, California's water supply is mainly from direct precipitation runoff and snowpack, usually from October to April. At least half of total precipitation occurs from December to February. But water demand is lowest in fall and winter. Spring and summer are when water is needed most for agriculture and cities, for crop and landscape irrigation. Spatial variability exacerbates this temporal variability. For example, 75 percent of the rainfall occurs in Northern California while 75 percent of water demand lies to the south (Hanak et al., 2011). Local, state, and federal agencies have built an extensive network of reservoirs, pumps, and conveyance facilities in the mid-20th century to respond to challenges regarding California's hydrologic, temporal, and spatial variability.

The Central Valley Project (CVP) under the United States Bureau of Reclamation (USBR) and State Water Project (SWP) under the California Department of Water Resources (DWR) were constructed to rebalance the state's water availability issues. Construction of Shasta Dam began in 1937 with water and power deliveries beginning in 1944 while Delta Mendota Canal pumping and San Joaquin River diversions began in 1951 (Hanak et al., 2011). SWP construction began in 1961, with the initial Oroville Dam facilities completed in 1965. By 1970, the Clifton Court Forebay, California Aqueduct, and Edmonston Pumping Plant were completed. Figure 5 displays a detailed map of California's major storage, pumping, and conveyance facilities. CVP facilities are shown in red while those of the SWP are in blue.

Figure 5. Map of California's local, state, and federal water project facilities (CA DWR, 2014)

North of the Delta, CVP overall has a storage capacity of about 7.9 million acre-feet (MAF) with Trinity Lake, Shasta Lake, and Folsom Lake combined. SWP's major storage facility is only Oroville Lake at 3.5 MAF. Thus, CVP has twice the reservoir capacity as the state. In terms of export capacity, SWP benefits from more flexible, higher diversion capacity at Banks pumping plant (10,300 cubic feet per second (cfs)). Jones or Tracy pumping plant under CVP has an export capacity of only 4,600 cfs. Figure 6 shows the geographic location, average inflow, storage, and export capacity for both projects.

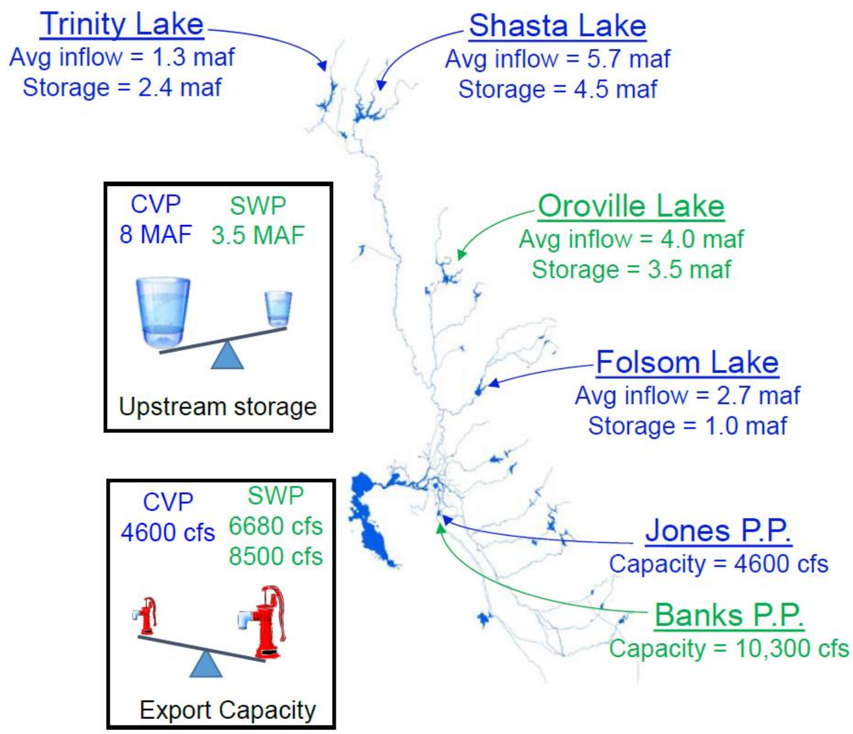


Figure 6. Major storage and pumping facilities for CVP and SWP (CA DWR, 2017).

The Projects help California manage the state's seasonal, inter-annual, and geographic variability and mismatches in water supplies and demands. However, challenges remain for managing the system across seasonal, monthly, daily, and interannual operations. Having only a few storms spanning a few days provides most of California's water resources highlights the importance of the complex CVP/SWP system being able to store water during the winter in upstream or off-stream reservoirs and groundwater storage. Due to year-to-year variability, these few storms could be the defining factor between extreme flood events resulting in single (2006, 2017) to multi-year (1995-2001) wet periods and single to multi-year (2012-2016, 2021-2022) droughts.

During intense flood events, operators need to prioritize flood management for public health and safety (on daily or hourly scales). Operators need to follow the United States Army Corps of Engineers (USACE) Water Control Manuals (WCM) and respective Water Control Diagrams (WCD) to ensure enough flood control pool space (reserved for flood storage). The WCD release schedules require reservoir releases when storage accumulates into the flood control pool.

In the flood season, operators also deal with temporal and spatial imbalance. During the winter, when water supply is plentiful, competing flood control objectives require reservoir releases to provide empty flood pool space according to the USACE WCDs. Additionally, water demand does not peak until spring and summer. So operators need to handle the spatial variability and transport the water downstream as is feasible considering physical and regulatory constraints. During winter storms, “surplus” flows can be captured at the Delta pumps (Banks and Tracy/Jones) and stored at San Luis Reservoir, the largest off-stream reservoir in the United States with a capacity of 2041 thousand-acre feet (TAF). San Luis storage can be then used in conjunction with upstream storage to supply water South of Delta. Additionally, operators need to make appropriate water allocations. This is to ensure enough carryover storage for the next year(s) (interannual) in case of few storms in the following years, or storms yielding insufficient precipitation.

Surplus flows from storms also can help mitigate groundwater overdraft in the Central Valley in addition to providing for water supply at San Luis. With passage of the Sustainable Groundwater Management Act (SGMA) in September 2014, local and regional agencies developed Groundwater Sustainability Plans (GSPs) that explain how they will ensure long term sustainability within their groundwater basins. In the same context of floods and groundwater storage, Flood Managed Aquifer Recharge (MAR) is a management strategy being analyzed that seeks to use high flows resulting from, or in anticipation of, precipitation or snowmelt for groundwater recharge on agricultural lands and working landscapes (CADWR, 2018).

The Projects need to adhere to Delta regulations (daily to weekly) such as the State Water Resources Control Board’s (SWRCB) Decision-1641 (D-1641), the 2019 National Marine and Fisheries Service (NMFS) and United States Fish and Wildlife Service (USFWS) Biological Opinions (BiOps) for the Long-Term Operation of the CVP and SWP (ROC LTO), the 2020 California Department of Fish and Wildlife (CDFW) Incidental Take Permit (ITP) for the Long-Term operations for the SWP.

During droughts, surface water supply is highly managed and constrained. During droughts, groundwater storage helps buffer supplies. However, some Central Valley aquifers have been overdrafted over decades from excessive pumping relative to recharge. SGMA requires groundwater sustainability which seeks to prevent overdraft and maintain aquifers at sustainable levels. As a result, in future drought periods, groundwater storage cannot be over-extracted which makes interannual planning even more crucial.

Overall, hydrologic variability, temporal gaps, and spatial mismatches in California water resources make operational management on daily, monthly, seasonal, and interannual scales difficult. Planning models are important tools that help explore alternatives and policy initiatives that support better water management in California.

1.4 History of California Water Supply Planning Models

Computer models help transform California's seemingly intractable problems into a quantifiable, systematic form where modelers, managers, and policy makers can analyze, explore, and compare solutions. As a result, water planners developed several models in the 1980s and 1990s called DWRSIM and PROSIM (Lefkoff and Kendall, 1996).

DWRSIM is generalized planning model developed at DWR to simulate CVP-SWP operations (Barnes and Chung, 1986). It is a monthly timestep simulation based on the HEC-3 model developed by the US Army Corps of Engineers using a network of control points. The control points are connected by links depicting river and canal reaches. DWRSIM models reservoir operating rules, inflow flow requirements, demands and diversions, Decision-1485 Delta requirements, and the 1986 Coordinated Operations Agreement between the CVP and SWP.

PROSIM is a similar model to DWRSIM that PROSIM emphasizes CVP operations. For example, PROSIM internally computes shortages to CVP contractors while DWRSIM relies on input data to fix CVP deliveries. DWRSIM contains a detailed representation of SWP contractors south of the Delta while PROSIM lumps them into a few network nodes (Lefkoff and Kendall, 1996).

CalSim's underlying modeling software is referred to as the Water Resources Integrated Modeling System (WRIMS), a generalized reservoir-river basin simulation modeling software developed at DWR and USBR (Munévar and Chung, 1999). CalSim was developed as a more flexible and efficient modeling tool. The issues with DWRSIM were that adding a new alternative or changing modeling assumptions required editing the Fortran source code. Over time, the DWRSIM Fortran source code grew and became too cumbersome and complex. It became increasingly difficult to change the model without unintentionally affecting other operations (Munévar and Chung, 1999).

CalSim uses the water resources simulation language (WRESL) for specifying objectives and constraints, simulation cycles, position analysis, and mixed integer linear programing (MILP) to route water through a network over time. Weights and constraints are assigned that represent the priorities and policies related water allocation and operating rules. Many other water resource system modeling packages employ a similar approach of using an optimization engine (network flow or mixed integer-linear programming) to implement operational priorities within constraints for a series of time-steps such as MODSIM, OASIS, Acres model in the Trent River System in Ontario, and WEAP (Labadie, 2006; Meyer et al., 1999; Sigvaldson, 1976; Yates et al., 2005).

CalSim II is an expanded application of WRIMS to the CVP/SWP system (Draper et al., 2004). It simulates the Central Valley over an 82-year planning horizon using monthly timesteps. The latest models cover regulations for the SWRCB Decision-1641, the 1986 Coordinated Operation Agreement (COA) along with the 2018 Addendum, the 2019 Biological Opinions (BOs), and Incidental Take Permit (ITP) 2020.

CalLite is a rapid, interactive screening tool for Central Valley water management. CalLite simulates hydrology, reservoir operations, project operations and delivery allocation, Delta salinity response, and habitat-ecosystem indices (Munévar et al., 2008). CalLite preserves the institutional and operational integrity of the more detailed CalSim II model. It runs the same 82-

year time frame and monthly timestep but completes in 3 minutes or less. CalLite runs depend on CalSim II outputs through a post-processing script called CalSim to CalLite (CS-CL). CalSim II runs take about 15 minutes to finish while CalSim 3 (explained in the next section) requires about 110 minutes. CalLite was designed to be more simplified and run faster to allow screening of a suite of alternatives of which a smaller subset would be eventually ported to the more detailed CalSim II/3 model (Islam et al., 2011).

CalSim 3 is the latest version of the CVP and SWP operations. CalSim 3 is an update to its predecessor CalSim II to perform planning studies. The first application of CalSim 3 for environmental review purposes is for the Delta Conveyance Project (DCP) Draft EIR (ICF International, 2022). CalSim 3 has many differences, some of the notable ones are (CA DWR and USBR, 2022):

- Finer spatial resolution of the major stream network, surface water diversions, and large water agencies or groups of smaller water agencies in the Central Valley
- Improved representation of mountain and foothill watersheds (rim watersheds) which surround the Central Valley floor
- Includes a C2VSIM groundwater module to simulate groundwater heads and stream-aquifer interactions more explicitly
- Extension of the simulation period from 1922-2003 to 1922-2015

The greater spatial representation, simulation period, and addition of groundwater, however, require more computation time. A CalSim 3 run takes two to three hours to complete depending on computational resources. Rapid evaluation of multiple alternatives is not feasible. As of now, a CalSim 3 to CalLite post-processing script is still under development to allow screening studies in CalLite based on CalSim 3 assumptions and hydrology like what has been done with CalSim II.

Table 2 summarizes the history of California DWR’s water resources planning models from DWRSIM to CalSim 3. CalSim II, CalLite, and CalSim 3 can either use the proprietary XA solver (Sunset Software Technology) or the free CBC solver (Moazzez et al., 2017). First publications are provided as well as the most recent known applications of each model. DWRSIM and PROSIM are legacy tools no longer in use for decades.

CalSim 3 is replacing its predecessor, CalSim II. The Delivery Capability Report (DCR) 2021 (CA DWR, 2022a) was the most recent publication with a Main Report, Technical Addendum, and an existing and future conditions scenario runs using CalSim 3. DWR is legally required to publish the DCR every two years under the Monterey Agreements (Jackson, 2006) and to provide SWP contractors information needed to formulate their Urban Water Management Plans. CalSim 3 was also one of the suite of models used to develop the Draft Environmental Impact Report (EIR) for the Delta Conveyance Project (DCP). Ray et al. (2020) coupled a physically based hydrological model (SAC-SMA-DS) and a water resources screening model (CalLite) for a climate change stress test on the California Central Valley Water System (CVS). Lastly, DWR Division of Planning uses the WEAP model in developing the California Water Plans while the SWRCB maintains a separate WEAP-based model called Sacramento Valley Water Allocation Model (SacWAM) for water rights and environmental regulations (SEI, 2019).

Table 2. Summary of California DWR, USBR, and SWRCB reservoir system planning models.

Model name	Publications	Currently in use?	Recent applications
DWRSIM	Barnes and Chung, 1986; Chung et al., 1989	No	N/A
PROSIM	USBR, 1990	No	N/A
CalSim II	Draper et al., 2004; Munévar and Chung, 1999	Yes	2019 DCR (CA DWR, 2020)
CalLite	Islam et al., 2011	Yes	Ray et al., 2020
CalSim 3	CA DWR and USBR, 2022	Yes	Delta Conveyance Project Draft EIR (ICF International, 2022); 2021 DCR (CA DWR, 2022a)
WEAP	Sieber, 2006; Yates et al., 2005	Yes	California Water Plan 2018, SacWAM Peer Review Response (CADWR, 2019; SWRCB, 2017)

1.5 WRIMS and WRESL Overview

CalLite and CalSim are applications of the Water Resources Integrated Modeling System (WRIMS). WRIMS is a generalized water resources modeling engine that evaluates operational and regulatory alternatives of complex systems such as the one in California. WRIMS or WRIMS1 used to need a proprietary Lahey Fortran compiler to run a model. WRIMS2 was developed to eliminate the need for proprietary modules or software to run the CalLite and CalSim models. WRIMS2 is developed using Java and can be downloaded as a standalone package (https://data.cnra.ca.gov/dataset/wrims-2-gui).

WRIMS2 parses the Water Resources Engineering Simulation Language (WRESL) or WRESL+ code during run time. Users can run the models with the free jCBC solver (Bai et al., 2017; Moazzez, 2016; Moazzez et al., 2017) or the commercial XA solver (Sunset Software Technology, 2003) to evaluate the MILP problem. For this thesis, WRIMS and WRIMS2 will be used interchangeably.

Equations (1) through (3) represent the MILP problem set as follows (Vanderbei, 2014):

$$\max Z \sum_{j=1}^{n} c_j x_j \quad (1)$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i \;\; (i = 1,2, \dots., m), \quad (2)$$

$$x_i \ge 0 \qquad (j = 1,2, \dots, n) \quad (3)$$

where:

- x_j = Decision variable (level of activity or binary integer)
- c_j = Cost coefficients to indicate priority
- n = number of decision variables
- m = number of constraints
- a_{ij} = constraint coefficients for decision variable i under constraint j
- b_i = value for constraint i

1.6 Report Organization

Chapter 1 states the problem and research objectives, provides a background of California water resources and models. Chapter 2 is a literature review of previous work on daily timestep models applied within WRIMS and other LP-based models that can perform daily timestep modeling and compare the channel routing techniques used/ This chapter also discusses previous research regarding channel routing within LP/MILP models and MTO. Chapter 3 details model formulation explains the incorporation of channel routing and multi-timestep optimization in WRIMS2 and discusses the model configurations and inputs. Chapter 4 presents the results and discusses them for the WY 1997. Lastly, Chapter 5 summarizes the research conclusions, study limitations, and future work recommendations.

Chapter 2 Literature Review

This section discusses previous research on WRIMS-based channel routing efforts and future or parallel timesteps (Chen, 2011; Fung, 2011; Hoffpauir, 2011). A brief overview of hydraulic and hydrologic routing is then presented. The most common routing methods are presented in more detail. Next, some of the most notable flood or river/reservoir models is discussed. Then previous work about channel routing with respect to MTO in river/reservoir models is explained. An application of MTO within WRIMS2 known as CAM is described. Lastly, the research questions that drove the study are listed.

2.1 Previous Work

Fung (2011) explored the use of hydrologic channel routing in WRIMS for application in a large-scale planning model such as CalLite. The methods compared were Muskingum, Lag, and Storage routing which are all coefficient based linear routings. In that study, the Muskingum method was recommended since it uses the most parameters compared to lag and storage routing which makes better fitting hydrographs easier. However, the Muskingum method requires more work calibrating. However, once calibration is done, this method is easy to implement and be used in systems such as California NOD.

The other main limitation at that time was the unavailability of future decision variable forecasting in WRIMS. As a result, it was difficult to handle the question of “how can the model know how much water to release in the current timestep knowing that there is a demand in future timesteps and associated travel time?”

Forecasting is needed so the model can employ estimated downstream conditions to make release decisions. The concept of forecasting is that for every time step, a “real” simulation and a forecast simulation are happening concurrently. This brings about the concept of multiple timesteps occurring simultaneously. However, WRIMS did not have multiple timestep capability back then. Fung's (2011) work had a 2-day forecast period. In Figure 7, yellow current releases are made on Day 1. Then the forecasted downstream outflow on Day 3 is calculated based on the Day 1 current releases. Perfect foresight can be used by setting the red forecasted outflow on Day 3 to be greater than or equal to a historical timeseries (e.g. Hood or Freeport) to meet objectives like Delta inflow. The solver then backtracks from the future timestep to find the optimal yellow current day release on Day 1 in the “real” simulation. Ultimately, the release from Day 1 only matters because the parallel releases in Day 2 and Day 3 are not used but are recalculated in the following timestep. Today, there is now multiple timestep capability within WRIMS (H. Xie, personal communication, May 18, 2022). This new feature enables evaluation of a daily timestep NOD run with and without MTO to understand its impacts.

Chen (2011) presented a CalLite Daily Operation Model. The features include coupling of monthly and daily simulations, monthly delivery allocations are used for daily simulation, reservoir releases and channel flows are determined with a forecasting scheme, daily routing is implemented in NOD. Linear storage routing was used within WRIMS and could be coupled with external models, back routing, and multi-period optimization. A model from January 26, 2011 was reviewed (Z.R. Chen, personal communication, May 30, 2022) but the MTO syntax was not implemented. This could be because the WRIMS2 MTO and forecasting module was not available until later (Islam, 2012). In summary, a routing method such as linear storage routing within WRIMS can be implemented. The missing component at the time was MTO capability.

Hoffpauir (2011) developed a daily time step simulation in one of Texas' main water resources models called the Water Rights Analysis Package (WRAP) and Texas Water Availability Modeling (WAM) System. One concern discussed was the complexity of adhering to water rights priority order with a routing time lag. Junior rights diverting water upstream can potentially affect water availability of senior rights downstream in future timesteps. The approach taken was to enable a simulation beyond the current timestep (future), record water availability information in future timesteps through arrays, and then go back to the "real" or current timestep to constrain water availability so future impacts to senior water right holders are mitigated. This forward simulation is known as forecasting in a WRAP's daily simulation model, SIMD.

Flow forecasting in SIMD enables the consideration of stream flow availability over a future forecast period. This can help assess future timestep water availability and flood flow capacity for water rights. Without forecasting, SIMD only considers the current timestep to calculate water availability and downstream flood flow capacity. With forecasting, future forecast days *Fp* are included in the simulation to examine available flows or senior water right holders at downstream control points.

An example of the SIMD forecasting algorithm is shown in Figure 8 with a forecast period of 5 days starting on Day 10. Before Day 10, all state variables are saved. On Day 10, a total of 6 timesteps happen in parallel: the "real" simulation on Day 10 and the forecast simulations from Day 11 to Day 15. Pertinent information is saved from the forecast simulations on Days 11-15. Once the last day of the forecast period, Day 15, is finished, SIMD returns to the current timestep at Day 10. Day 10 of the real simulation then proceeds which is similar to Fung's (2011) conceptual example of the solver backtracking from the last day of the forecast period to find the optimal operation or release in the real simulation.

In summary, Fung (2011) and Hoffpauir (2011) emphasized the ability of forecasting or multi-timestep simulation when using channel routing in a system where travel times from upstream reservoirs take longer than the timestep (one day in this case) to reach a demand, water right, control point flow requirement, etc.

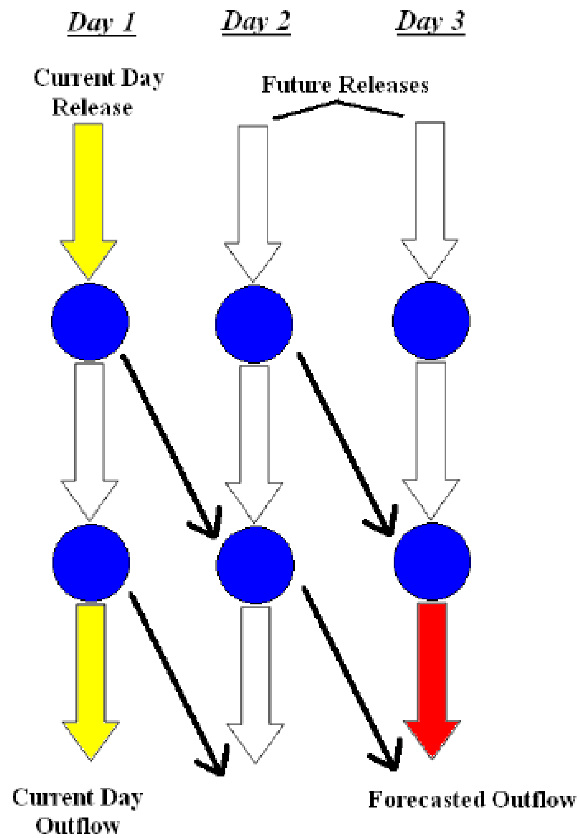


Figure 7. Parallel system of releases with a 2-day forecast period (Fung, 2011)

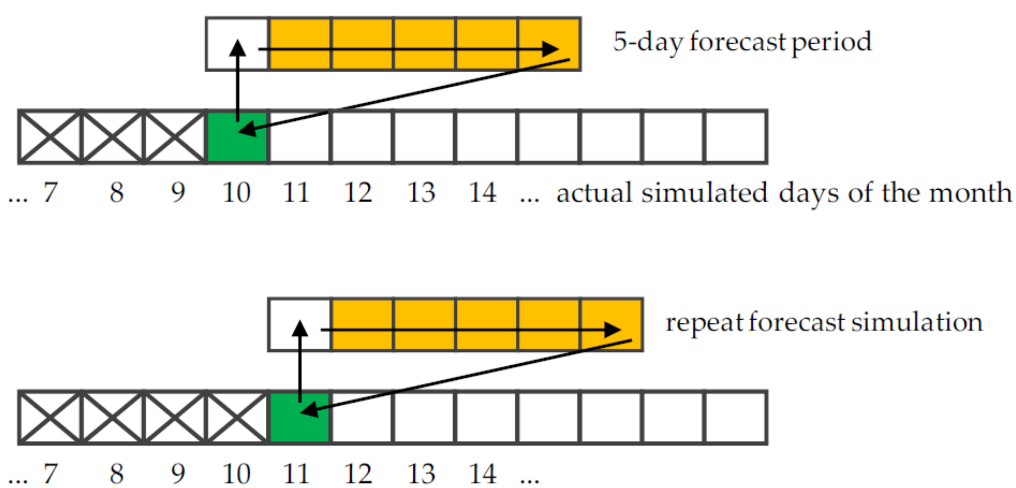


Figure 8. SIMD Forecast Algorithm Conceptual Example (Hoffpauir, 2011)

2.2 Hydraulic and Hydrologic Routing Overview

Routing is a procedure to calculate the outflow hydrograph's magnitude and timing given an inflow hydrograph. Routing techniques are split into two main categories: hydraulic and hydrologic. Hydraulic routing techniques solve the partial differential equations of unsteady open channel flow. The equations used are referred to as the St. Venant or dynamic wave equations. Hydrologic routing solves the mass balance (continuity) equation and an analytical or empirical relationship between reach storage and outflow discharge (USACE, 1994). Hydraulic methods are known for their additional complexity and long computations which may not be practical for large-scale MILP models such as the California CVP/SWP system. But hydrologic routing methods are relatively easy to implement and require few inputs compared to hydraulic methods. So hydrologic routing methods will be the emphasis of this section.

Hydraulic routing, also referred to as unsteady flow routing, is based on the Saint-Venant equations or one-dimensional unsteady flow equations. Hydraulic routing computes flow rate and water surface elevation or depth as a function of space and time. The conservation forms of the continuity and momentum equations are shown below:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \frac{g\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0$$

where Q = flow rate, x = longitudinal distance along the channel or river, t = time, A = cross-sectional area of flow, S_f = friction slope, S_0 = channel bottom slope, g = acceleration due to gravity, and y = depth of flow

Hydrologic routing is a lumped procedure which calculates flow rate as a function of only time. This method relates the inflow, $I(t)$, outflow, $O(t)$, and storage, $S(t)$, through the continuity equation (4. Hydrologic routing methods generally use the simple finite difference approximation of the continuity equation (Equation (5). Then it is rearranged so that the unknowns are at the left-hand side of the equation (Equation (6). Inflow is known in the current and previous timestep, but outflow and storage are unknown for the current timestep. This means there are two unknowns and just the conservation of mass equation is not sufficient. A second equation that relates outflow with storage is needed.

$$\frac{dS}{dt} = I(t) - O(t) \tag{4}$$

$$\frac{(S_t - S_{t-1})}{\Delta t} = \frac{(I_t + I_{t-1})}{2} - \frac{O_t + O_{t-1}}{2} \tag{5}$$

$$\frac{2S_t}{\Delta t} + O_t = I_{t-1} + I_t + \frac{2S_{t-1}}{\Delta t} - O_{t-1} \qquad (6)$$

2.3 Common Routing Methods

This section describes the most common hydrologic routing methods. The methods included are used in popular modeling tools such as HEC-HMS and HEC-ResSim (Table 3). These hydrologic and reservoir operation models will consist of more comprehensive channel routing options compared to system models or generalized river/reservoir models. Table 4 summarizes some of the most common routing methods in river/reservoir management models.

Table 3. Routing method options in HEC-HMS, HEC-ResSim, and CHPS

Model	Purpose	Routing Method Options
HEC-HMS	To simulate the complete hydrologic processes of dendritic watershed systems	• Lag • Kinematic Wave • Modified Puls • Muskingum • Muskingum-Cunge
HEC-ResSim	To model reservoir operations at one or more reservoirs for a variety of operational goals and constraints	• Coefficient • Muskingum • Muskingum-Cunge 8-pt Channel • Muskingum-Cunge Prismatic Channel • Modified Puls, SSARR, and Working R&D • Variable Lag and K
Community Hydrologic Prediction System (CHPS)	To meet the National Weather Service (NWS) River Forecast Centers (RFCs) operational requirements	• Lag and K • Layered Coefficient • Muskingum • SSAR • Tatum Coefficient

2.3.1 Muskingum

The Muskingum model is one of the most popular and widely used channel routing methods in flood control modeling and generalized river/reservoir modeling. The Muskingum routing method also used a simple finite difference approximation of the continuity equation shown in Equation (5). The Muskingum method splits the storage reach into wedge and prism volumes to overcome the looped relationship between storage and outflow in channels (Figure 9).

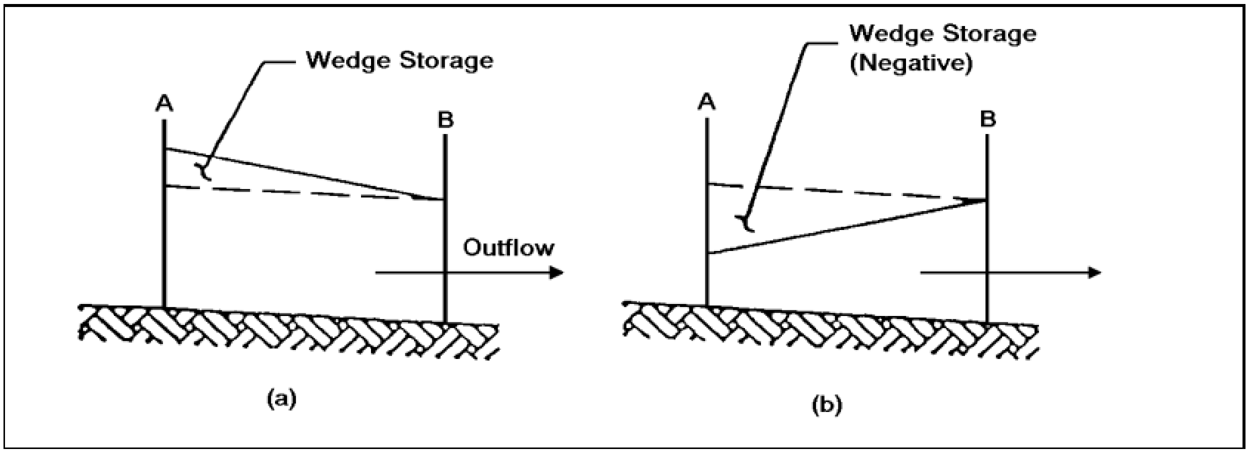


Figure 9. Muskingum prism and wedge storage concept (USACE, 1994)

The storage equation is the sum of prism storage, outflow times the travel time through the reach (K), and wedge storage which is the weighted difference (X) between inflow and outflow multiplied by the travel time K.

$$S = KO + KX(I_t - O_t) = K((XI) + ((1-x)O)) \tag{7}$$

Where:

K = Travel time for water that enters the reach to exit the reach

X = Attenuation coefficient from 0.0 to 0.5. A value of 0.0 implements maximum attenuation while a value of 0.5 simple translates the hydrograph through the reach

The Muskingum outflow equation can be determined by combining the storage equation (7) with the continuity equation then solving for outflow.

$$O_t = C_1 I_t + C_2 I_{t-1} + C_3 O_{t-1} \tag{8}$$

The routing coefficients are based on Δt*, K, and X* as follows:

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \tag{9}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \tag{10}$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} \tag{11}$$

One common way to estimate K and X is through analysis of the observed inflow and outflow hydrographs. The K parameter can be estimated as the elapsed time between the centroid of areas of the two hydrographs, between the hydrograph peaks, or between the midpoints of the rising limbs. X can then be estimated through trial and error once K is determined. For ungagged watersheds, K and X can be estimated from channel characteristics by calculating flood wave velocity using Seddon's law, dividing channel length and velocity to obtain K, and using Cunge's (1969) equation for X (USACE, 1994).

2.3.2 Muskingum-Cunge

The Muskingum-Cunge method uses the Muskingum routing equation as well, but the X and K parameters are physically based since the method approximates a diffusion wave. One difference in the solution is that lateral flow (q_L) is now included in a form of the continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L \tag{12}$$

The momentum equation is also considered unlike the Muskingum method which uses an empirical relationship to determine storage:

$$S_f = S_o - \frac{\partial y}{\partial x} \tag{13}$$

Combining Equations (12) and (13) using a linear approximation result in the convective diffusion equation:

$$\frac{\partial Q}{\partial t} + \frac{c\partial Q}{\partial x} = \mu \frac{\partial^2 Q}{\partial x^2} + cq_L \tag{14}$$

where:

Q = discharge (cfs)

A = flow area (square feet)

t = time (s)

x = distance along channel (ft)

Y = flow depth (ft)

qL = lateral inflow per unit of channel length

Sf = friction slope

So = bed slope

C = wave celerity in the x direction

Ultimately the main outflow equation is:

$$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} + C_4 (q_L \Delta x) \quad (15)$$

Where the coefficients are:

$$C_1 = \frac{\frac{\Delta t}{K} + 2X}{\frac{\Delta t}{K} + 2(1 - X)} \quad (16)$$

$$C_2 = \frac{\frac{\Delta t}{K} - 2X}{\frac{\Delta t}{K} + 2(1 - X)} \quad (17)$$

$$C_3 = \frac{-\frac{\Delta t}{K} + 2(1 - X)}{\frac{\Delta t}{K} + 2(1 - X)} \quad (18)$$

$$C_4 = \frac{2\frac{\Delta t}{K}}{\frac{\Delta t}{K} + 2(1 - X)} \quad (19)$$

Parameters K and X can be determined using:

$$K = \frac{\Delta x}{c} \quad (20)$$

$$X = \frac{1}{2}(1 - \frac{Q}{B S_o c \Delta x}) \quad (21)$$

A distinction between Muskingum and Muskingum-Cunge is that the coefficients change over time because the *Q*, *B*, and *c* also change for every distance and timestep, making this method non-linear. The data requirements are:

- Channel cross section
- Reach length
- Manning roughness coefficient
- Friction or channel bed slope

Muskingum-Cunge is more applicable on ungagged streams unlike Muskingum, despite having similar routing equations. The weighting factor X is more physically based whereas in Muskingum the X is estimated after establishing K. Another difference is the solution technique. The Muskingum method treats the reach as a single routing distance step while the Muskingum-Cunge method defines a routing distance step length and sub-reaches if needed (USDA, 2014)

2.3.3 Modified Puls

The Modified Puls method, also known as storage or level-pool routing, is based on a finite difference approximation of the continuity equation and an empirical representation of the momentum equation. This method can be used for reservoir and streamflow routing. In streamflow routing, the river is treated like a reservoir.

The storage-discharge function of a river is non-unique or "looped." Routing in natural rivers is complicated by storage in a river reach not depending on outflow alone. The modified puls method treats the reach as a set of cascading reservoirs (Figure 10). Each reservoir is assumed to have a level pool. In other words, there is now a unique storage-discharge relationship.

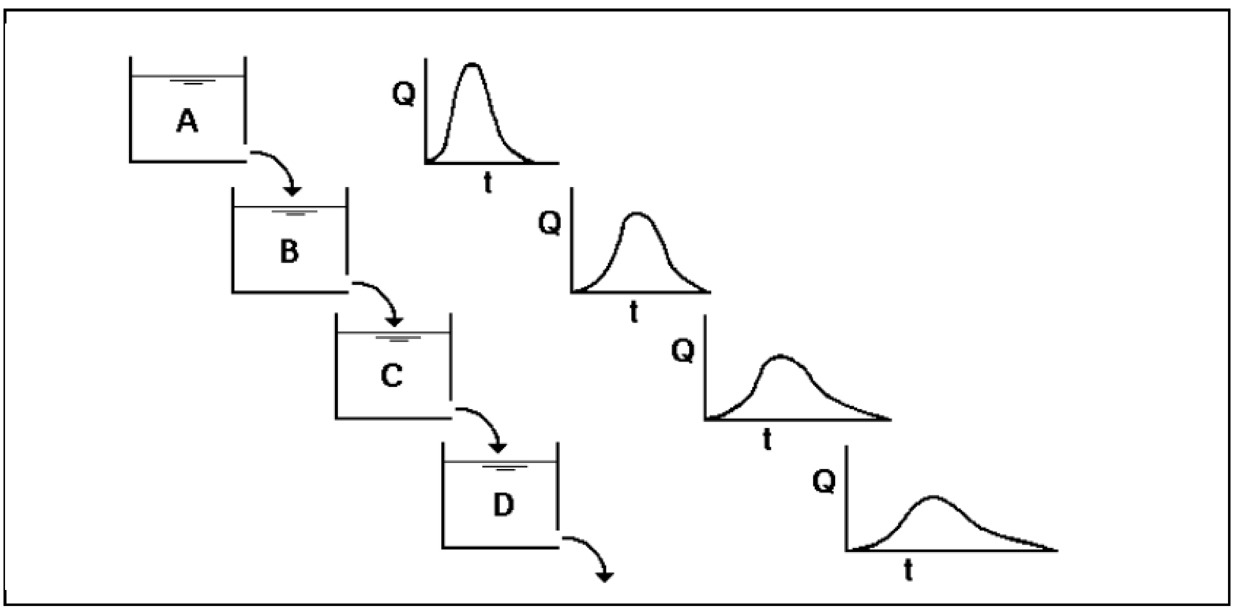


Figure 10. Modified Puls assumption of cascading reservoirs to represent channel storage routing (USACE, 1994)

Modified puls has two unknowns of storage and outflow which is the LHS of equation (6). A backward differencing scheme and rearrangement of Equation (4) leads to:

$$(\frac{S_t}{\Delta t}+\frac{O_t}{2})=(\frac{I_{t-1}+I_t}{2})+(\frac{S_{t-1}}{\Delta t}-\frac{O_{t-1}}{2}) \tag{22}$$

At all times t, all terms on the LHS are known. The two unknowns are current timestep storage and outflow which makes this a non-linear equation. A tabular relationship between storage versus outflow is needed to determine outflow. This can be determined through one of many methods (USACE, 1994):

- Steady-flow profile computations
- Observed water surface profiles
- Normal-depth calculations
- Observed inflow and outflow hydrographs
- Optimization techniques applied to observed inflow and outflow hydrographs

2.3.4 SSARR

The SSARR routing method is based on the computer program *Streamflow Synthesis & Reservoir Regulation (SSARR)* from the Corps' Northwestern Division. It is a variable coefficient routing method dependent on channel flow. The model relies on an empirical relationship between travel time and flow for a channel. The reach storage is determined by the Time of Storage (T_s) in hours. The Modified Puls method uses a storage-outflow relationship. On the other hand, SSARR uses T_s versus outflow.

A derivation of the SSARR method was provided by Optimal Solutions Ltd., (2020) and summarized here. SSARR's governing equation related to channel storage over a timestep is a function of average inflow and outflow shown in Equation (23).

$$\frac{I_{t-1}+I_t}{2}-\frac{O_{t-1}+O_t}{2}=\frac{\Delta S}{t} \tag{23}$$

After rearranging the equation and setting $\Delta S/(O_t\text{-}O_{t-1}) = Ts$, this yields Equation (24):

$$O_t=\frac{\left[\frac{I_t-1+I_t}{2}-O_t-1\right]\cdot t}{Ts+\frac{t}{2}}+O_t-1 \tag{24}$$

T_s (time to storage) can also be defined by the Equation (25) instead of using the interpolation table relating T_s and Q:

$$T_s=\frac{KTS}{Q^n} \tag{25}$$

Where:

T_s = time to storage in hours

KTS = Constant determined by trial and error or estimated from physical measurements of flow and route times

Q = Discharge in cubic meters or feet per hour

n = Coefficient between -1 and 1

Assuming the steady-state initial condition where $O_{t-1} = O_t$, one can linearize the problem.

The main SSARR outflow equation has the form which looks like that of the Muskingum method:

$$O_t = \frac{t}{2T_s + t} I_{t-1} + \frac{t}{2T_s + t} I_t + \frac{T_s - \frac{t}{2}}{T_s + \frac{t}{2}} O_{t-1} \quad (26)$$

2.3.5 Working R&D

The Working R&D method uses a nonlinear storage-outflow relationship similar to the Modified Puls method. It also uses the wedge storage concept like the Muskingum method. This method is useful when using a variable K (travel time). Since Working R&D is nonlinear, a variable K is necessary. This method is also useful when the level pool surface assumption in the Modified Puls is not applicable (USACE, 1994).

The Working R&D procedure can also be referred to as "Muskingum with variable K" or "Modified Puls with wedge storage. For a linear storage-discharge relationship, this procedure works the same as the Muskingum method. When there is no wedge storage assumed (X=0), the procedure is the same as Modified Puls (USACE, 1994).

Wedge storage can be computed using the Muskingum equation (Equation (27)) or the working discharge concept (Equation (28)). Equating (27) and (28) and solving for O will lead to Equation (29). After combining the two equations and solving for O, Equation (30) is determined.

$$WS = KX(I - O) \quad (27)$$

$$WS = K(D - O) \quad (28)$$

$$K(D - O) = KX(I - O) \quad (29)$$

$$O = D - \frac{X}{1 - X}(I - D) \quad (30)$$

Where:

I = reach inflow

O = reach outflow

D = working value discharge or working discharge

WS = Wedge storage

X = dimensionless weighting factor, ranging from 0.0 to 0.5 (from Muskingum method)

Equation (30) is then plugged into the continuity equation. There is a relationship called "working value of storage" that represents an index of natural storage. Working discharge is analogous to the storage indication in the Modified Puls model. Outflow can be determined using a lookup table of working storage vs working discharge.

Ultimately the outflow equation is as follows:

$$O_t = D_t - \frac{X}{1-X}(I_t - D_t) \quad (31)$$

2.3.6 Lag and K

Lag and K is one of the methods in the National Weather Service's (NWS) Community Hydrologic Prediction System (CHPS) model. The California-Nevada River Forecast Center (CNRFC) uses variable Lag and K for streamflow forecasting on an hourly timestep using forecast domains of weeks (P. Fickenscher, personal communication, January 22, 2022). DWR's reservoir forecasting unit works with CNRFC's modeling system. DWR (N. Burley, personal communication, February 24, 2022) and CNRFC use Lag and K for flow forecasting instead of the more common Muskingum method.

Lag and K is a special case of the Muskingum method. Channel storage is represented by the prism volume alone without wedge storage (Muskingum X = 0). This method allows the routing lag to be a constant or a function of inflow. The attenuation K could also be fixed or a function of outflow. This differs from the Muskingum method's K which represents time travel or lag in a channel.

The Lag algorithm has two options for initial conditions. The first method sets inflow equal to outflow (steady-state assumption) while the second method sets inflow equal to specified discharge as the inflow hydrograph and is lagged by a constant or variable time. Lag is entered as inflow-lag curves while K is entered as an outflow-attenuation curve.

The K algorithm using the storage routing procedure attenuates flow in an outflow hydrograph. K is related to outflow downstream instead of being related to inflow in the lag algorithm. In constant Lag and K, only one value of K is needed. But if using the variable Lag and K algorithm, a K versus outflow table is needed (NOAA, 2002).

The equation for Lag and K is based on the mass balance equation between inflow, outflow, and change in storage shown in Equation (32):

$$\frac{(I_{t-1} + I_t)}{2}\Delta t - \frac{(O_{t-1} + O_t)}{2}\Delta t = S_t - S_{t-1} \tag{32}$$

The unknowns are outflow and storage at the end of the routing interval (t). Moving the unknowns to one side leads to Equation (33):

$$I_{t-1} + I_t + \frac{2S_{t-1}}{\Delta t} - O_{t-1} = \frac{2S_t}{\Delta t} + O_t \tag{33}$$

To solve this equation, a relationship between storage and outflow on the RHS is needed. This table relates O_t and $2S_t/\Delta t + O_t$.

The K algorithm can also be used with period averaged flows instead of instantaneous flows. Equation (4) is then replaced with:

$$\bar{I} - \frac{O_{t-1} + O_t}{2}\Delta t = S_t - S_{t-1} \tag{34}$$

Equation (6) then becomes:

$$\frac{\overline{2I}}{\Delta t} + \frac{2S_{t-1}}{\Delta t} - O_{t-1} = \frac{2S_t}{\Delta t} + O_t \tag{35}$$

One potential problem using Lag and K is the multiple intercept problem especially when the lag vs inflow relationship is highly variable. Multiple intercepts occur when a lagged inflow hydrograph doubles back upon itself. This is when two or more discharges occur at the same time or ordinate (Figure 11).

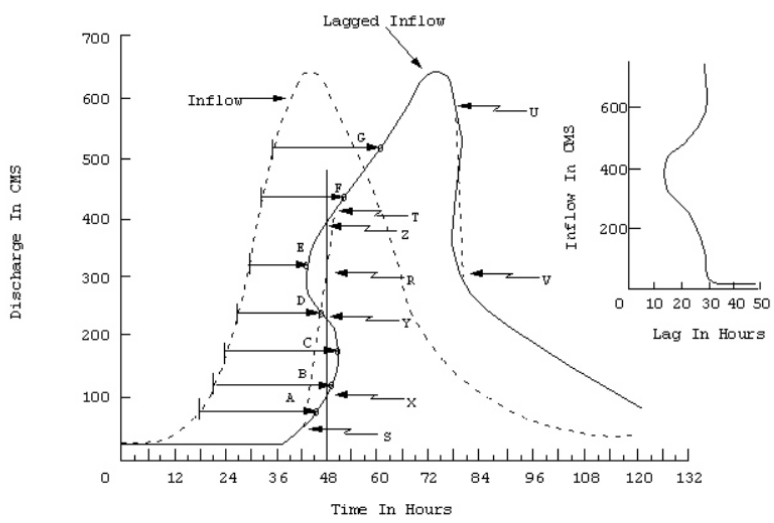


Figure 11. Lagged Inflow Graph with Multiple Intercepts (NOAA, 2002)

Table 4. Selected channel routing methods summary

Routing Method	Governing equation	Inputs	Pros	Cons
Lag and K	$(I_{t-1}+I_t)+\frac{2S_{t-1}}{\Delta t}-O_{t-1}=\frac{2S_t}{\Delta t}+O_t$	Inflow vs. Lag relationship, Outflow vs. K relationship, O_t and $2S_t/\Delta t + O_t$ relationship	• Can use fixed or variable routing parameters	• Multiple intercepts possible which can cause volume errors and peak attenuation
Modified Puls	$(\frac{S_t}{\Delta t}+\frac{O_t}{2})=(\frac{I_{t-1}+I_t}{2})+(\frac{S_{t-1}}{\Delta t}-\frac{O_{t-1}}{2})$	O_t and $2S_t/\Delta t +$ O_t relationship	• Easily applied in ungauged basins since parameters are physically based and can be estimated from channel characteristics • Only hydrologic routing method that incorporates backwater effects	• Determining storage-outflow relationship can be tedious • Not applicable if the reservoir surface is not horizontal • Not appropriate for very channel slopes < 2 ft/mile
Muskingum	$O_t = C_1 I_t + C_2 I_{t-1} + C_3 O_{t-1}$ $C_1 = \frac{\Delta t - 2KX}{2K(1-X)+\Delta t}$ $C_2 = \frac{\Delta t + 2KX}{2K(1-X)+\Delta t}$ $C_3 = \frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}$	X, K	• Ease of implementation • Only two routing parameters are needed	• Negative outflows possible if criteria are not met • Does not hold well when the storage-outflow relationship is non-linear

Muskingum-Cunge	$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} + C_4(q_L \Delta x)$ $$C_1 = \frac{\frac{\Delta t}{K} + 2X}{\frac{\Delta t}{K} + 2(1-X)}$$ $$C_2 = \frac{\frac{\Delta t}{K} - 2X}{\frac{\Delta t}{K} + 2(1-X)}$$ $$C_3 = \frac{-\frac{\Delta t}{K} + 2(1-X)}{\frac{\Delta t}{K} + 2(1-X)}$$ $$C_4 = \frac{2\frac{\Delta t}{K}}{\frac{\Delta t}{K} + 2(1-X)}$$	X, K $X = \frac{1}{2}(1 - \frac{Q}{BS_o c\Delta x})$ $$K = \frac{\Delta x}{c}$$	• Applicable to the widest range of channel slopes and inflow hydropgrahs • Easily applied in ungauged basins since parameters are physically based and can be estimated from channel characteristics • Compares well with full unsteady flow equations • Solution is independent of the user-specified computation interval	• Does not account for backwater effects • Begins to diverge from the full unsteady flow solution when hydrographs rapidly rise
SSARR	$O_t = \frac{t}{2T_s+t} I_{t-1} + \frac{t}{2T_s+t} I_t + \frac{T_s - \frac{t}{2}}{T_s + \frac{t}{2}} O_{t-1}$ $T_s = \frac{KTS}{Q^n}$	Table of time of storage vs discharge or as a power function of discharge	• Updates routing coefficients depending on flow conditions instead of assuming fixed parameters	• Time of storage is very sensitive to changes in *n* • Many more steps to determine reach characteristics
Working R&D	$$O_t = D_t - \frac{X}{1-X}(I_t - D_t)$$	Working discharge, D and working storage, $S_t/\Delta t\ (1\text{-}X) + D/2$ relationship	• Accommodates non-linear flood waves through channels • Useful where the horizontal reservoir surface assumption of modified puls is not applicable	• More complex to implement. Requires developing a rating curve of working storage vs working discharge

Fung (2011) compared and summarized the three general categories of routing methods (coefficient, storage, and lag). Overall, he found that Muskingum method or storage will be more accurate than simple lags. However, this is only comparing fixed coefficient methods between the three types. Using Lag and K instead of just the lag model could have improved accuracy.

Criteria	Muskingum	Storage	Lag
Accuracy	· Accurate for short time frames subject to calibration	· Accurate for short time frames subject to calibration	· Low
Sensitivity	· Highly sensitive to large changes in parameters	· Less sensitive to large changes in parameters	· N/A
Range of Possible Solutions	· Largest range	· Modest range	· Small range
Number of Coefficients	3	2	· Varies

Figure 12. Summary of routing methods compared (Fung, 2011)

2.4 Selected River/Reservoir Models

This chapter reviews eight generalized river-reservoir system models that can simulate monthly and sub-monthly timesteps (weekly, daily) and have some channel routing capability. These are summarized in Table 5. Model background and routing techniques will be explained to summarize the channel routing methods implemented in some of the most used river basin management models. Channel routing with respect to MTO will be discussed. Then CAM, an application MTO within WRIMS2, will be explained. Lastly, this study's research questions will be presented.

2.4.1 HEC-ResFloodOpt

HEC-ResFloodOpt is a mixed-integer linear programming optimization model for flood reduction studies. This model stands out from the rest of the following models because HEC-ResFloodOpt is more tailored for flood control analysis and more less so river/reservoir management. It warrants special attention because previous work on a California NOD application was used to update the study's model schematic (Connaughton, 2014; Jones, 2013, 1999) It was formerly known as the Flood Control Linear Program (FCLP) and developed by David Ford Consulting Engineers (Needham et al., 2000).

HEC-ResFloodOpt simulates releases from reservoirs to minimize user-defined penalties accumulated when river flows violate operational guidelines. A simulation embedded in the HEC-ResFloodOpt LP model uses releases as input and storage and downstream flows as output. Reservoir continuity and Muskingum channel routing are accommodated. This model has been applied to examine benefits of expanding the Sacramento River Watershed bypass system in California (Jones, 2013) and evaluate priority-based reservoir optimization, operating constraints, and penalty values for the Iowa/Des Moines system (Brown, 2005). Model timesteps range from hourly to daily (USACE, 2000). This model can use either 1) user specified linear routing coefficients or the 2) Muskingum method.

2.4.2 MODSIM

MODSIM is a generalized river basin management decision support system based on network flow programming (NFP) developed at Colorado State University (Labadie, 2006). MODSIM employs a minimum cost network flow optimization algorithm for simulation water allocation according to water rights, storage ownership contracts, interstate compacts, and economic valuation. One of the powerful features of MODSIM is a graphic user interface (GUI) for network creation, data import and editing, and georeferenced graphical output results.

MODSIM uses Muskingum or user-specified time-lagged hydrologic stream flow routing. MODSIM also applies a backrouting procedure which looks ahead to future time periods to maintain legal water allocation under appropriate water rights (Labadie, 2010).

2.4.3 OASIS

OASIS (Operational Analysis and Simulation of Integrated Systems) is a mixed-integer linear program that models water resources systems operations (Randall et al., 1997). OASIS simulates water routing through a system of nodes and arcs (Hydrologics, 2009) solving the linear program where all operation rules are expressed as goals or constraints. Like CalSim/CalLite, OASIS uses an MILP solver (M. Rivera, personal communication, July 29, 2022), and an English-like code syntax called Operations Control Language (OCL) comparable with WRESL.

OASIS implements the hydrologic Muskingum routing technique for situations where travel times through model region exceed the timestep length. Reservoirs fill and release according to the constant routing coefficients (Alberta Innovates Energy and Environment Solutions and WaterSMART Solutions Ltd., 2012). Time steps range from hourly to monthly although an OASIS modeling practitioner said that the "timestep can be anything as dictated by the data available and the client (e.g., we could run 23.7 second timesteps if the data was there)" (Alberta Innovates Energy and Environment Solutions and WaterSMART Solutions Ltd., 2012). OASIS has been applied in numerous systems such as California's State Water Project system, New York City's Operations Support Tool (OST), and Florida's Kissimee Basin Modeling and Operations Study (KBMOS).

Table 5. Selected river-reservoir simulation models which can represent channel routing.

Model	Simulation Timestep(s)	Routing techniques	Developer
HEC-ResFloodOpt	Hourly to daily	Muskingum and Linear Coefficient	USACE HEC https://www.hec.usace.army.mil/
MODSIM	Daily to monthly	Muskingum and Time Lag	Colorado State University, with support from Bureau of Reclamation and other agencies http://modsim.engr.colostate.edu/
OASIS	Hourly to monthly	Muskingum	Hazen-Sawyer (previously Hydrologics) https://www.hazenandsawyer.com/
PyWR	Daily to monthly	Time Lag	Tomlinson, J.E., Arnott, J.H. and Harou, J.J. https://github.com/pywr/pywr
RIVERWARE	Hourly to annual	Fixed and Variable Time Lag, Impulse Response, Fixed and Variable Step Response, Muskingum, Muskingum with Segments, Kinematic, Kinematic Improved, Muskingum-Cunge, Muskingum-Cunge Improved, MacCormack, Fixed and Variable Storage Routing, Modified Puls	University of Colorado Boulder, Center for Advanced Decision Support for Water and Environmental Systems, Bureau of Reclamation, Tennessee Valley Authority https://riverware.org/
WEAP	Daily to monthly	None by default but can be coded	Stockholm Environment Institute https://www.weap21.org/
WEB.BM	Hourly to annual	SSARR	Optimal Solutions Ltd. (Ilich, 2022) https://www.riverbasinmanagement.com/
WRAP	Daily to annual	Lag and Attenuation (K)	Texas A&M University sponsored by the Texas Water Resources Institute, Texas Commission on Environmental Quality, USACE Forth Worth District, other Texas agencies

2.4.4 PyWR

PyWR is a recent open-source, generalized water resource network model Python library developed at the University of Manchester (Tomlinson et al., 2020). It solves cost-minimization network resource allocation problems at user-defined time steps using linear programming. One key feature is an interface to specify multi-objective optimization problems. This allows modelers to apply advanced water resources research techniques like robust decision making (RDM) and robust optimization (RO). PyWR was used in England to inform the most efficient combination of transfers and local supply options such as reservoirs or desalination to meet future demand scenarios (Environment Agency, 2020).

Time steps range from daily to monthly. PyWR currently does not have a built-in channel routing method. It currently uses a delay node that allows a user to offset flows by a specified time step (J. Tomlinson, personal communication, September 16, 2020). Due to PyWR's open-source nature, a Muskingum project has already been initiated in the Github repository. Though not currently implemented, PyWR can incorporate routing in the future.

2.4.5 RiverWare

RiverWare is the product of a long-term endeavor in object-oriented programming. It is a general river and reservoir modeling software for operational scheduling and forecasting, policy evaluation, and other operational analysis and decision making. RiverWare can be used to model river systems, reservoirs, diversions, canals, consumptive uses, groundwater interactions and conjunctive use, hydropower production, water rights and water accounting measures.

RiverWare employs three computational approaches for reservoir/river operations: 1) pure simulation, 2) rule-based simulation, and 3) optimization combining linear programming with preemptive goal programming. Pure simulation is useful for if-then scenarios and calibration. Rule-based simulation uses system operational policies to drive the simulation instead of inputting data such as fixed reservoir releases for a pure simulation. Lastly, linear pre-emptive goal programing optimization is driven by a set of prioritized goals. Each goal can be a simple objective or set of constraints transformed to an objective.

RiverWare has the most routing options at 15 (9 if excluding the "improved" methods) (CADSWES, 2019):

1. Time Lag
2. Variable Time Lag
3. Impulse Response
4. Step Response
5. Variable Step Response
6. Muskingum
7. Muskingum with Segments
8. Kinematic
9. Kinematic Improved
10. Muskingum-Cunge
11. Muskingum-Cunge Improved

12. MacCormack
13. Storage Routing
14. Variable Storage Routing
15. Modified Puls

2.4.6 WEB.BM

WEB.BM is a web-based river basin management model (Ilich, 2022) that uses an open-source MILP solver. The model is intended to provide a user-friendly web interface for planning and operational studies. WEB.BM also can optimize basin operations using single or multiple timesteps and with hydrologic channel routing constraints. WEB.BM uses the Stream Synthesis and reservoir Routing (SSARR) method (US Army Corps of Engineers, 1975). The solver is iteratively called at least three times to refine the routing coefficients (N. Ilich, personal communication, June 9, 2022). The model couples hydrologic channel routing with MTO.

There are three modes in WEB.BM: 1) STO mode, 2) MTO solution mode, and 3) Combined STO/MTO mode. Combined STO/MTO mode is used when shorter timesteps (e.g., daily) are modelled but the total basin travel time exceeds the length of the timestep. Figure 13 shows an example schematic for when a runoff forecast is available for four days ahead. The solver generates solutions for t+0 to t+4 days but only the solution at the current timestep, t+0, is used. This is similar to graphical examples from Fung (2011) and Hoffpauir (2011).

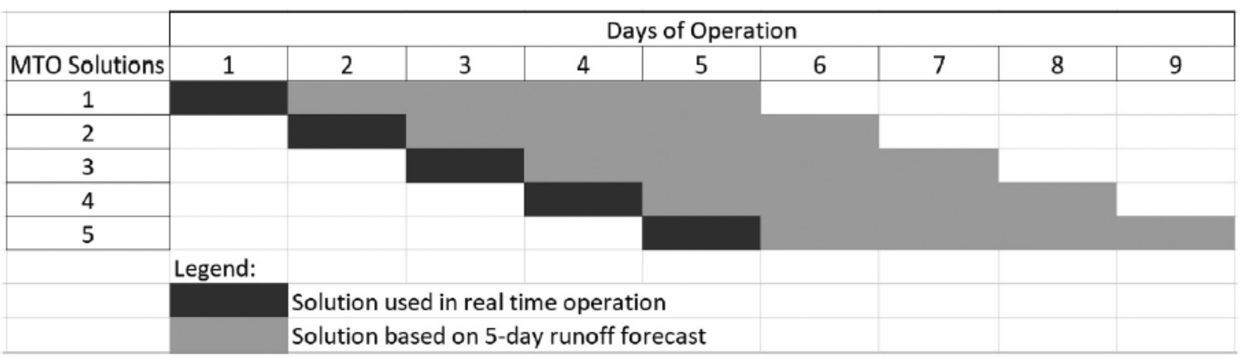


Figure 13. WEB.BM STO/MTO solution mode example for a 4-day future period

2.4.7 WEAP

WEAP is an integrated water resources planning tool that aggregates and processes hydrologic and operational elements to support water managers (Yates et al., 2005). It allows users to build physical-based hydrology and agricultural, municipal/industrial, and environmental demand models. WEAP solves a water allocation problem between the demand priority and supply preference. This is solved at each timestep using an iterative linear programming approach.

One strength of WEAP is that is data-driven and can use daily, weekly, monthly, or annual time-steps depending on the available data describing the water system (Sieber and Purkey, 2015). WEAP does not have built-in hydraulic or hydrologic channel routing options (a. Hereford, personal communication, July 31, 2022), but it is possible to code in routing (S. Sandoval-Solis, personal communication, November 9, 2020).

2.4.8 WRAP

Texas' water availability modeling (WAM) system is maintained by the Texas Commission on Environmental Quality (TCEQ). The WAM system consists of the generalized Water Rights Analysis Package (WRAP) developed and maintained at Texas A&M University (TAMU). WRAP has a daily simulation model called SIMD. Arslan and Wurbs (2022) applied the WRAP's SIMD model in Texas' Brazos River System. SIMD adds monthly-to-daily naturalized flow disaggregation, flow routing changes, forecasting, flood control reservoir operations, and multiple-components environmental instream flow requirements (Wurbs and Hoffpauir, 2021). The daily SIMD uses the lag and attenuation or Muskingum routing methods in conjunction with flow forecasting. Both routing methods require two parameters representing flow travel time and storage attenuation in a river reach (Wurbs and Hoffpauir, 2021).

The WRAP SIMD has forecasting and reverse routing capability to specifically deal with the effects of water right actions in a timestep on downstream flows in a future timestep. Forecasting serves two purposes: (1) protecting water rights from lag effects from stream flow depletions of upstream junior water rights and (2) facilitating reasonable flood control reservoir operations by preventing excessive flood control releases that cause flooding in future timesteps (Wurbs, 2019).

2.5 Channel Routing and Multi-Timestep Optimization

Flow routing when travel times from the most upstream node exceed the model time step necessitates the use forecasting or MTO. Forecasting is needed because this allows systems of timesteps simultaneously. Once multiple timesteps are present, optimization over this period over just one timestep is possible.

Single timestep optimization (STO) as employed in monthly simulation poses problems described by Ilich (2008). The two main issues were 1) Hydrologic channel routing with STO in an LP-based model will violate the assumption of "demand driven reservoir releases"; and 2) the inclusion of routing in MTO could require nonlinear relationships of routing coefficients because they should update when flow regimes change during low to high-flow seasons.

In a monthly timestep modeling, releases from time *t* are expected to meet all downstream demands. This is a reasonable expectation because within a week, reservoir releases from NOD or the upper San Joaquin River can be expected to arrive in the Delta, California's water supply and environmental hub, to meet environmental requirements for channel flows and limiting salinity (Operations Compliance and Studies Section, 2002). Generally, the travel time estimates to the Delta of water released from Shasta is five days, three days for water releases from Oroville, and one day for Folsom or New Melones releases (USBR, 2020).

Ilich (2008) indicated that channel routing would not be able to work within a STO LP model unless the system is so small that the entire travel time is shorter than the timestep length required for routing. When using a monthly timestep, the entire travel time is shorter (five to seven days potentially for Shasta) than the length of the model time step, so routing is not needed for a monthly timestep. As a result, STO is appropriate for monthly timestep modeling.

For example, Goharian et al., (2020) developed a MATLAB-based American River water system model (Figure 14). The model can run with a daily timestep. Channel routing was not implemented because travel time of Folsom releases to the Sacramento-American River confluence (the downstream boundary of FolSim) would arrive within the one-day timestep (E. Goharian, personal communication, November 29, 2022). In this case, the FolSim schematic (Folsom reservoir to Sacramento-American River confluence) is small enough that the travel time (one day) is shorter than the timestep length needed for routing. So routing and MTO are not needed.

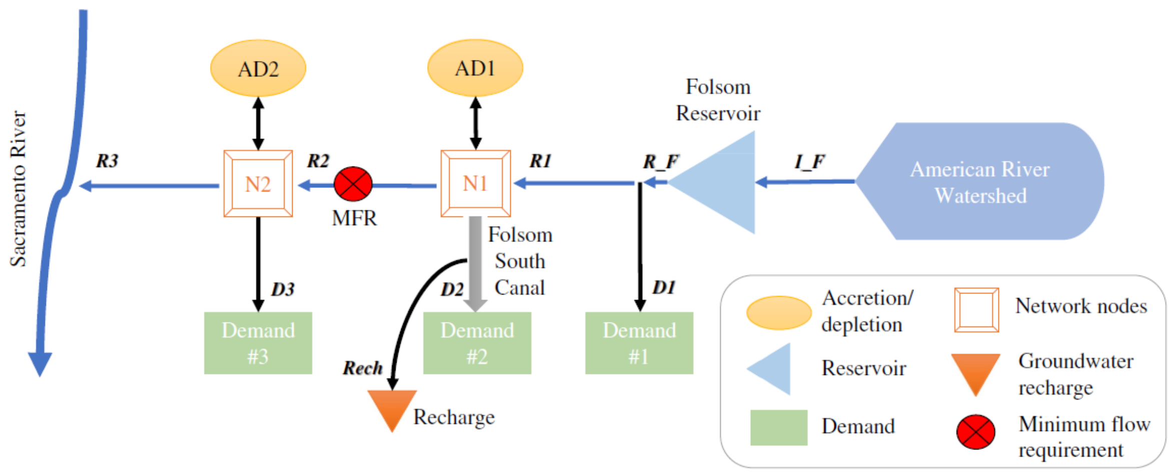


Figure 14. FolSim American River model schematic (Goharian et al., 2020)

On the other hand, for a daily timestep model with channel routing constraints, releases from the current day are made to meet demands at least one day into the future, something common in a large system such as California. MTO is needed in this case because otherwise, the model will force extreme high reservoir releases to overcome the routing constraints due to travel time and attenuation (Ilich, 2008). Aside from Delta requirements to meet salinity, there are also minimum instream flow (MIF) requirements upstream. For example, a MIF requirement at Sacramento River below Wilkins Slough or Navigation Control Point (NCP) ranges from 3,250 to 5,000 cfs. Travel time from Shasta to Wilkins Slough is about three days. So in real-time operations, Shasta releases are made days in advance to ensure that current and future flow requirements are met at NCP.

Tying back to previously mentioned future work (Fung, 2011; Hoffpauir, 2011), parallel timestep optimization is needed in a daily timestep model with channel routing. Ilich (2008) mathematically demonstrated the shortcoming of STO in a daily model where travel times from one point to another take well more than the one-day timestep. As a result, MTO implementation with channel routing in WRIMS2 will be pursued.

2.6 CAM and WRIMS2 Multi-Timestep Optimization

The CalSim Allocation Module (CAM) and Forecast Allocation Module (FAM) are applications of MTO (Islam, 2012; Xie, 2014). CAM was based on DWR Operations Control Office (OCO) spreadsheets. These spreadsheets determine allocations based on hydrologic conditions, storages, demands, regulations, and other factors developed in WRIMS as CAM (Figure 18). CAM is coupled with CalSim II as a sub-module or cycle. CAM determines optimal SWP deliveries subject to physical capacities, forecasted inflows, Delta regulations, and SWP operating rules (CA DWR, 2005).

CAM has simplified and aggregated schematic (Figure 19) than the main model, CalSim II. CAM can be coupled with CalSim II in two ways: 1) sequential run or 2) position analysis (PA) run. In a sequential run, CAM determines the monthly allocation using MTO mode in one CalSim timestep (one month). In MTO mode, CAM determines the optimal allocation from January to May. For example, if the CalSim run is in January 1922, the CAM sub-model also starts in January 1922. Since CAM uses future timesteps and MTO, it looks forward from February 1922 up to December 1922 to determine the optimal January 1922 allocation which is then passed to the CalSim II model. Then in February 1922 in the CalSim II model, CAM looks forward from March 1922 to December 1922 to calculate the optimal February 1922 allocation.

In a PA run, actual initial conditions (mainly reservoir storage) are provided in which 81-year hydrology from WY 1922-2002 is applied and forecasted hydrology using a dynamic link library (DLL) is used (CA DWR, 2021). The PA run results present the wide range of possible operations and deliveries that would occur under the historical range of hydrologic conditions (FitzHugh, 2016). For example, initial conditions for December 2022 are provided. In a PA run, the model takes the initial conditions then applies the WY 1922 hydrology to determine one realization of end of December 2022 operations and optimal SWP allocation using CAM. This is considered one trace. For the next PA trace, the model applies WY 1923 hydrology to have another possible snapshot of December 2022 operations and SWP allocation. By the end of the PA run, there is an ensemble of 81 traces of possible operations and deliveries to inform operational decision making. The New York Department of Environmental Protection (NYC DEP) also uses PA runs in their New York Operations Support Tool (NY OST) based on the OASIS model (National Academies of Sciences, 2018).

CAM previously used an older version of MTO syntax which was hardcoded. This meant that the forecast or future period could not be changed easily. Otherwise, the whole model had to be updated to account for the new forecast period. One of the WRIMS2 and WRESL updates made the forecast period dynamic (Figure 17).

The WRESL+ language within WRIMS2 can employ single and multi-timestep optimization. As a result, any MTO run has the general form of the objective function:

$$max\ Z = \sum_{t=1}^{m} \sum_{i=1}^{nwt} w_i X_{i,t} \tag{36}$$

where *m* is the total number of timesteps (days, months), *Z* is the objective value, *nwt* is the number of weighted variables, *X* is a decision variable, *w* is a priority weight (or penalty)

MTO can optimize over 12 months and is already used with CAM. MTO also can be theoretically used to optimize for multiple years to determine optimal operations in a multi-year drought (1929-1934, 1987-1992 for example).

The Forecast Allocation Module (FAM) is an improvement on CAM. FAM was first coupled with CalLite to provide users the option to choose a CAM/FAM-based allocation using MTO or the Water Supply and Delivery Index (WSI-DI) using STO. The benefit of using FAM is that a pre-model run to optimize tables is not needed. For WSI-DI, any major change to the system such as new regulations and usage of climate change hydrology require an additional process outside the actual model run. This is called WSI-DI retraining which optimizes a pair of water supply versus delivery index tables. FAM is interchangeable with CAM in this thesis.

The CAM module coupled with CalSim II was reviewed to understand fundamental differences with an MTO model like CAM compared to a typical STO model like CalLite or CalSim II. The major premise of CAM is that instead of optimizing only for the current month, CAM optimizes from the current month to the future December month. For example, if the current month is January, then CAM optimizes 12 months from January to December. The next 11 months' future variables can be determined and accessed. If the current month is February, then CAM optimizes 11 months from February to December. The next 10 months future variables can be determined and accessed. In other words, the period is not rolling 11 months into the future. The end future month is always December. Figure 15 shows a visual example of this concept. CAM's main task is to determine the optimal SWP allocation over a contract year, which is from January-December. Another way to set up MTO is to use a moving 11-month future period shown in Figure 16 though CAM does not use this.

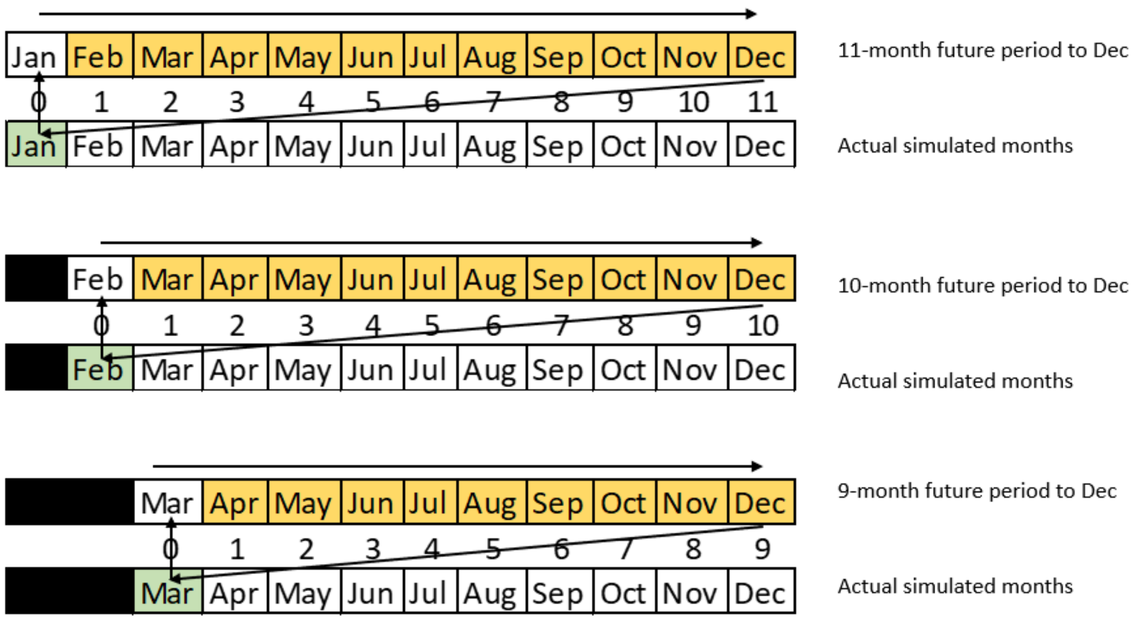


Figure 15. CAM MTO future period to December conceptual example based on SIMD example

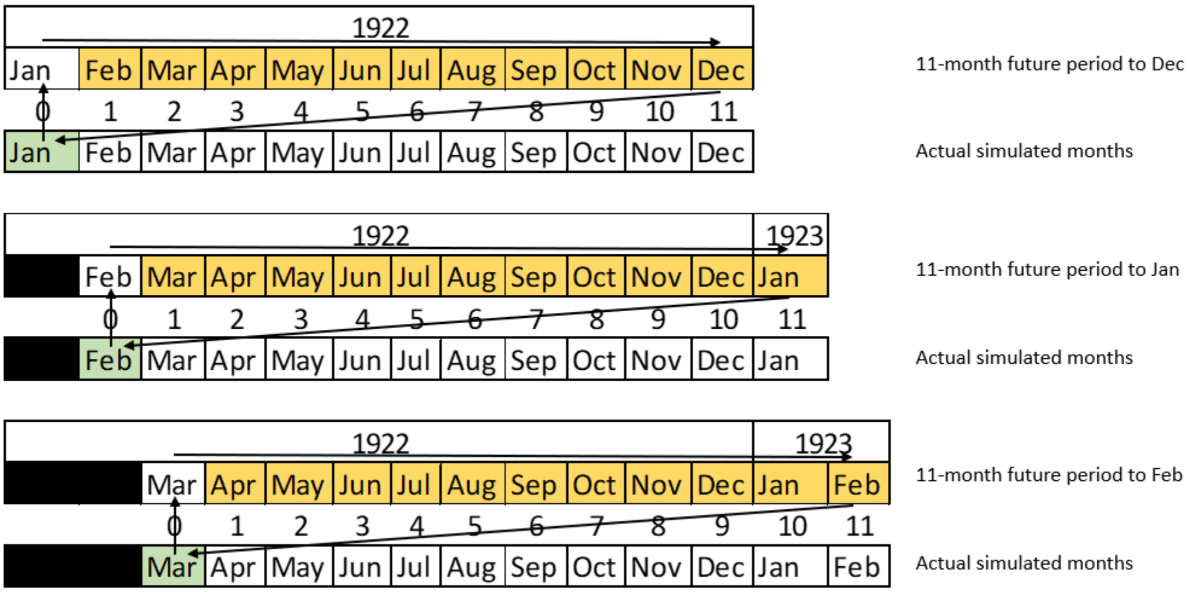


Figure 16. CAM MTO rolling 11-month future period conceptual example based on SIMD example

The weight structure in CAM and a typical CalSim II run was compared. A notable difference is how storage variables are weighted. In the CalSim run, each storage variable is split up into multiple storage zones with their own weights (see 3.1.3 Weights and Penalties). Rule curves are used to direct storage zones to desired volumes. In CAM, future storage targets are used in months like September or December, with penalties if storage is above (lower penalty) or below (very high penalty) the future target. Each reservoir (Shasta, Trinity, Folsom, Oroville) has its own pairs of above and below target storage penalties.

CAM's weighting structure is more focused on telling the model what is not desired. Penalties are what mainly drive the objective function. The weighted variables are SWP and CVP total deliveries which makes sense because the purpose of CAM is to determine optimal allocation for the projects which is passed on to the main CalSim model. For example, CAM MIF arcs are not weighted. The formulation is that the channel arc is always greater than or equal to the MIF arc minus a slack arc that is highly negatively weighted. This ensures that the model always meets the MIF requirement. If the hydrology is dry, a highly penalized slack arc allows relaxation of the MIF requirement. This arc is only to prevent infeasible solutions in very low water supply conditions.

CalSim II's weighting structure has a standard weight table of the model's priorities. There are also penalties in the model formulation. For example, MIF arcs have weights generally around 5000. The MIF channel arc is set to be less than or equal to the requirement. In a typical CalSim II run where historical hydrology is used, MIF requirements are violated rarely except in extended dry periods which can happen in some climate change hydrology scenarios.

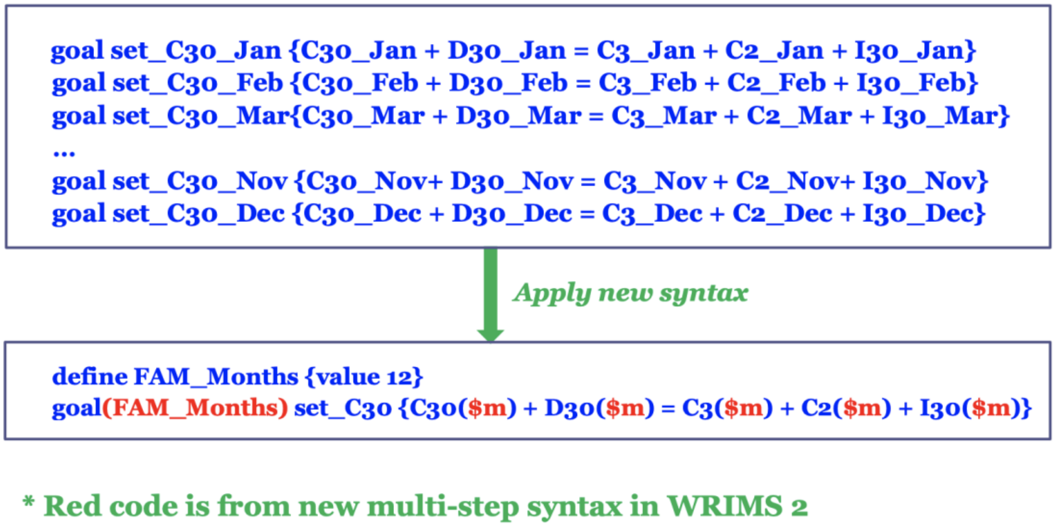


Figure 17. Old and new multi-timestep syntax in WRESL (monthly)

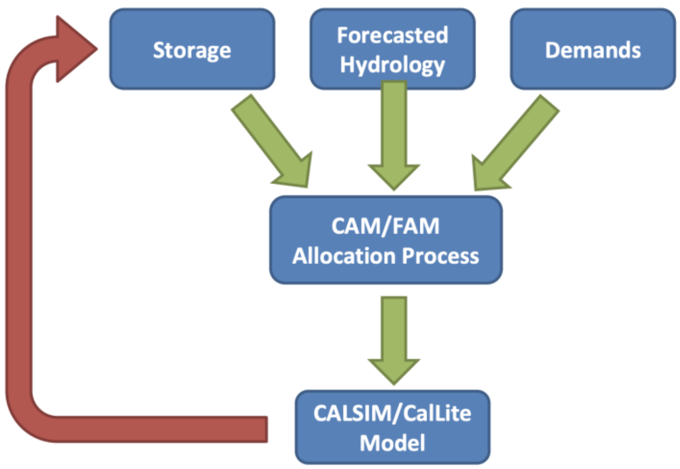


Figure 18.CAM workflow (monthly)

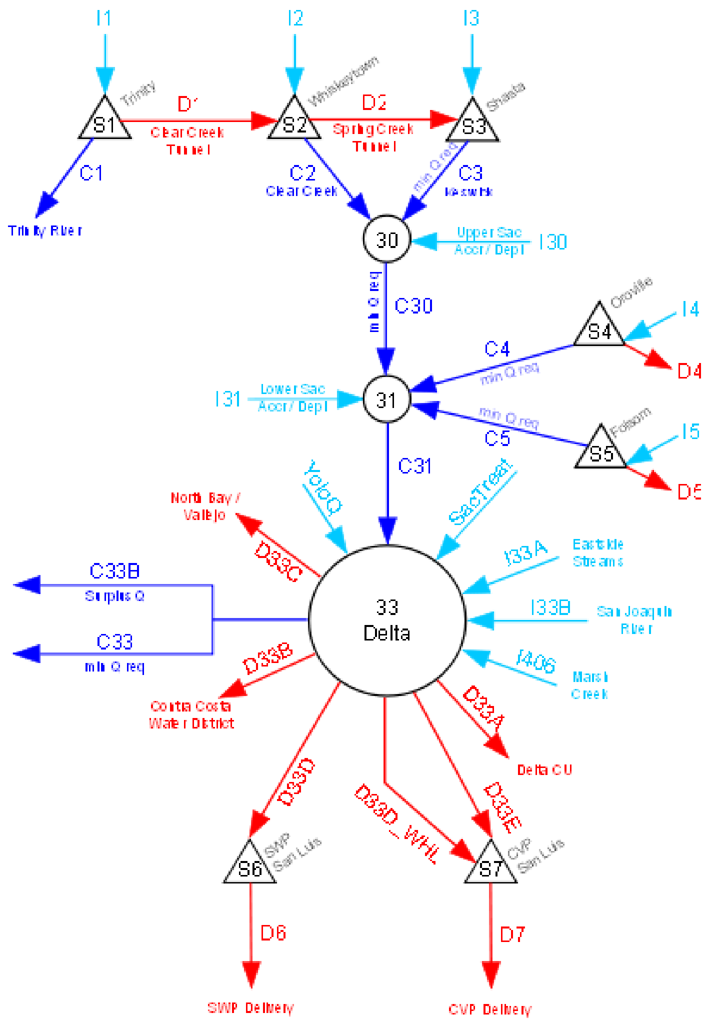


Figure 19. CAM schematic (monthly)

2.7 Research Questions

The following questions guide this study after reviewing the literature:

1. What channel routing method could be used within WRIMS that has ample data availability in the NOD and fits within an MILP framework?
2. How can channel routing be implemented within WRIMS?
3. What is multi-timestep optimization (MTO)?
4. What model application has MTO within WRIMS been used?
5. How can MTO be coupled with a channel routing method to prevent the shortcomings of single timestep optimization with routing?

Chapter 3 Methods

3.1 Model Formulation

This section reviews the CalSim/CalLite weighting structure, the model objective function, constraints, and equations for channel routing and MTO. For water system simulation, the main decision variables are usually channel flows, deliveries, exports, reservoir releases and storages in each timestep. The constraints represent node mass balances, physical facility limitations like pumping or channel capacities, maximum reservoir storage, dead pool storage, minimum in-stream flow requirements. The cost coefficients (weights or benefits) reflect priorities in operating the system. The weighting structure is somewhat arbitrary and often requires trial-and-error. Ferreira (2007) developed a method to determine penalty weights more formally.

For example, negative weights are given to surplus Delta outflow and high positive weights (+5000) for required Delta outflow. Table 6 shows each of the C407 (surplus outflow) sub-components' weights are around -2000. The required Delta outflow, used to repel salinity from going further inland the Delta, must be released first before any additional Delta outflow.

Another example is that unused federal share also is assigned a negative weight (Table 6). Unused federal share is water that CVP cannot pump due to pumping plant or regulatory limitations, and which is then available to SWP (the Tracy pumping limit is around 4,600 cfs while that of Banks is 10,300 cfs). Unused state share is of the same concept but applied to the SWP. The negative weight, currently set at -1285, for unused federal pumping share discourages the LP solver from letting the SWP take CVP water.

Table 6. Weights for unused federal and state share and different sub-components of surplus Delta outflow

Decision variable	Weight	Description
UNUSED_FS	-1285	Water that the CVP cannot export which then is available for SWP
UNUSED_SS	-1285	Water that the SWP cannot export which then is available for CVP
C407_CVP	-2000	Surplus outflow from CVP
C407_SWP	-2000	Surplus outflow from SWP
C407_ANN	-2050	Outflow from the projects to meet salinity requirements for D-1641

Two types of constraints are permitted in WRESL: hard and soft constraints. Hard constraints must be met exactly, such as mass balance continuity at each node. Figure 20 shows the WRESL code stating that total Delta outflow (C406) must equal required (D407) plus surplus outflow (C407). Figure 21 graphically shows the node 407 obtained from the CalSim II schematic.

```
goal continuity407 {C406-D407-C407=0} !Delta Outflow
```

Figure 20. Mass balance hard constraint on node 407 for Delta outflow in CalSim II.

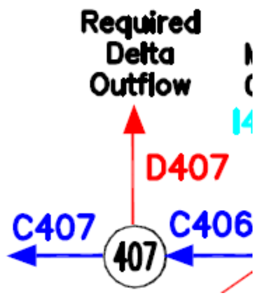


Figure 21. Node 407 including required Delta outflow (D407) and surplus outflow (C407) in CalSim II schematic.

Soft constraints allow solver flexibility in the MILP problem. Soft constraints are useful in extreme circumstances like drought years where some regulatory requirements can be relaxed since water unavailable to meet all requirements (constraints). To prevent the solver from taking advantage of this soft constraint in common situations, a high penalty is applied in the objective function when the “constraint” is violated. For example, Figure 22 shows that D419_SWP, Banks SWP exports, can go below the health and safety requirement of 300 cfs because a hard constraint is not used (D419_SWP = banksminpump). However, if that occurs, the objective function incurs a penalty of 2700 for each cfs D419_SWP goes below 300 cfs. For example, if Banks SWP exports decrease to 299 cfs, then the objective value incurs an added penalty of 2700. If Banks SWP exports decrease to 200 cfs, then the objective value incurs a penalty of 270,000 (2700 times 100 cfs below the 300 cfs Banks minimum pumping).

```
! Banks PP Minimum Cap
define banksminpump {value 300.}
define banksminpumpdv {alias banksminpump kind 'health-safety' units 'cfs'}

goal setbanksminpump {
     lhs D419_SWP
     rhs banksminpump
     lhs>rhs penalty 0
     lhs<rhs penalty 2700
}
```

Figure 22. WRESL code which uses a soft constraint on Banks SWP minimum pumping in CalSim II (banks_pump_allow.wresl)

WRESL is a natural language syntax interface for the MILP solver. Operational criteria and rules specified using WRESL are then transformed into constraints and objective function terms that the MILP solver can interpret. Input data in the form of HEC-Data Storage System (HEC-DSS) timeseries, previous decision variables, and relational lookup table values are all available when formulating the WRESL code (CA DWR, 2000). WRESL+ is an updated parser which includes new features while still being compatible with the legacy WRESL files. New WRESL+ functionalities are 1) future array syntax for multi-period optimization, 2) an if statement for preprocessing variables and files inclusion, 3) a network statement for system grids and automatic continuity generation (CA DWR, 2018). Throughout the rest of the document, WRESL and WRESL+ will be interchangeable.

3.1.1 Objective Function

CalSim and CalLite are mixed-integer linear programming (MILP)-based simulation models. The solver maximizes the objective value for each timestep individually (instead of other models which optimize over the whole period altogether) given a set of priorities and penalties, including soft constraints that incur penalties on slack or surplus variables. The objective function structure for this study, similar to the CalLite/CalSim models, is:

$$max\ Z = \sum_{i=1}^{nwt} w_i X_i + \sum_{j=1}^{npen} -p_i\ x_j^{+} | x_j^{-} \tag{37}$$

where *Z*=objective value, *nwt*=number of weights, *npen* = number of penalties, *w* = weight, *X* = decision variable, *p* = penalty for slack or surplus, *x*- = slack variable, *x*+ = surplus variable.

3.1.2 Constraints

3.1.2.1 *Reservoir Continuity*

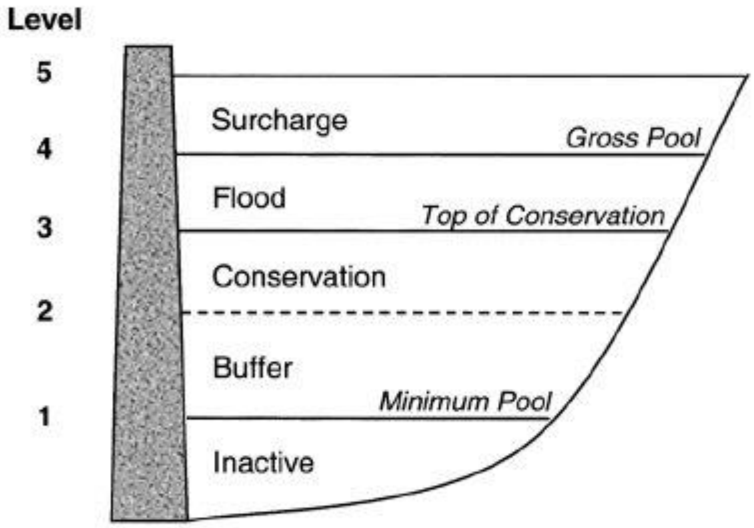
Each node consists of a mass balance constraint. For storage arcs, the constraint is as follows:

$$I_{i,j} - R_{i,j} - E_{i,j} = S_{i,j} - S_{i,j-1} \tag{38}$$

where $I_{i,j}$ = inflow to the reservoir during period *j*, $R_{i,j}$ = reservoir releases in period *j*, $E_{i,j}$ = evaporation losses in period *j*, and $S_{i,j}$ and $S_{i,j-1}$ = storage at the end and beginning of period *j*.

3.1.2.2 *Storage Zones*

Reservoirs are split into zones in reservoir operation models. This helps the model balance storage across reservoirs. For example, CVP has its own balancing scheme among Trinity, Shasta, and Folsom reservoirs. The inactive or dead pool zone volume cannot be withdrawn except by evaporation. Storage in this area is not considered in water supply and allocation formulations. The conservation pool is the next common zone. Water in this zone can be used to meet various demands such as environmental, agricultural, municipal and industrial, and hydropower. The flood pool zone stores water when releases may cause damaging, excessive flows downstream. This flood pool zone is typically empty except before and during a flood event. The last zone is the surcharge pool. This is uncontrolled storage above the flood control zone and below the maximum reservoir elevation. Once water is in this zone, release operations are driven by the Emergency Spillway Release Diagrams found in each reservoir's USACE Water Control Manual (Wurbs, 2005).



Reservoir Storage Zones and Levels

Level 1 **Top of Inactive Pool –** The storage at this level may be zero or a minimum allowable pool.

Level 2 **Top of Buffer Pool –** The Buffer Pool is a division of the Conservation Pool. When the water level drops into the Buffer only essential demands will be met.

Level 3 **Top of Conservation –** Space in the Conservation Pool is reserved for the various water demands on the reservoir, including agricultural, environmental, municipal and industrial, and hydropower.

Level 4 **Flood Pool –** Water is stored in this zone when it cannot be safely passed downstream within allowable flow limits.

Level 5 **Surcharge Pool –** Typically, a reservoir has surcharge storage to accommodate water above the emergency spillway. In the surcharge zone, outflow is determined by the spillway capacity (if ungated) or by the Emergency Spillway Release Diagram.

Figure 23. Concept of reservoir zoning (Hickey et al., 2003)

Total storage in a reservoir is a sum from all individual zones (Equation (39). Each zone is constrained by a maximum value (Equation (40). The reservoir continuity equation can then be updated as shown in Equation (41).

$$S_{i,j} = \sum_{z=1}^{NZ} S_{i,j,z} \tag{39}$$

$$S_{i,j,z} \leq Smax_{i,z} \tag{40}$$

$$I_{i,j} - R_{i,j} - E_{i,j} = \sum_{z=1}^{NZ} S_{i,j,z} - \sum_{z=1}^{NZ} S_{i,j-1,z} \tag{41}$$

where *NZ* = number of storage zones, *z* = index of storage zone.

3.1.2.3 ***Maximum reservoir outflow***

The storage-maximum discharge function is linearly approximated. A lookup table is used that maps the storage from period ***j-1*** to determine the maximum discharge. This table was obtained from the monthly timestep CalSim model. Future work could be to refine the storage-discharge capacity table for finer timesteps.

$$f_{i,j} \leq \beta_0 + \beta_1 [\sum_{z=1}^{Z} S_{i,j-1,z}] \tag{42}$$

where $\beta_{0,}\beta_1$=linear coefficients for reservoir maximum outflow capacity

3.1.2.4 ***Weir Spills***

Two weirs are simulated in this study: Fremont and Sacramento weirs. An equality constraint requires weirs to spill (flow) only when a flow threshold is exceeded. Otherwise, weir diversion is zero. Binary variables ensure the flow zones fill in the proper order since they indicate which zone is active. In this study, two flow zones determine weir spills. Zone 2 can only be active if Zone 1 reaches capacity.

The study uses two cycles (also known as sub-model) for weir spill determination. The first cycle determines the total flows upstream of the weir node without weir spills and determines the binary variable indicating whether a flow threshold has been reached or not. A linearized weir diversion function is then used in the next cycle. In this following cycle, the flows before spills are known. As a result, the input of flows (state variable) can be used to map weir spills (decision variable). Figure 24 and Figure 25 show the weir diversion spill functions for Fremont and Sacramento weirs.

$$D = \sum_{z=1}^{2} \alpha_z f_z \tag{43}$$

$$f_z \geq Y(f_z^{max}) \tag{44}$$

$$\sum_{z=1}^{2} f_z \leq Y \sum_{z=1}^{2} f_z^{\max} \tag{45}$$

$$0 \leq f_z \leq f_z^{max} \quad l = 1{,}2 \tag{46}$$

$$Y \in \{0,1\} \tag{47}$$

where D = flow or spill over a weir, f_z = flow in zone z, f_z^{max} is the capacity of zone z.

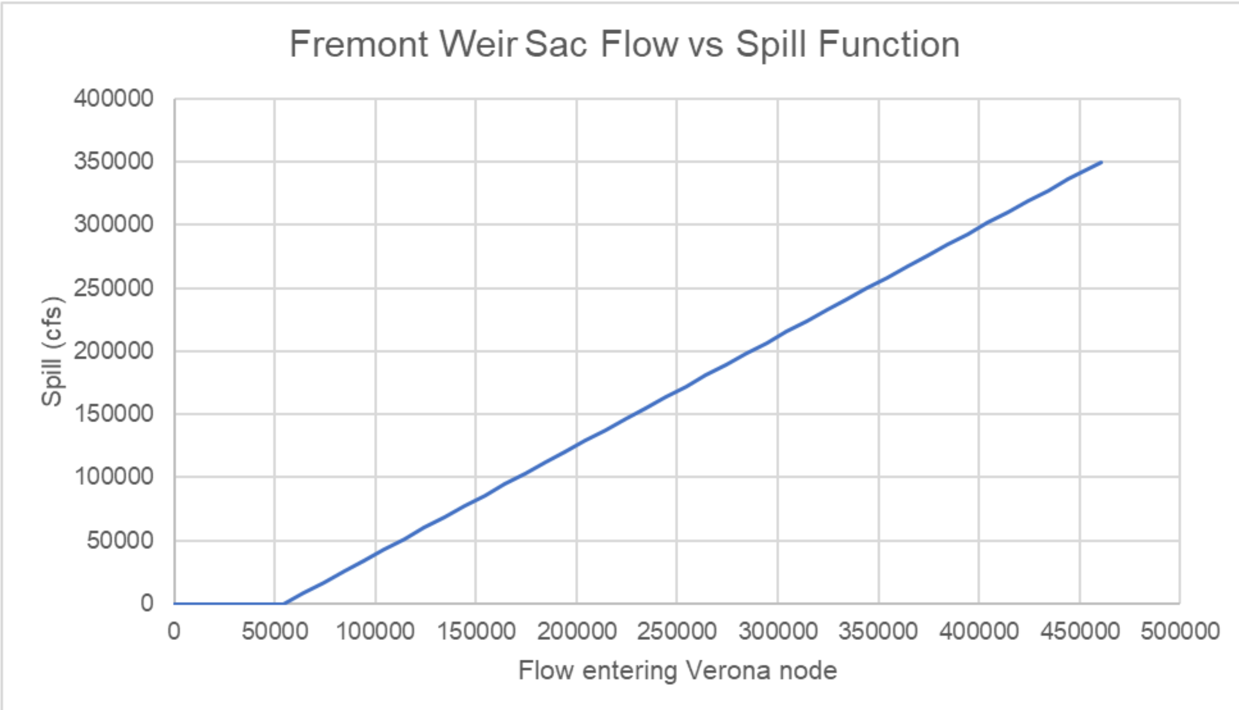


Figure 24. Fremont weir spill function

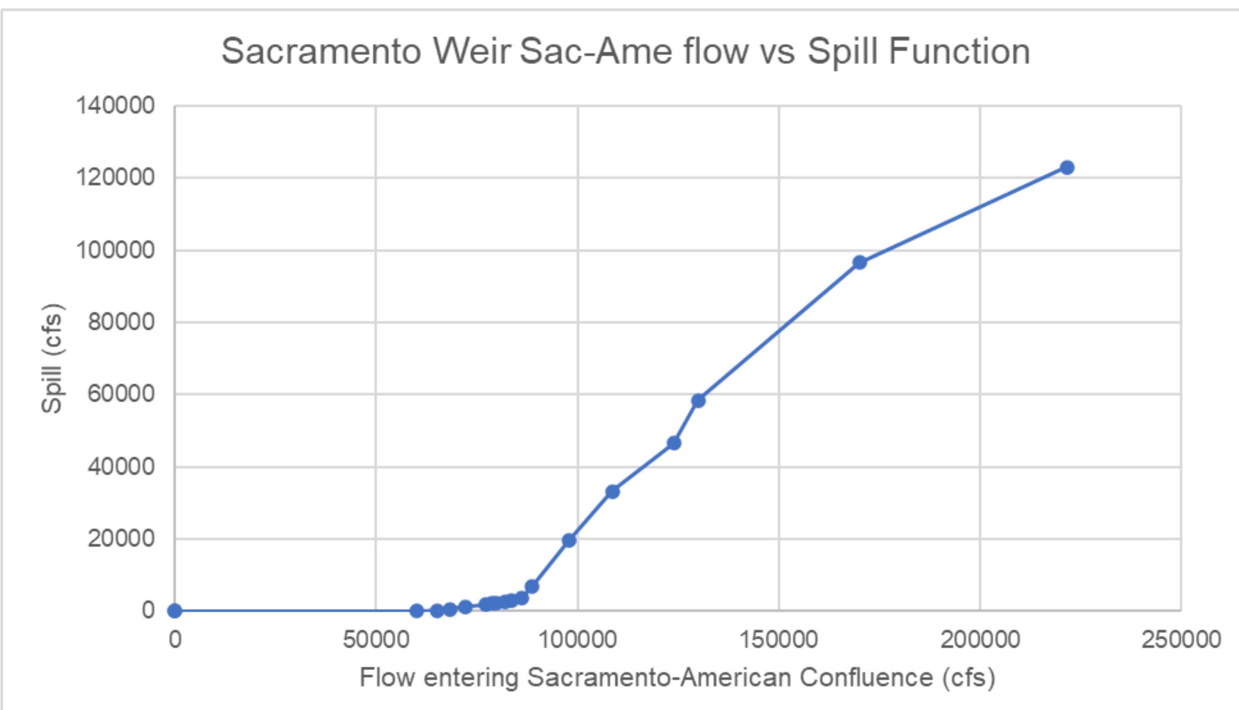


Figure 25. Sacramento weir spill function

3.1.2.5 *Control Point Continuity*

The continuity in a downstream control point is the mass balance between upstream node inflow, accretion-depletion (AD) terms, also known as incremental flows, and outflow.

$$f_{i-1,j} + AD_{i,j} - f_{i,j} - D_{i,j} = 0 \quad (48)$$

where $f_{i-1,j}$ = inflow from upstream control point *i-1* in period j, $AD_{i,j}$ = accretion-depletion or local inflows during period j, $f_{i,j}$ = outflow from control point *i* in period j, and *D* = diversion or delivery to demand node

3.1.3 Weights and Penalties

Weights used in this thesis can be grouped into several categories:

- Storage zones
- MIF requirements
- Weir flows

Water deliveries weights are also an integral part of MILP-based models like CalLite and CalSim. However, this thesis assumes that the water deliveries are considered within the accretion-depletion terms and thus does not explicitly weight and determine water deliveries.

Dead pool zone weights have the highest priorities because the model should always ensure there is storage in this inactive zone. The intermediate nodes from conservation to flood pool zone weights are similar although the trend is monotonic decreasing. Lastly, the surcharge zone is highly negative because storage above the flood control pool upper bound is highly discouraged.

Channel arcs which have MIF requirements are split between “MIF” and “EXC” arcs. The MIF arcs are limited by the requirement which is elaborated on a later section. MIF arcs have high weights so that the model will seek to meet these flow requirements. The EXC arcs have zero weights to indicate indifferent to flows in this zone. Omitting the EXC weight is also another way to indicate indifference. Table 7 shows the weight-table in the study. Weights were obtained from CalLite and mapped to the similar variables in the model.

In CalLite, weir flows have a small negative weight to prevent the model from letting water spill to the weirs unnecessarily. For example, Table 7 shows that the weir spill weights are -50. Compared to the MIF requirements and storage zone weights, the -50 weight is insignificant and is meant as a deterrent.

Table 7. Decision variable weights in the model – STO mode

Decision variable	Weight	Description
C_Folsm_EXC	0	Additional flows to MIF
C_Folsm_MIF	5500	MIF requirement
C_Grdley_UPS_EXC	0	Additional flows to MIF
C_Grdley_UPS_MIF	5500	MIF requirement
C_Hst_UPS_EXC	0	Additional flows to MIF
C_Hst_UPS_MIF	5500	MIF requirement
C_Kswck_Ups_EXC	0	Additional flows to MIF
C_Kswck_Ups_MIF	5500	MIF requirement
C_Nclaus_EXC	0	Additional flows to MIF
C_Nclaus_MIF	5500	MIF requirement
C_Nimbus_UPS_EXC	0	Additional flows to MIF
C_Nimbus_UPS_MIF	5500	MIF requirement
C_Orovl_EXC	0	Additional flows to MIF
C_Orovl_MIF	5500	MIF requirement
C_RedBlf_Ups_EXC	0	Additional flows to MIF
C_RedBlf_Ups_MIF	5500	MIF requirement
C_Shsta_EXC	0	Additional flows to MIF
C_Shsta_MIF	5500	MIF requirement
C_Wilkns_Ups_EXC	0	Additional flows to MIF
C_Wilkns_Ups_MIF	4950	MIF requirement
D_FreWeir	-50	Weir spill penalty
D_SacWeir	-50	Weir spill penalty
S_Folsm_1	40000*taf_cfs	Deadpool storage zone
S_Folsm_2	93*taf_cfs	Conservation storage
S_Folsm_3	88*taf_cfs	Conservation storage
S_Folsm_4	84*taf_cfs	Conservation storage
S_Folsm_5	50*taf_cfs	Conservation storage
S_Folsm_6	-10000*taf_cfs	Storage above flood control rule curve
S_Orovl_1	40000*taf_cfs	Deadpool storage zone
S_Orovl_2	93*taf_cfs	Conservation storage
S_Orovl_3	88*taf_cfs	Conservation storage
S_Orovl_4	84*taf_cfs	Conservation storage
S_Orovl_5	62*taf_cfs	Conservation storage
S_Orovl_6	-10000*taf_cfs	Storage above flood control rule curve
S_Shsta_1	40000*taf_cfs	Deadpool storage zone
S_Shsta_2	93*taf_cfs	Conservation storage
S_Shsta_3	88*taf_cfs	Conservation storage
S_Shsta_4	84*taf_cfs	Conservation storage

S_Shsta_5	50*taf_cfs	Conservation storage
S_Shsta_6	-10000*taf_cfs	Storage above flood control rule curve

Penalty categories are as follows:

- Excessive flood flow penalties – set to 99,999
- Accretion-Depletion terms diverging from original values penalties – set to 10,000
- Shortage in meeting future flow requirement or demand penalty – set to 5,000
- Calibration penalties – These penalties were imposed to prevent the model from unreasonably draining reservoir storage at Folsom and Shasta. These behaviors were occurring due to the limitation of the AD terms calculation. In summary, these penalties were added to make the results more reasonable.
    - Folsom storage – Ensure that storage between January to February is at least 300 TAF. The penalty for deviating is 9,999 per TAF converted to cfs.
    - Shasta storage – Ensure that storage between December to February is at the flood control rule curve. If storage is greater than the flood control rule curve, impose a penalty of 50 units per TAF converted to cfs. If storage is less than, then impose a penalty of 100 units per TAF converted to cfs.

Penalties in the model are introduced to discourage specific behaviors. Penalties for exceeding flood control flows are set to 99,999. Ideally these penalties would be more based on damage functions from flood control LP models such as HEC-ResFloodOpt. In general, methodological updating of the weights and penalties is required when developing an MILP-based model. This study mainly used preexisting weights and penalties from the CalLite and CalSim II models. Future work would be to estimate better weights and penalties through a methodological approach (Ferreira, 2007; Israel and Lund, 1999).

3.1.4 MTO Implementation

The WRESL+ language within WRIMS2 can support both single and multi-timestep optimization. Any MTO run has a general form of the objective function which is only slightly different from Equation (37):

$$max\ Z = \sum_{t=1}^{m} \sum_{i=1}^{nwt} w_i X_{i,t} + \sum_{t=1}^{m} \sum_{j=1}^{npen} -p_j\ x_{j,t}^{+}|x_{j,t}^{-} \qquad (49)$$

where *m* is the length of the future period.

3.1.4.1 *MTO Periods*

The MTO horizon is generally six days but can vary from five to seven days depending on the month or the month's sub-period. Table 8 shows the MTO length sub-periods in a month. For example, period 1 in October would be from October 1 to 6. On October 1, the future timesteps are October 2 to 6. In total, there are five future and one current daily timesteps to be optimized. Then on October 2, the future timesteps are October 3 to 6. The final timestep is still October 6 since the model is still in period 1. There are four future and one current timestep. In total, on October 2, the total MTO period is five days. On October 25, the model is in period 5 from October 25 to 31. The future timesteps are October 26 to 31. In total, there are six future and one current timestep with a total of seven MTO days. Figure 26 presents a visualization of the October MTO periods 1, 2, and 5. In summary, the MTO sub-periods generally assume an MTO period of six days except in months with 31 days or in February months.

Another way to implement the MTO period is to use a rolling future period. This is the approach in WEB.BM. With this method, assuming a 6-day MTO period, on October 2, the future timesteps are October 3 to 7. The final timestep is now October 7 instead of October 6 because the MTO period is moving forward. The 6-day MTO period or five future timesteps continues in October until October 27. The model is only set up to access future timesteps within the same month. As a result, the October 27 MTO period ends on October 31 (5-day MTO period or four future days) instead of ending on November 1 (6-day MTO period or five future days). Figure 27 shows a visualization of this rolling MTO period concept. The fixed MTO periods were implemented because this was the approach in CAM which is a monthly MTO application that optimizes allocation considering future storage targets. Future work would use a rolling MTO period in a daily model application.

Table 8. MTO sub-period lengths within a month (days)

Month	Days	Period 1	Period 2	Period 3	Period 4	Period 5
October	31	6	6	6	6	7
November	30	6	6	6	6	6
December	31	6	6	6	6	7
January	31	6	6	6	6	7
February	28	7	7	7	7	N/A
February Leap	29	6	6	6	6	5
March	31	6	6	6	6	7
April	30	6	6	6	6	6
May	31	6	6	6	6	7
June	30	6	6	6	6	6
July	31	6	6	6	6	7
August	31	6	6	6	6	7
September	30	6	6	6	6	6

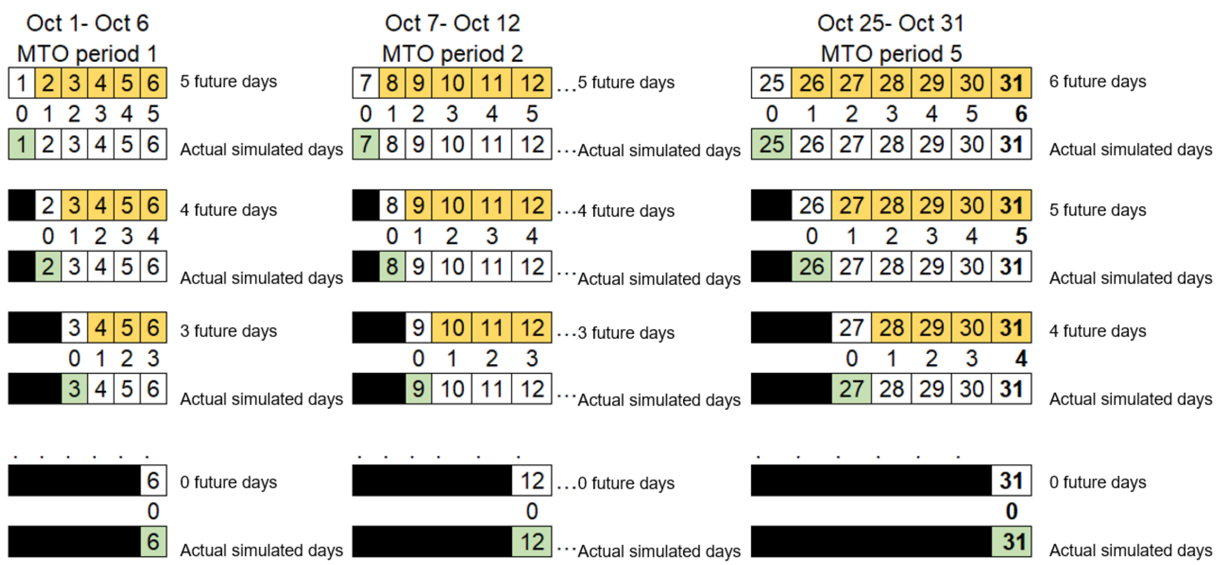


Figure 26. October MTO sub-period visual example for periods 1, 2, and 5

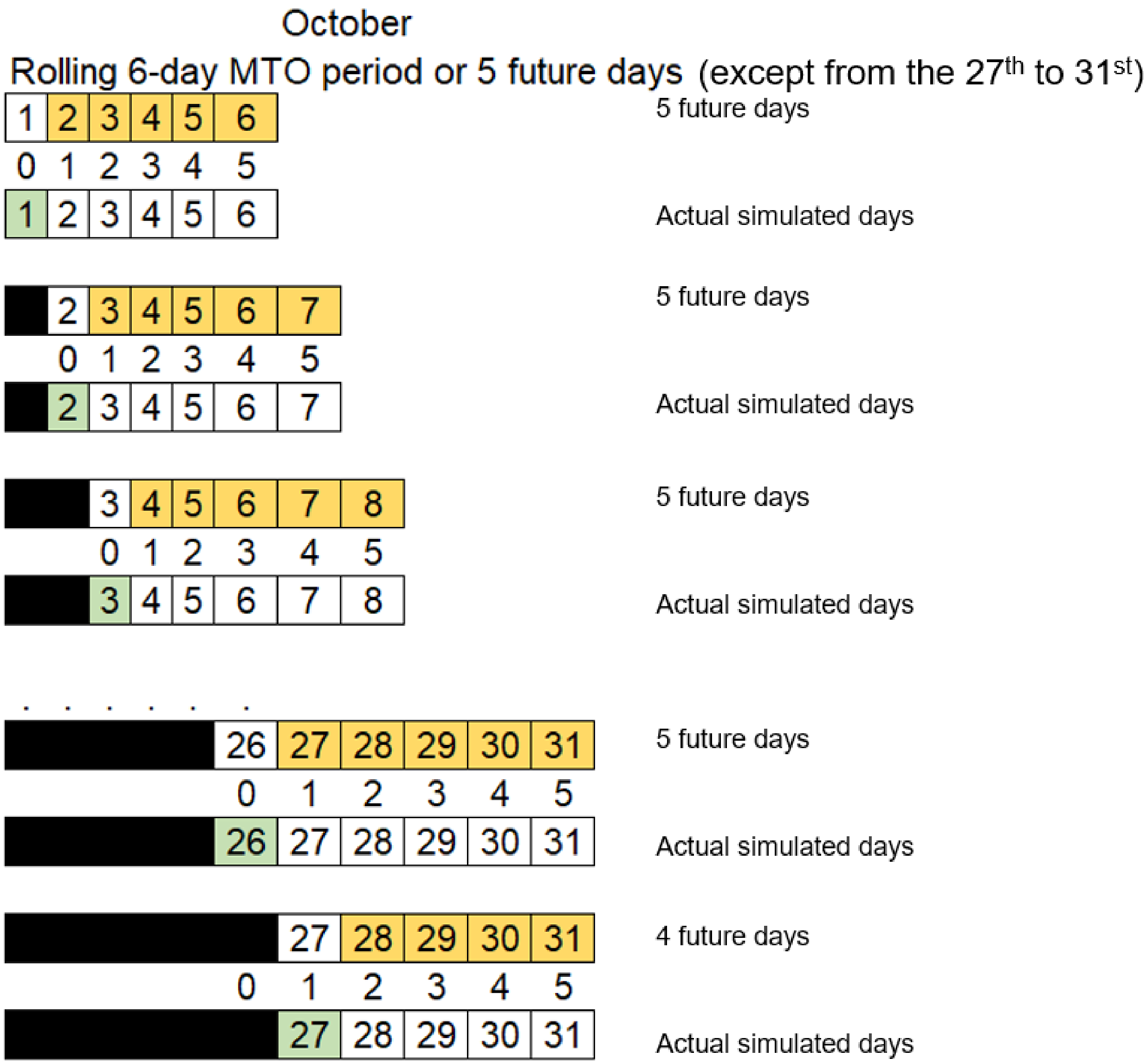


Figure 27. October rolling 6-day MTO period example

3.1.4.2 *Joint STO/MTO Weights and Penalties*

An STO model can be converted to MTO mode in WRIMS2 using the appropriate syntax. However, the solution will not change unless future-driven goals are written with future flow, storage, or delivery values. A penalty for deviating from future targets should be added.

Comparing how Oroville storage rule curves or storage targets are set between STO and MTO mode (CAM) is useful. Oroville has end-of-September (EOS) storage targets. In the current STO models, this is set to 1.6 million acre-feet (1,600 TAF). This target is embedded in the Oroville level 4 timeseries calculation. The difference between level 4 and level 3 is the target for zone 4 in Oroville. Figure 28 shows the Oroville rule curve logic that constraints reservoir zones based on storage levels. The storage level specifics are explained in the model configurations section. Figure 29 shows the Oroville storage pool weights in CalLite. These weights are the same in all timesteps.

CAM MTO uses the future array capability in WRESL+. CAM does not have storage zones. The storage operating rules are driven by future targets with penalties for deviating from future storage targets. The penalty for storage being under target is one of the highest in CAM, usually above 10,000. There is a smaller penalty for being over target since this prevents model decisions from keeping storage high unreasonably. Figure 30 shows the CAM Oroville EOS formulation. For example, if the current month is January, then the goal is for future month September to be 1,600 TAF. The CAM simulation starts with the current month of January then steps through the future months from February to September. If the future storage is 1,600 TAF exactly, then there is no MTO penalty on this goal. However, if the target is below (say 1,599 TAF), then a penalty of 1500 is added in the multi-step objective function in the future month of September.

A test simulation was done in a CAM month where the future September target was below the 1,600 TAF. The goal is to understand what could cause the future target to not be met. After forcing a hard constraint of 1,600 TAF, the model incurred a huge penalty from not meeting MIF requirements. In CAM, MIF goals are set so the MIF arc always equals or exceeds the requirement minus a slack variable that can reduce the requirement if the hydrology is so dry that the requirement cannot be met physically. This slack variable had a very high penalty because this arc was basically a relaxation variable that reduces the true requirement to prevent infeasible solutions. Forcing the target to be exactly met resulted in a future month MIF requirement being relaxed. In summary, future storage targets may not always be met because it can cause violation of regulatory requirements.

```
goal S_OrovlZone3 {S_Orovl_3 < max(S_OrovlLevel3adj - S_OrovlLevel2,0.)}
goal S_OrovlZone4 {S_Orovl_4 < max(S_OrovlLevel4 - S_OrovlLevel3adj,0.)}
goal S_OrovlZone5 {S_Orovl_5 < max(S_OrovlLevel5 - S_OrovlLevel4,0.)}
goal S_OrovlZone6 {S_Orovl_6 < max(S_OrovlLevel6 - S_OrovlLevel5,0.)}
```

Figure 28. Oroville rule curve constraints in CalLite

```
[S_Orovl_1,40000*taf_cfs],
[S_Orovl_2,93*taf_cfs],
[S_Orovl_3,88*taf_cfs],
[S_Orovl_4,84*taf_cfs],
[S_Orovl_5,62*taf_cfs],
[S_Orovl_6,-10000*taf_cfs],
```

Figure 29. Oroville storage zone weights in CalLite

```
goal(fm) sS6_EOS_Sep {lhs S6($m)
    case aa { condition mv($m)==Sep .and. month==Feb
    rhs S6Septarget !+ S6_Sep_hi - S6_Sep_lo !w=> -1500, -13000
    lhs>rhs  penalty 1500
    lhs<rhs  penalty 1500
    }
    case a { condition mv($m)==Sep
    rhs S6Septarget !+ S6_Sep_hi - S6_Sep_lo !w=> -1500, -13000
    lhs>rhs  penalty 1500
    lhs<rhs  penalty 13000
    }
}
```

Figure 30. CAM Oroville EOS future target goal

3.1.4.3 *Future Shortage Minimization*

The algorithm for minimizing future requirement minimization is as follows:

1. Define decision variables
    a. Shortage in meeting requirements – MIF or Delta inflow
    b. Summation of shortages to minimum instream flows
2. Calculate shortage in meeting requirements
    a. Shortage = MIF or Delta inflow requirement – Actual flow
3. Calculate cumulative shortage per MTO sub-period
    a. Cumulative shortage = cumulative shortage (-1) + shortage
    b. Reset counter when new MTO sub-periods starts
4. Set goal to minimize future end of MTO sub-period shortages
    a. If end of MTO sub-period cumulative shortage is 0, then there is no penalty
    b. Else, accrue penalty of 5000 per cfs of cumulative shortage

This logic is applied to ensure more efficient operation to meet Sacramento River at Wilkins Slough MIF and Delta inflow demand represented by historical Freeport flows.

3.2 Channel Routing

3.2.1 Conceptual Basis

A different approach in building mass balance equations within WRESL/WRIMS is needed once channel routing is introduced in a sub-monthly (weekly, daily) timestep. In a monthly timestep, reservoir releases upstream are expected to arrive at the Delta by the end of the month. In other words, inflow is equal to outflow between all nodes. This is also referred to as steady-state condition and in which the channel storage can be represented as a prism storage (Figure 31).

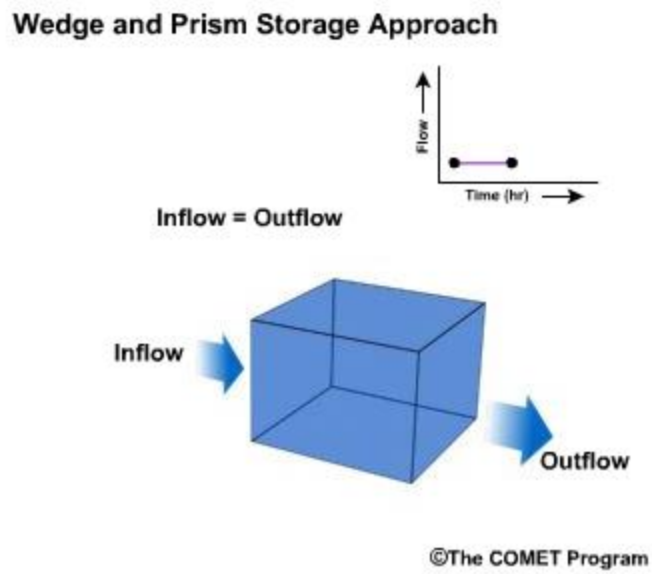


Figure 31. Prism storage during steady-state condition (inflow = outflow) (University Corporation of Atmospheric Research, 2010)

When a daily timestep is used in the California NOD region, the total discharge from a reservoir like Shasta does not reach a downstream node like Sacramento River at Freeport during the same time step. For example, if Shasta releases were 5000 cfs in one day, then only a portion of that volume would arrive at the Delta in the same timestep. The rest would be stored temporarily in the river between Shasta reservoir and the Delta inflow point (Sacramento River at Freeport for example).

The volume stored in the river reach can be represented in a wedge storage based on the Muskingum method. The wedge storage can be positive or negative depending on whether inflow or outflow from the control volume is greater. A reach has a positive wedge storage when it is on the rising curve of the hydrograph (Figure 35). When the flow wave is receding, the reach storage decreases and results in a negative wedge storage where outflow is greater than the inflow (Figure 33).

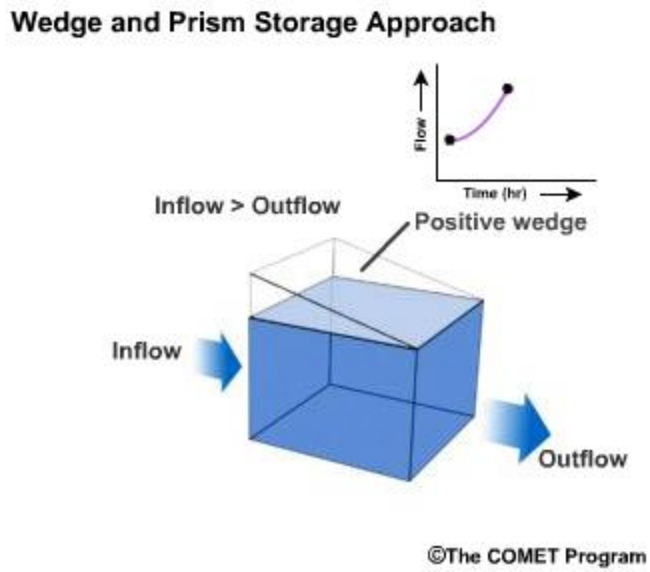


Figure 32. Positive wedge storage when inflow is greater than outflow (University Corporation of Atmospheric Research, 2010)

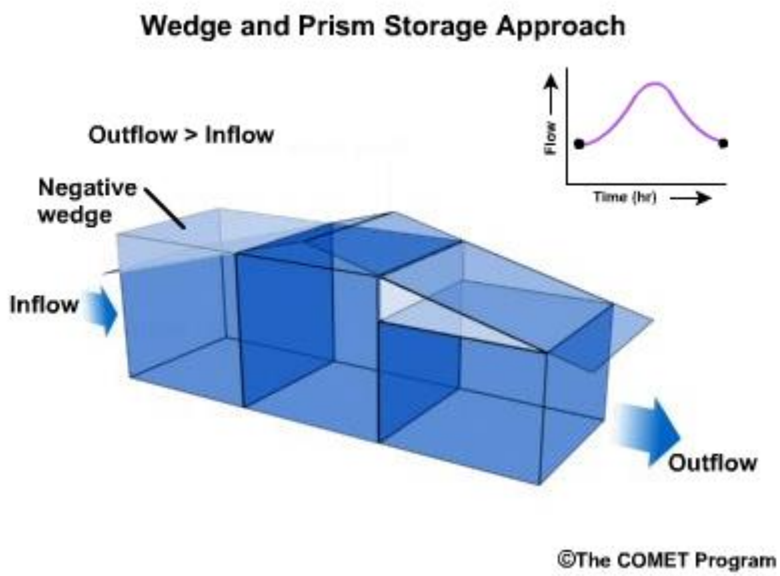


Figure 33. Negative wedge storage when outflow is greater than inflow (University Corporation of Atmospheric Research, 2010)

In summary, in a network which nodes have time delay (lag) and attenuation, the representation needs to be modified. In this case, an intermediate reach storage node was added in between river control points. The storage equation is based on the Muskingum routing method.

The Muskingum routing method was chosen in this thesis because:

- Muskingum method is a widely used routing method in LP-based models and in flood control LP models (Jones, 2013; Needham et al., 2000)
- Muskingum routing parameters were available from previous research (Jones, 1999)
- Muskingum routing requires only two inputs: X which represents the flood peak attenuation and K which represents travel time between inflow and outflow hydrograph
- Muskingum was the recommended method in a previous related study of a simplified Upper Sacramento CalLite-based model (Fung, 2011)

The Muskingum parameters used were based on HEC-FCLP model in Table 13 from Jones (1999). The main reason for using these parameters is because HEC-FCLP or now HEC-ResFloodOpt was used in multiple California flood analysis. A limitation is that this model is run usually with a 6-hour timestep although a 1-hour timestep is possible. The model in this study, however, is run with a 1-day timestep. Future work could recalibrate Muskingum parameters or use routing methods like variable Lag and K or SSARR which update coefficients based on flow conditions.

Not all reaches displayed have routing enabled. For example, routing from Bend Bridge to Red Bluff is not simulated because the travel time is negligible compared to the one-day timestep and because including routing in this reach produced unrealistic operations in accumulating water in reach storage, treating Bend Bridge reach storage as an actual reservoir instead of a channel routing construct.

Table 9. Muskingum routing parameters where K is in units of days and X is a dimensionless factor.

Reach	K	X	From and To
1	0.4583	0.1	Keswick to Bend Bridge
2	2.1458	0.2	Red Bluff to Wilkins Slough
3	0.5417	0.38	Wilkins Slough to Fremont Weir/Verona
4	0.3333	0.2	Oroville to Gridley
5	0.7500	0.17	Gridley to Yuba City
6	0.1667	0.34	Yuba City to Nicolaus
7	0.1667	0.2	Nicolaus to Verona/Fremont Weir
8	0.3333	0.2	Fremont Weir/Verona to Sacramento Weir
9	0.2500	0.2	Fremont Weir to Woodland
10	0.2917	0.2	Woodland to Lisbon
11	0.0417	0.4	Folsom reservoir to Fair Oaks/Nimbus
12	0.1250	0.2	Fair Oaks/Nimbus to H St
13	0.0833	0.2	H St to Sacramento Weir/SacAmerican node
14	0.2083	0.2	Sacramento Weir/SacAmerican to Freeport
15	0.2500	0.2	Sacramento Weir/SacAmerican to Lisbon
16	0.3333	0.2	Freeport to Rio Vista
17	0.6667	0.2	Lisbon to Rio Vista
18	0.0833	0.37	Marysville to YubaFeather confluence (ESTIMATED)
19	0.0625	0.1	Bend Bridge to Red Bluff
20	0.3125	0.2	Red Bluff to Vina-Woodson Bridge
21	0.7292	0.15	Vina-Woodson Bridge to Ord Ferry
22	0.8542	0.2	Ord Ferry to Colusa City
23	0.2500	0.25	Colusa City to Wilkins Slough

3.2.2 Muskingum Routing in WRESL

The general procedure to include Muskingum routing using WRESL is:

1. Define "upstream" channel. This is the flow upstream of the occurrence of routing.
2. Define a downstream channel. This is the flow appearing at the current timestep due to flows from the upstream link before the current timestep.
3. Define reach storage arc.
4. Define the routing control point continuity (Equation (50)). The structure is like a reservoir mass balance equation except the reservoir is now the channel reach storage. Without this intermediate reach storage node, inflow will always equal outflow so time lag and attenuations cannot be simulated.
5. Input the Muskingum routing K and X routing parameters lookup table and define the Muskingum routing parameters as state variables
6. Define the Muskingum routing equation as a goal statement.

3.2.3 Routing Control Point Continuity

$$f_{i-1,j} - f_{i,j} = RS_{i,j} - RS_{i,j-1} \tag{50}$$

The Muskingum routing constraint formulation was inspired by Braga and Barbosa (2001) who implemented Muskingum routing within a network flow programming model. Muskingum routing was chosen because of accuracy and simplicity. Figure 34 shows the representation of two reservoirs in series without routing. There is only one direct link (*I(t)*) between the first and second reservoir (*Y(t)*). In long intervals such as monthly timestep runs, this schematic is valid. However, this representation is not valid when there is time lag involved.

To incorporate in the network flow model, an intermediate node was introduced (Figure 35). In the updated representation, the discharge *I(t)* from R_1 does not reach R_2 in the same timestep since a portion of the flow was stored temporarily in the river. As a result, only a fraction of *I(t)* represented as *O(t)* will arrive in R_2 in the same timestep.

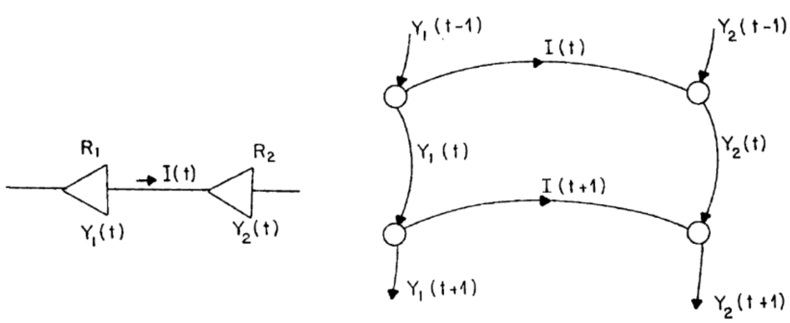


Figure 34. Network flow representation of two reservoirs in series (Braga and Barbosa, 2001)

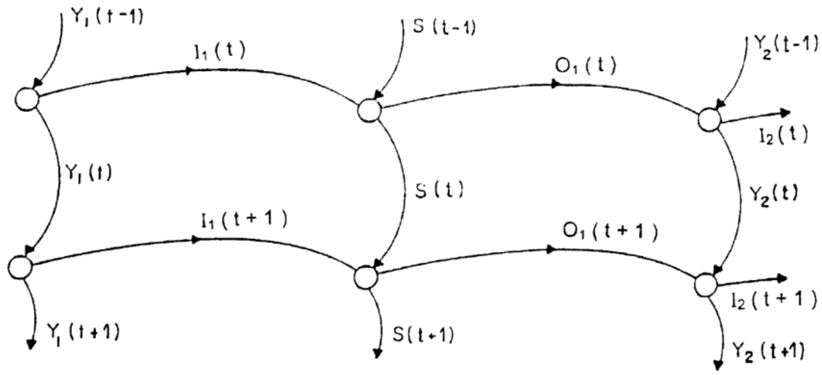


Figure 35. Network flow representation of two reservoirs in series with routing (Braga and Barbosa, 2001)

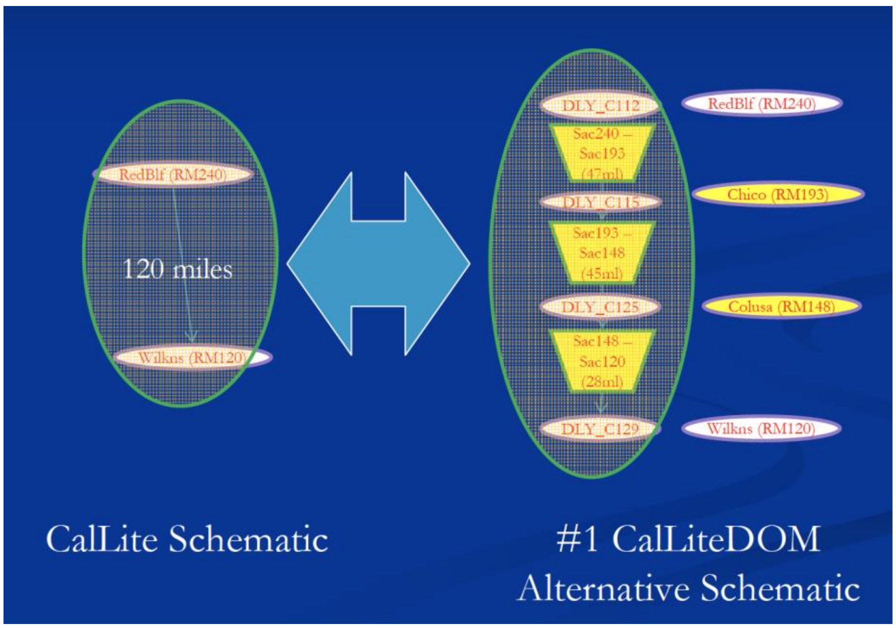


Figure 36. Red Bluff to Wilkins Slough CalLite and DOM comparison (Chen, 2011)

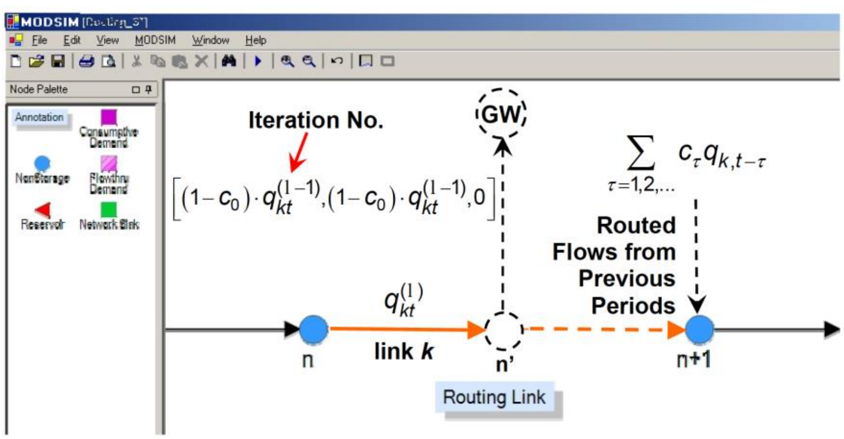


Figure 37. MODSIM successive approximations channel routing procedure (Labadie, 2010)

The main idea of this procedure is that a “reservoir”, storage arc, or groundwater storage arc is introduced between two control points. The concept of introducing an additional node to represent storage accumulation in a channel has also been shown in previous work (Chen, 2011; Labadie, 2010) as shown in Figure 36 and Figure 37.

3.2.4 Verification

This section examines if the coded WRIMS routing implementation provides the same results as a more explicitly coded routing. A simple spreadsheet-based Muskingum routing simulation is compared with the WRIMS-based simulation. No downstream demands or other priorities are included in this WRIMS model. This can be categorized as a “pure simulation” run since only the fixed reservoir releases are driving the model subject to general constraints such as mass balance and routing.

3.2.4.1 *Single Reach*

Two reaches are compared in the Upper Sacramento River: 1) Keswick reach to Bend Bridge (Figure 38) and Bend Bridge reach to Red Bluff (Figure 40). Two reaches are compared for the Feather River and American River: 1) Gridley reach to Yuba City (Figure 42), and 2) Natoma reach to H St (Figure 44). The scatterplots comparing the calculated outflow using Excel and WRIMS implementation show that both are consistent (Figure 39, Figure 41, Figure 43, Figure 45.

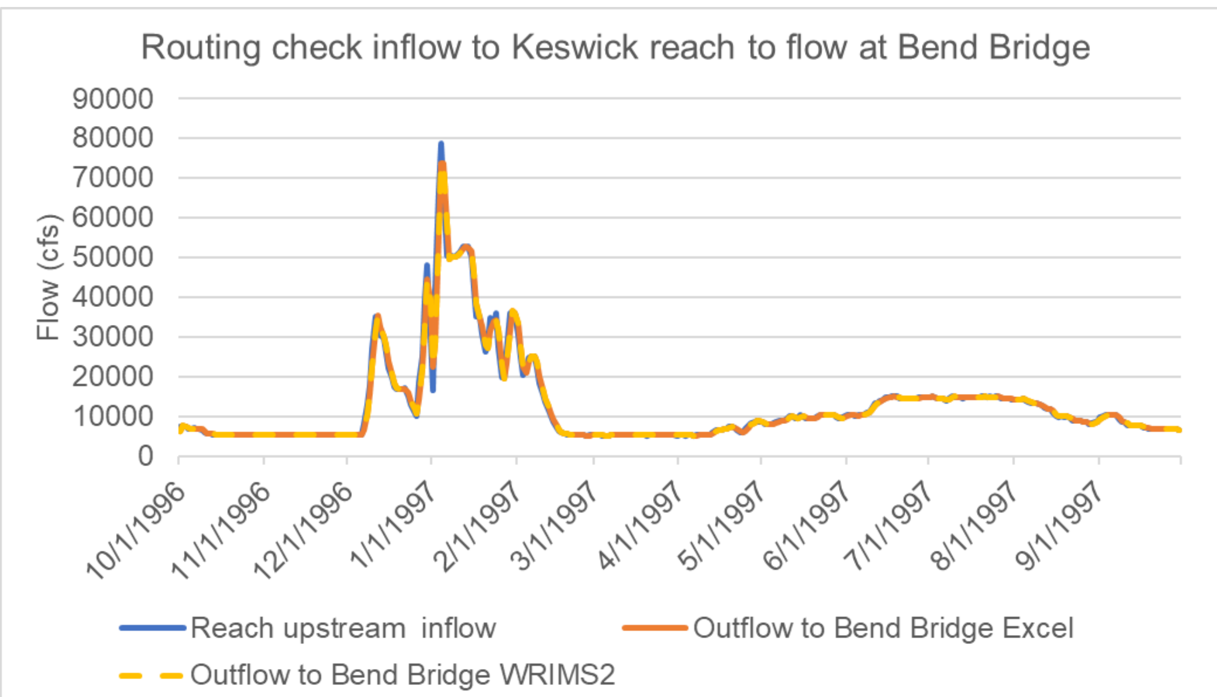


Figure 38. Sacramento River at Keswick reach flowing into Sacramento River at Bend Bridge Muskingum routing comparison between Excel results and WRIMS2 simulation

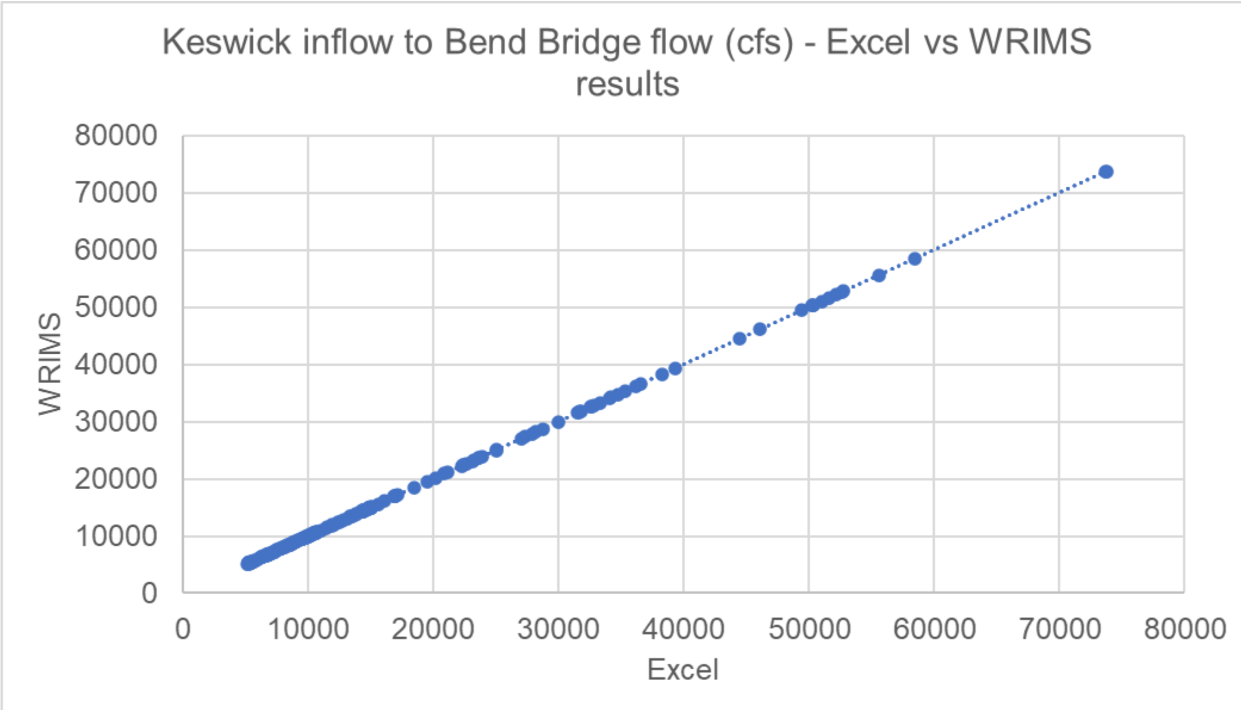


Figure 39. Scatterplot of Sacramento River at Bend Bridge Excel and WRIMS flow (cfs) comparison

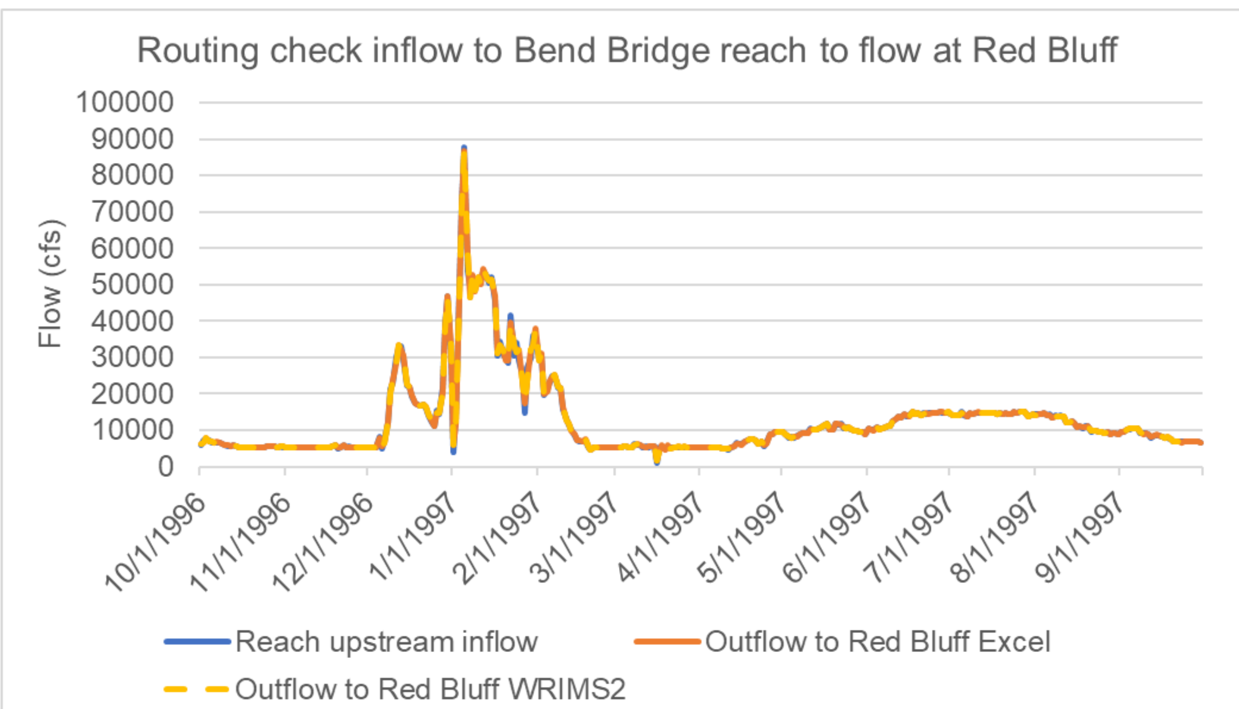


Figure 40. Sacramento River at Bend Bridge reach flowing into Sacramento River at Red Bluff Muskingum routing comparison between Excel results and WRIMS2 simulation

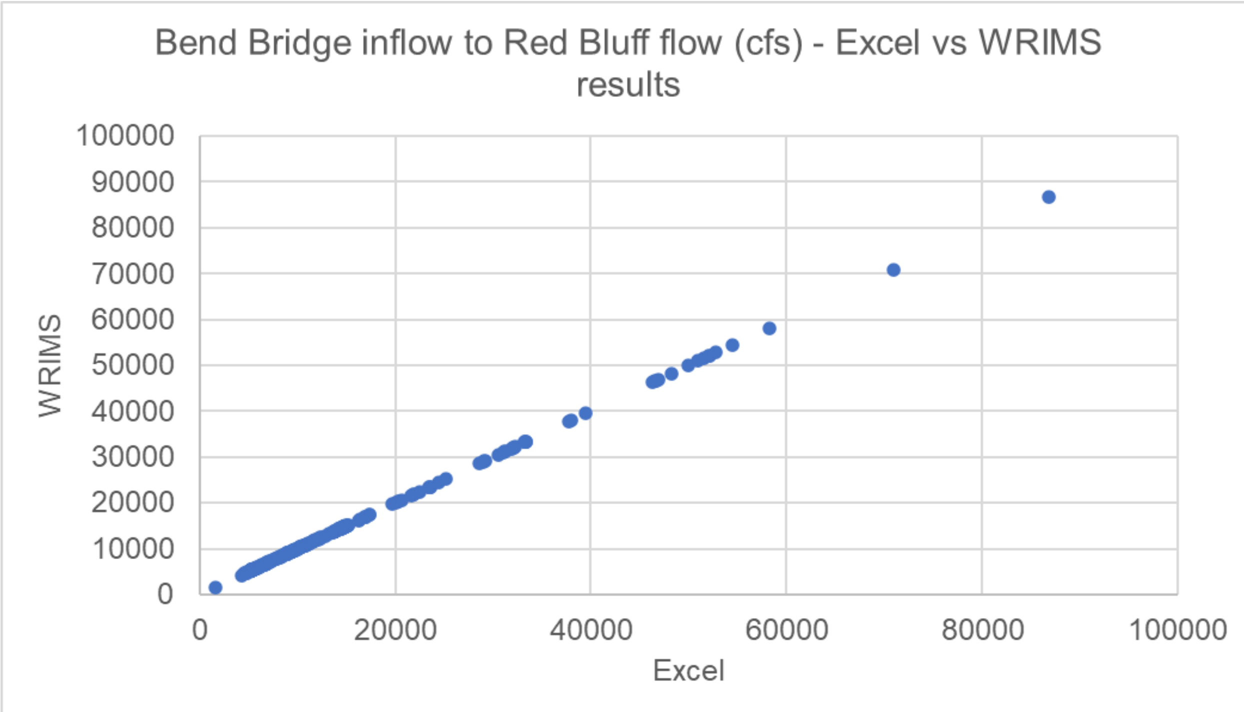


Figure 41. Scatterplot of Sacramento River at Red Bluff Excel and WRIMS flow (cfs) comparison

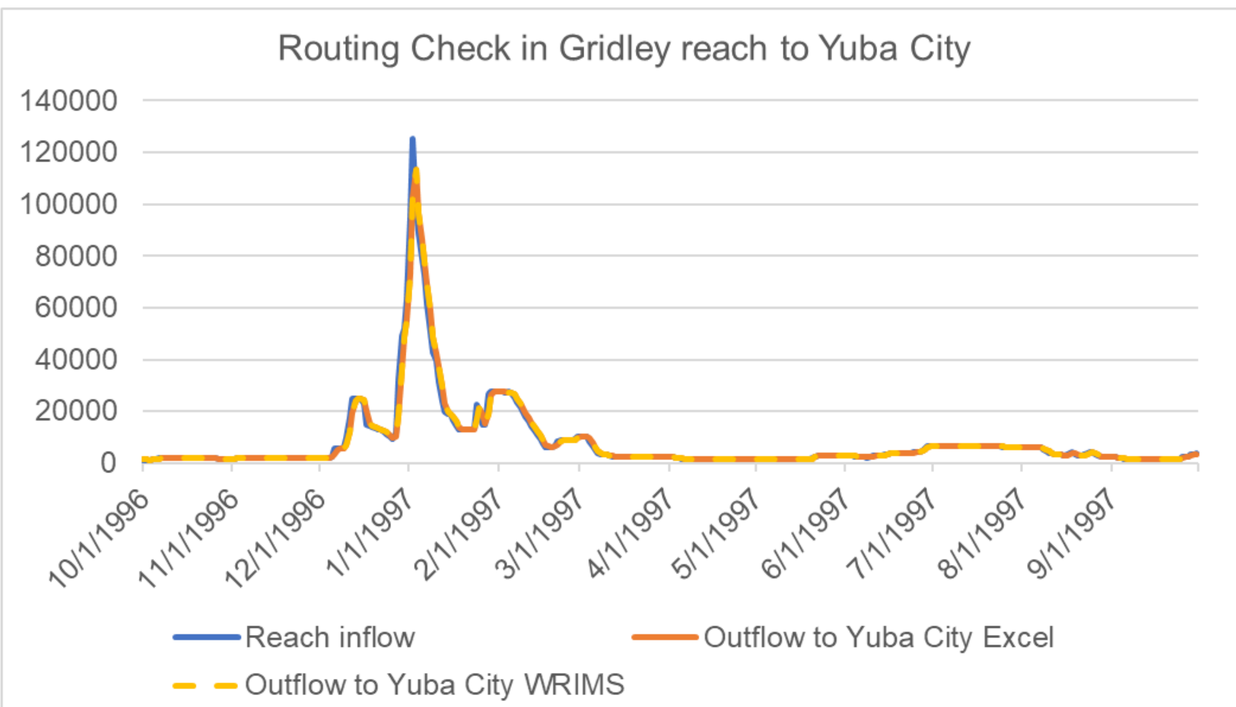


Figure 42. Feather River - Gridley reach flowing into Feather River - Yuba City Muskingum routing comparison between Excel results and WRIMS2 simulation

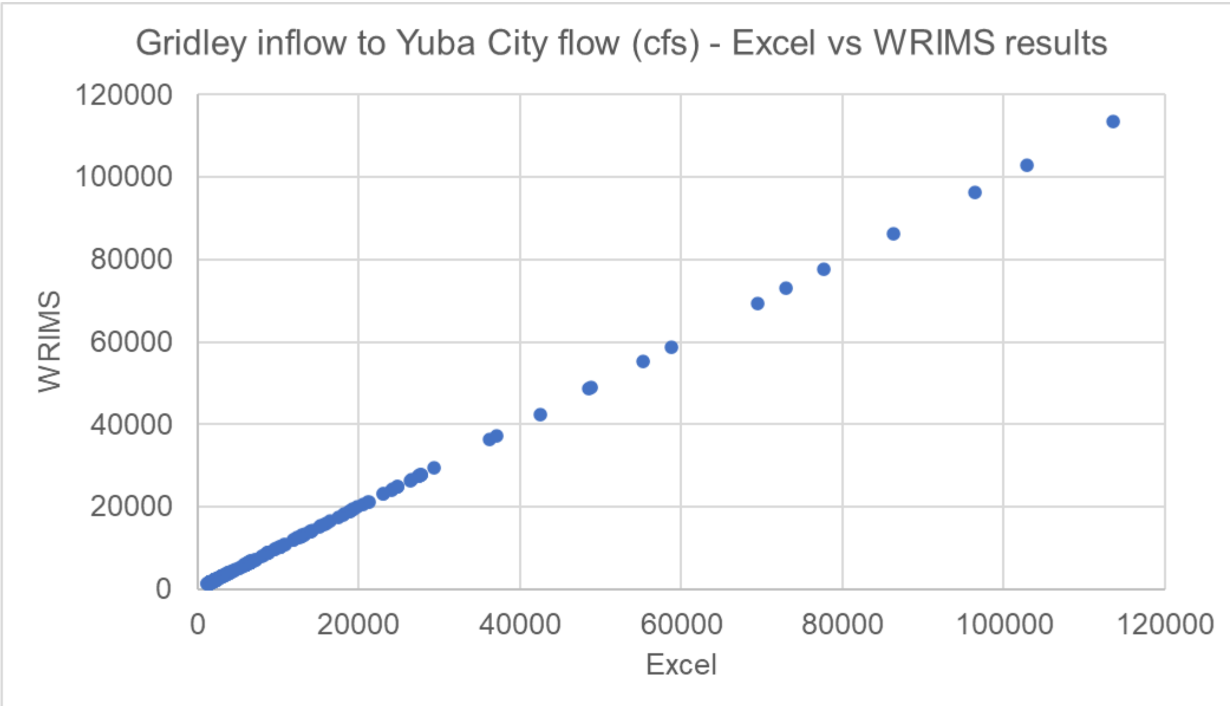


Figure 43. Scatterplot of Feather River at Yuba City Excel and WRIMS flow (cfs) comparison

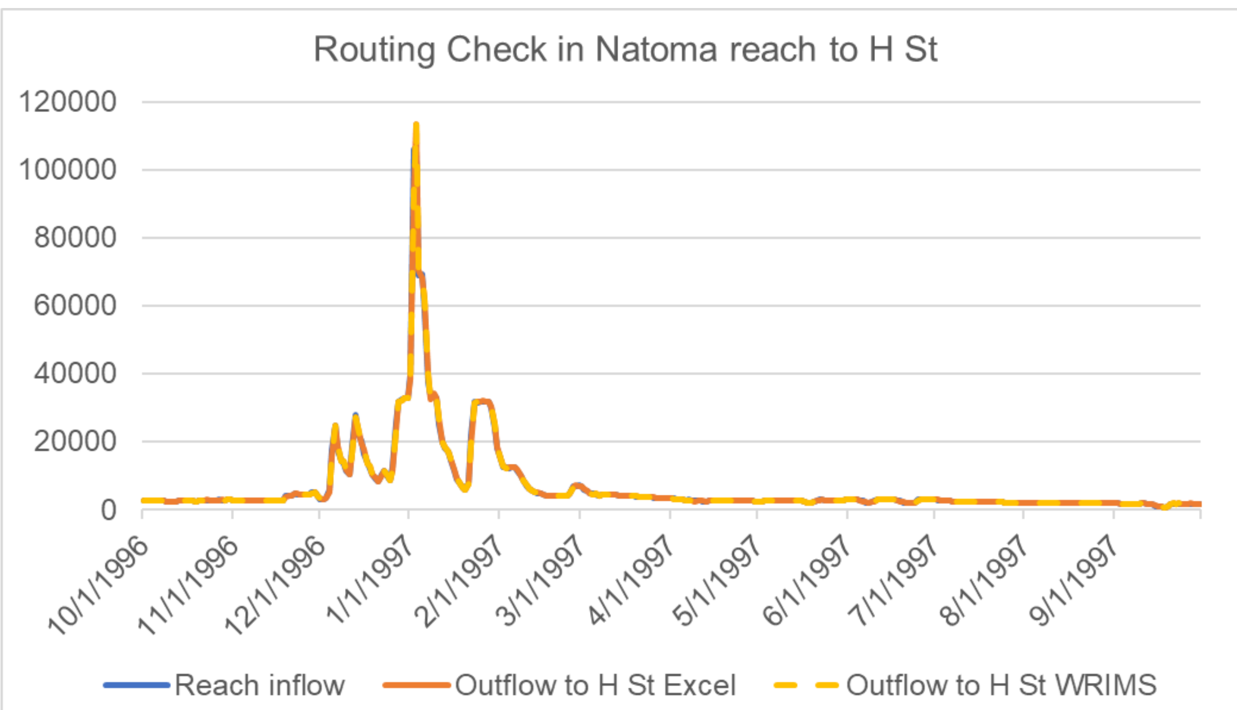


Figure 44. American River - Natoma reach flowing into American River - H St Muskingum routing comparison between Excel results and WRIMS2 simulation

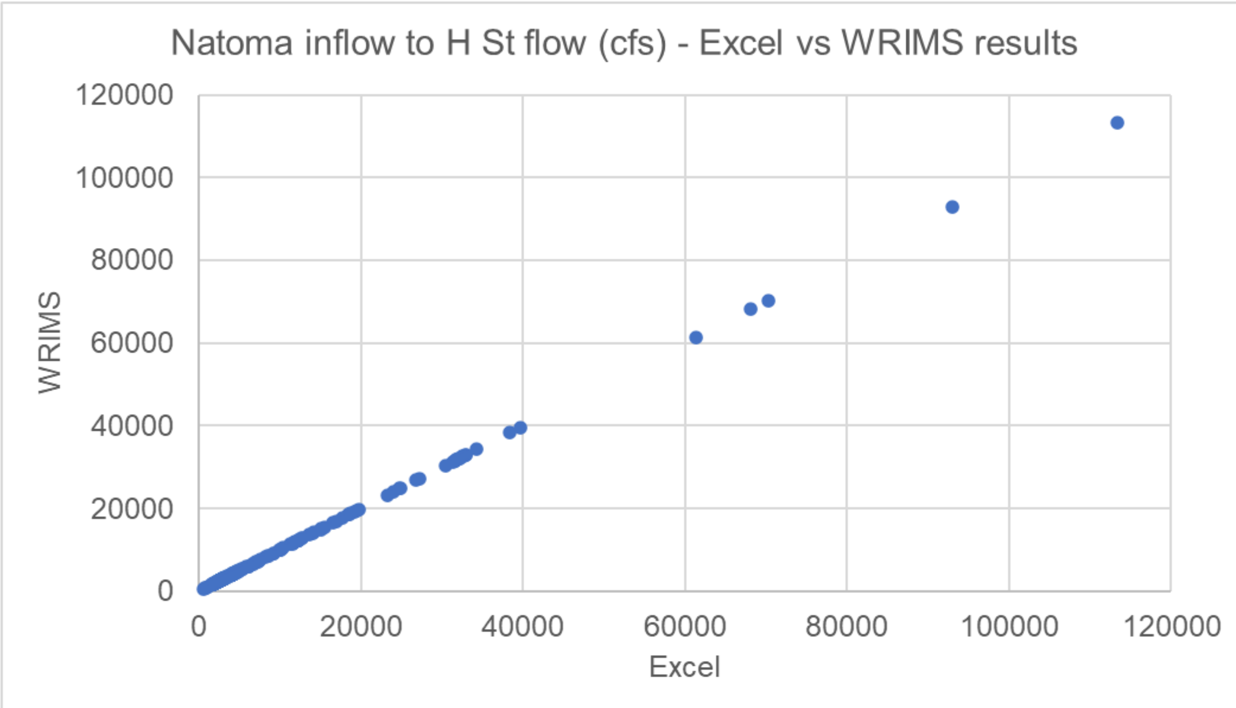


Figure 45. Scatterplot of American River at H St Excel and WRIMS flow (cfs) comparison

3.2.4.2 *Multiple Reaches*

Figure 46 shows the scope of the multiple reach verification. The upstream inflow is a state variable timeseries of Shasta dam releases. The orange inflows are incremental, or accretion-depletion flows derived from mass balances of the upstream and downstream historical data. The yellow triangles are wedge storage in the reach. The outflow result in a reach is set as the upstream inflow in the next reach. The objective is to verify that when multiple reaches are put together, the results should show consistency between Excel and WRIMS2 simulations as was found in the single reach test.

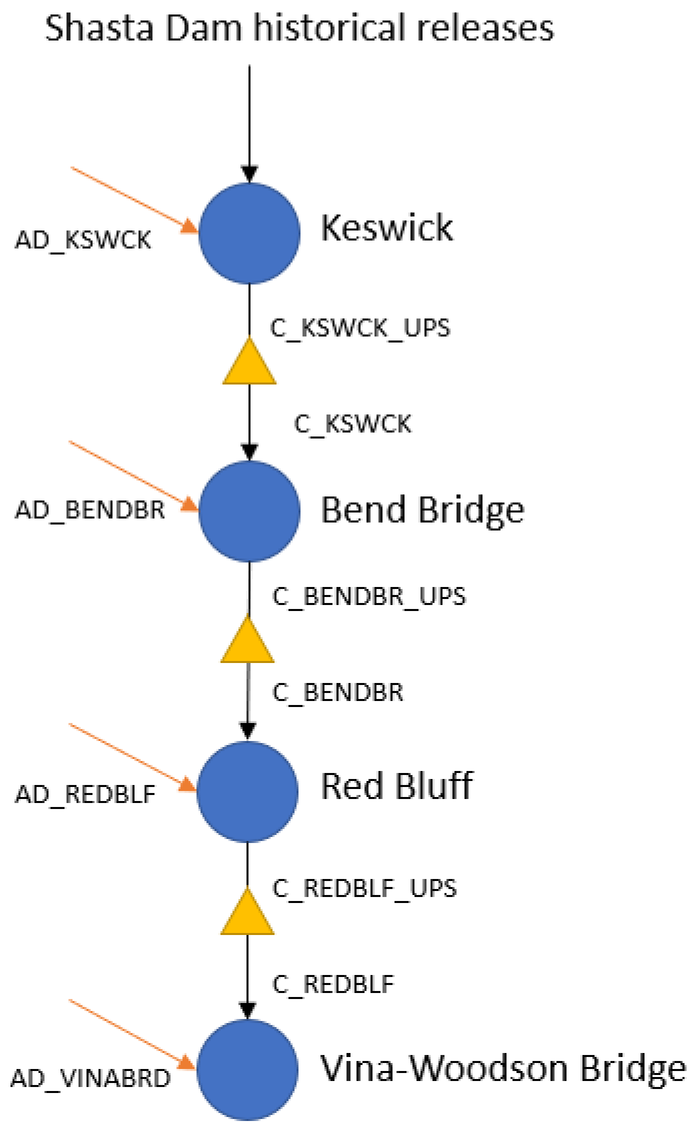


Figure 46. Multiple reach verification schematic.

Figure 47 shows the results using an Excel-based calculation using the Muskingum routing method. Figure 48 shows the same results that is simulated using WRIMS2. Overall, the WRIMS2 simulation matches with Excel which shows the Muskingum WRIMS2 simulation implementation is sound. The results in these figures show similar agreement between the WRIMS2 and Excel simulations.

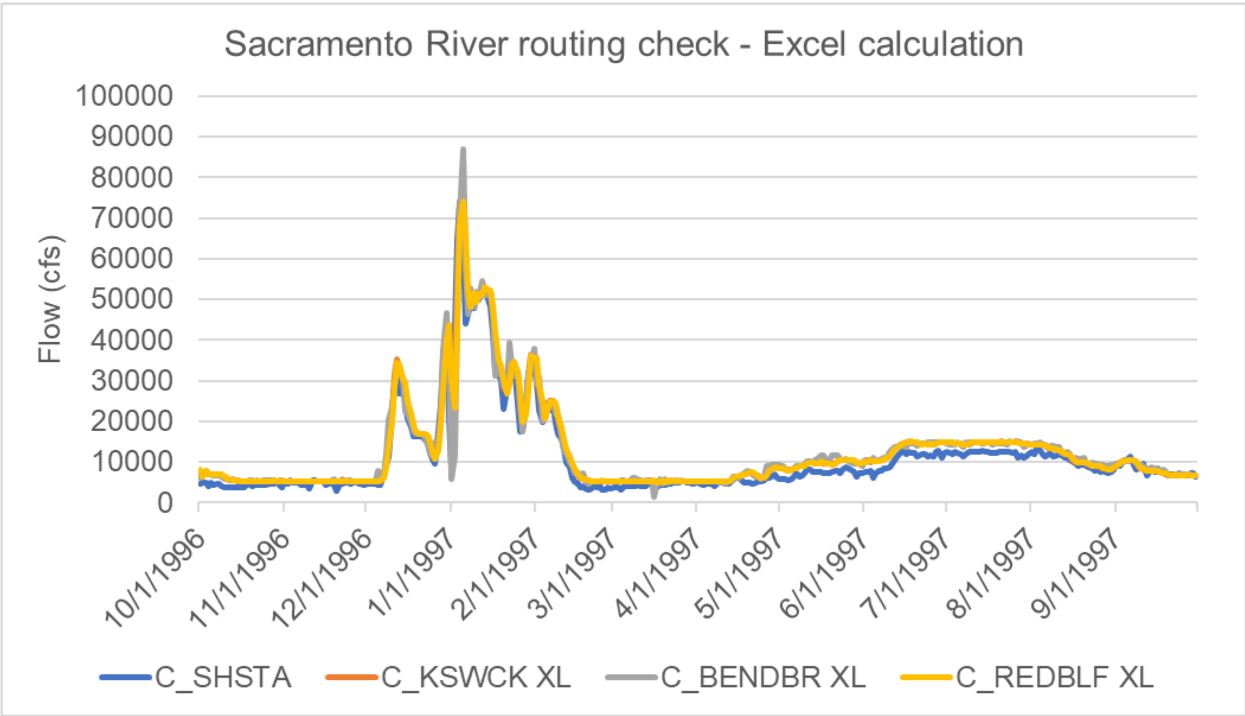


Figure 47. Sacramento River multiple reach routing exercise performed using Excel spreadsheet calculations.

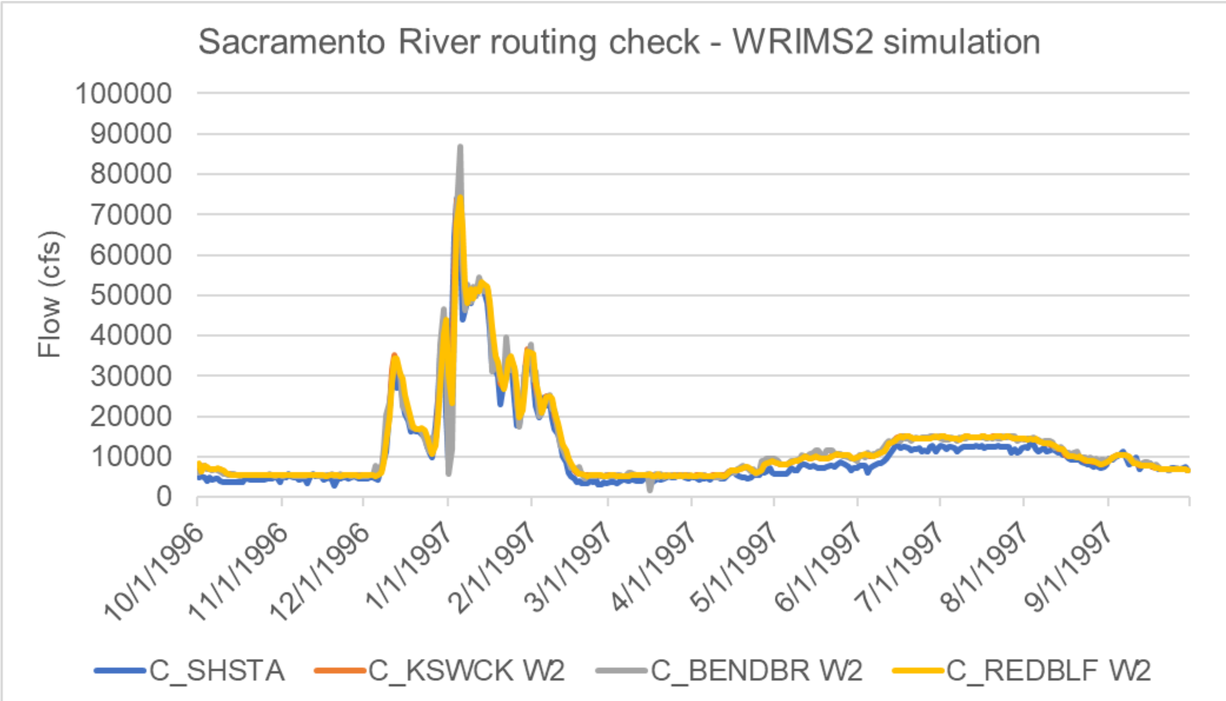


Figure 48. Sacramento River multiple reach routing exercise performed using WRIMS2 simulation.

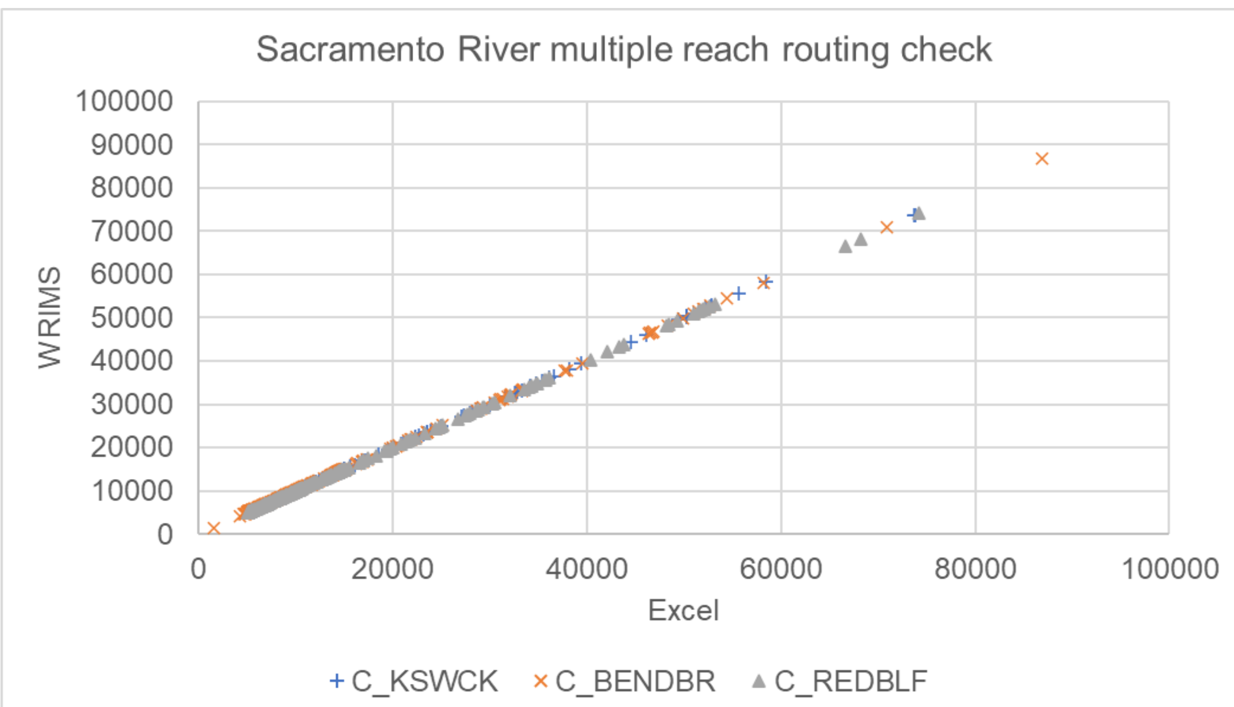


Figure 49. Scatterplots of Sacramento River at Keswick, Bend Bridge, and Red Bluff Excel and WRIMS flow (cfs) comparion

3.3 Model Configurations

This section discusses how the model schematic was selected, as well as the hydrologic inputs and calculation methods, general structure of the reservoir operating zones, how flood control operations are represented, which MIF requirements are included, and how Delta inflow demand was represented. The study is based on the 2017 Delivery Capability Report (DCR) CalSim II model. The CalLite model was then updated to reflect the 2017 DCR in terms of code and model inputs. The script CS2CL (CA DWR and USBR, 2014) was used to generate CalLite inputs based on a CalSim II model (2017 DCR in this case). The CS2CL script allows users to develop CalLite models with comparable assumptions with CalSim II.

The study's model was built from scratch incrementally starting with a pure simulation mode with routing, then adding reservoir zones and rule curves, then adding MIF requirements. Then STO and MTO-based goals for Delta inflow demand were developed. Starting from scratch helped ease switching from STO to MTO modes and required a specific syntax not used in CalLite or CalSim II models. Another reason was for easier interpretation and debugging of the results. Developing and analyzing a simplified CVP/SWP NOD model made it easier to understand how the different model components such as weights, AD terms, STO vs MTO mode interacted.

3.3.1 Model Schematic Design

The study schematic is based on the CalLite model because the eventual goal is to develop a daily timestep mode for CalLite. Figure 50 shows the study schematic. Table 10 summarizes model coverage and includes river flow requirements.

Additional nodes were added to fulfill Muskingum sub-reach criteria and to allow explicit representation of flood control flow objectives. For example, the travel time from Sacramento River at Red Bluff to Wilkins Slough exceeds the one-day timestep. Muskingum routing criterion recommends that long routing reaches "should be subdivided into subreaches so that the travel time through each sub reach is approximately equal to the routing interval (USACE, 1994)." That is, the number of sub reaches should be the travel time K divided by the time step (one day in this case) shown in Equation (51). As a result, one additional node between Red Bluff and Wilkins Slough was added: Sacramento River at Ord Ferry.

$$\#\ sub\ reaches = \frac{K}{\Delta t} \tag{51}$$

Storage arcs like Trinity and Whiskeytown were omitted in this study. The AD term calculation is expected to account for upstream operations in these reservoirs. Shasta and Folsom are the two major NOD CVP reservoirs in the system so these were the focus of this study. Some nodes were also replaced, such as Feather River below Thermalito with Feather River near Gridley because historical flow data was not directly available for Thermalito. Next, Sacramento River at Hood was replaced with Freeport for the same reasons. Other nodes were added to be more consistent with flood control system models like HEC-ResFloodOpt. For example, Yolo Bypass is not just one node as in CalLite. Yolo Bypass at Woodland and Lisbon were added to be more consistent with Figure 52.

NOD demands and deliveries aside from weir diversions are not simulated. AD terms may include losses through agricultural and municipal and industrial diversions. Including these diversions dynamically may overestimate model depletions.

The Delta and South of Delta were omitted here. The reasons for this are:

- Simulating salinity requirements in the monthly STO models used an artificial neural network (ANN) to emulate DSM2 flow-salinity relationships. CAM does not use the ANN for salinity requirements simulation but instead uses a complex set of lookup tables and case/conditions. This is because the ANN requires knowledge of the previous five months from the current month. In MTO and forecasting mode, the future previous five months are unknown. For example, if the current month is January and the future end month is December, then future December month needs the previous five months to simulate Delta salinity. But these previous five months, July to November, are also future months from the current January month and thus are unknown. In other words, using ANN in an MTO run becomes a non-linear problem requiring more sophisticated approaches. Further research is needed to incorporate salinity forecasting capability in a daily MTO model. Researchers at UC Davis Department of Computer Science, Department of Electrical and Computer Engineering, and Department of Mathematics are working with DWR MSO’s Delta Modeling Group on this matter (Qi et al., 2022).
- This study focuses on routing water from the NOD reservoirs. In this case, setting the model boundary condition at the Delta inflow nodes like Yolo Bypass at Lisbon and Freeport is adequate for now.
- Including South of Delta operations such as San Luis and project deliveries requires further review and potentially modification of the allocation methods. The Delta also needs to be adequately represented because of tradeoffs in project allocation and meeting Delta regulations.

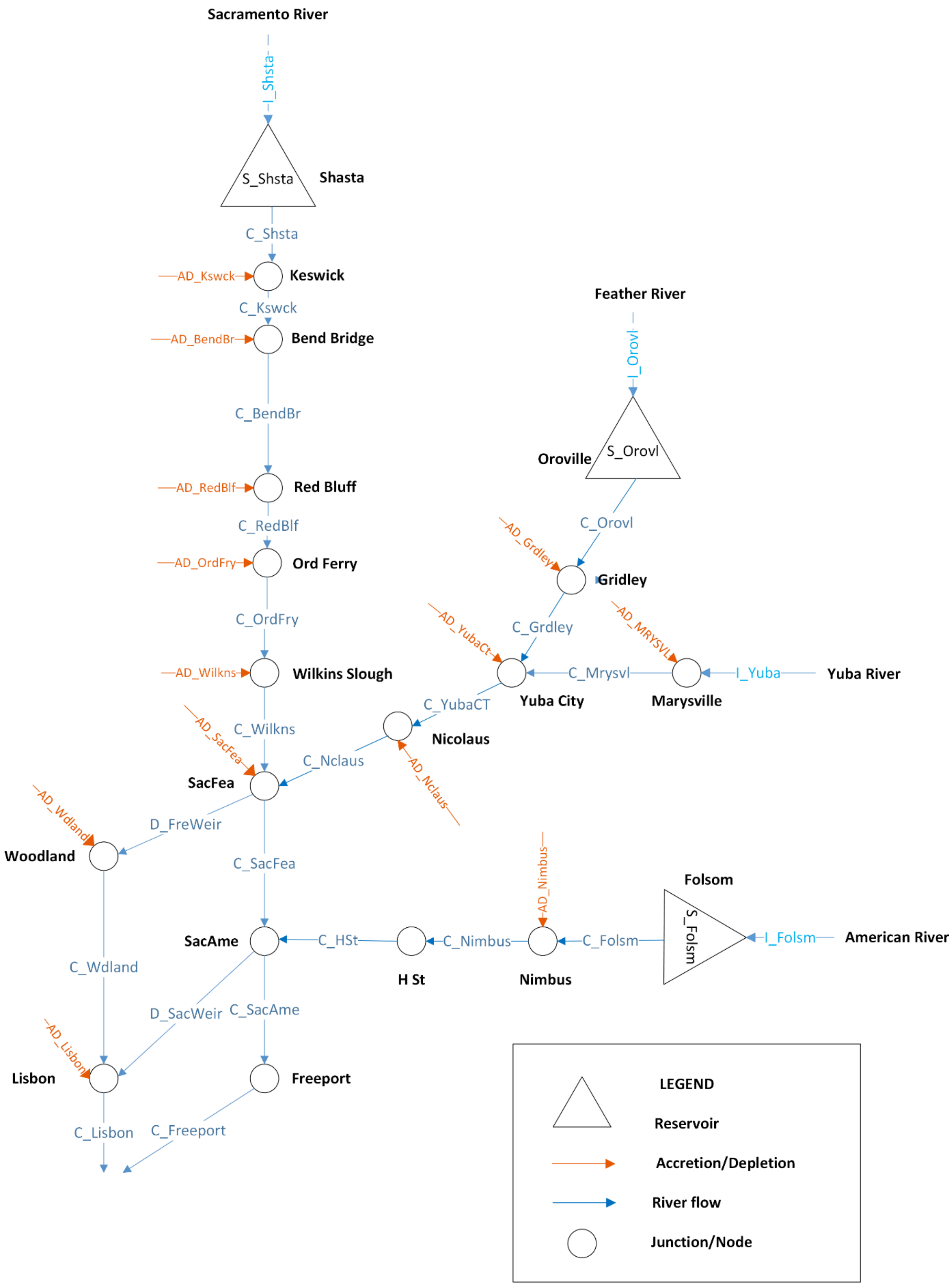


Figure 50. Study Model Schematic NOD only

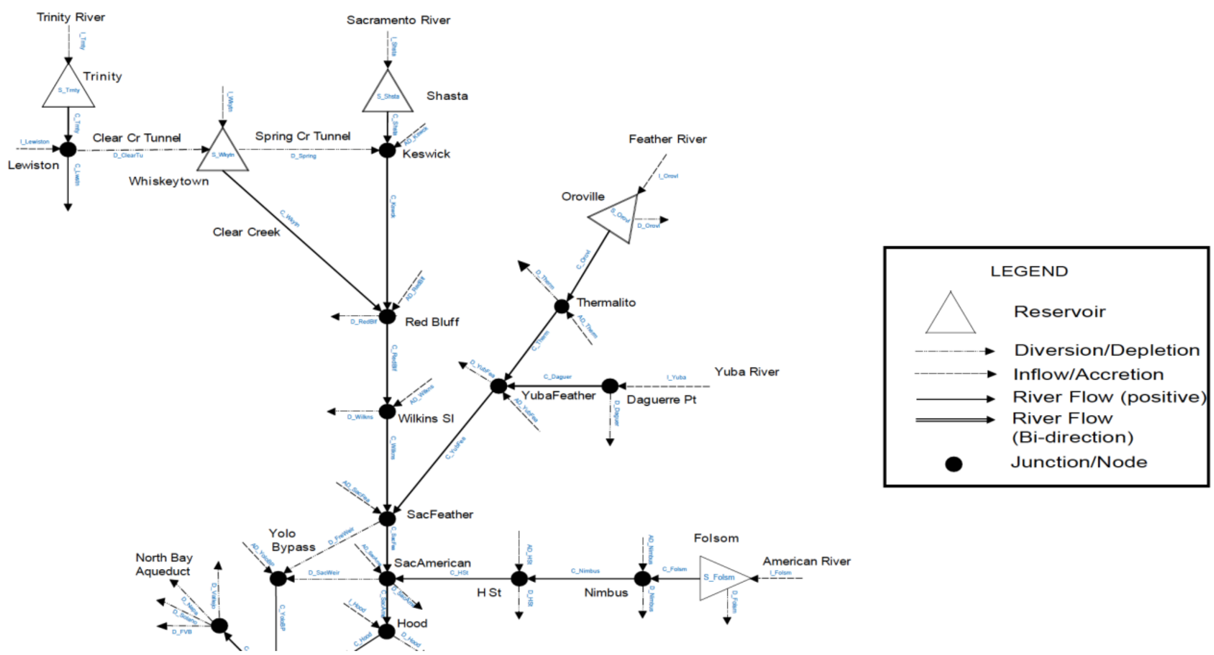


Figure 51. CalLite NOD schematic and legend

Table 10. Summary of model coverage

North of Delta storage facilities	**Conveyance Facilities**	**Operational/Regulatory Constraints**
Shasta Lake Lake Oroville Folsom Lake	• Sacramento River • Feather River • American River • Yuba River • Fremont Weir • Sacramento Weir • Yolo Bypass	• Keswick Minimum Flow • Red Bluff Minimum Flow • Navigation Control Point at Wilkins Slough • Feather River Minimum Flows • Nimbus Minimum Flows • American River Min Flows at H St

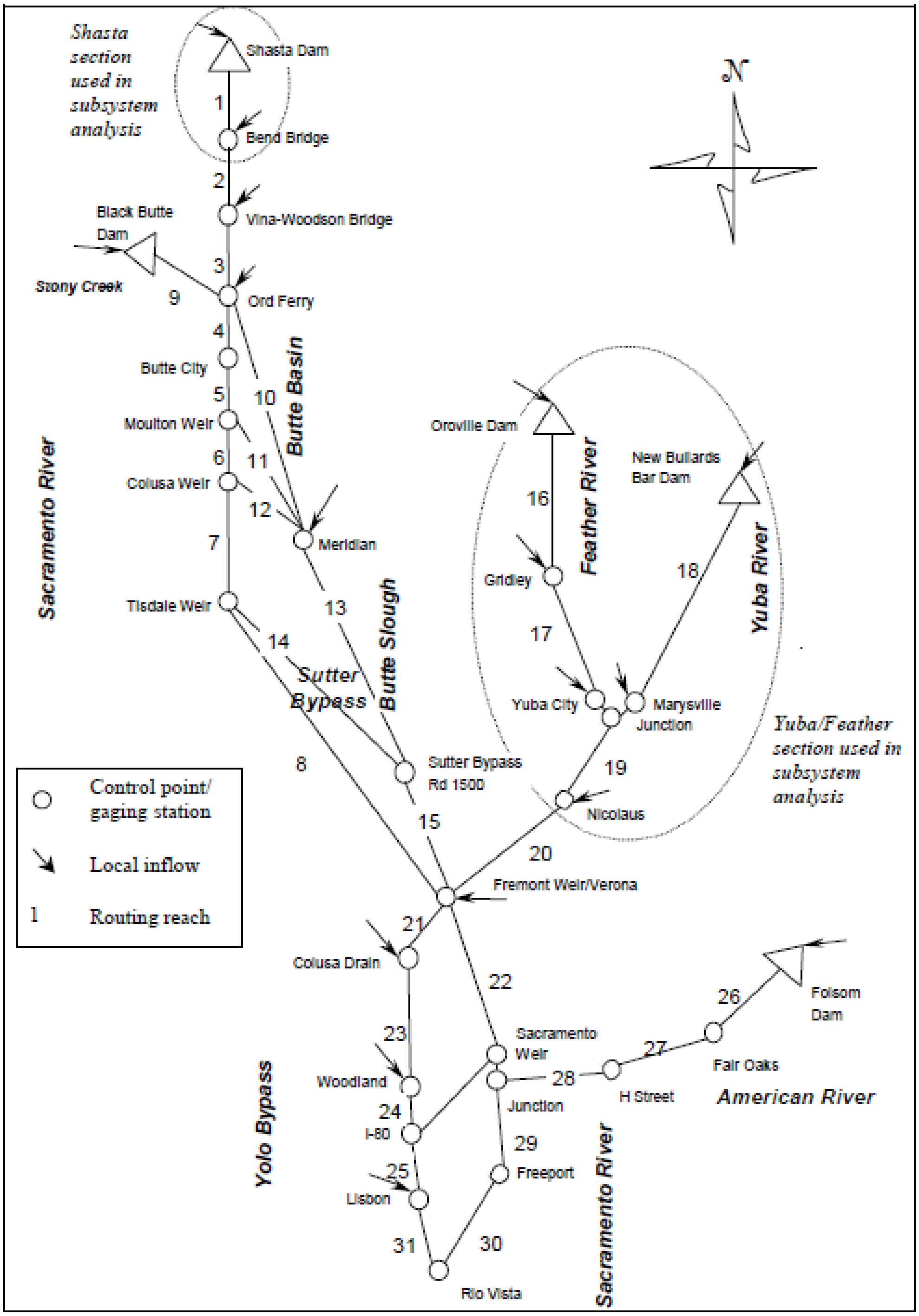


Figure 52. HEC-FCLP Schematic

3.3.2 Hydrologic Inputs and Data Sources

There are two main hydrologic inputs: 1) Reservoir inflows and evaporation, and 2) Accretion-Depletion (AD) terms. Reservoir inflows and evaporation losses were obtained from CDEC. AD terms depict losses and gains for a node. These terms can be positive or negative and are referred to as “local inflows.” AD terms were calculated using data from CDEC, USGS, or DAYFLOW, depending on where data are available. Appendix A - Accretion-Depletion Term Calculations and Estimation explains how the AD terms were calculated. Appendix B - Historical Data Sources lists the data sources. The remaining inputs aside from AD terms are summarized in Appendix C – Other State Variable Inputs and Sources.

A major limitation is that some data were unavailable. For example, historical flow at Feather River at Yuba City and Nicolaus are not provided due to backwater effects. This is also why flow data at American River at H St and Sacramento River at I St are not available. Therefore, AD term error is higher in the lower Feather, American, and Sacramento Rivers. Appendix D – Data QAQC and Estimation Methods shows various data quality issues (missing, negative, outliers) and how historical data from CDEC and USGS NWIS were pre-processed.

Aside from directly using historical data as inputs, existing monthly hydrologic inputs from CalLite or CalSim can be converted to daily data. One approach would be to map historical daily flow patterns to the monthly data. This concept is already applied to estimate daily Fremont and Sacramento weir spills in CalSim II. Hoffpauir (2011) compared three disaggregation methods employed WRAP’s daily model (SIMD). Figure 53 is a disaggregation of one year of daily flows using the three methods. Depending on data availability, either one of the three disaggregation methods can be applied to determine daily inputs from monthly CalSim inputs.

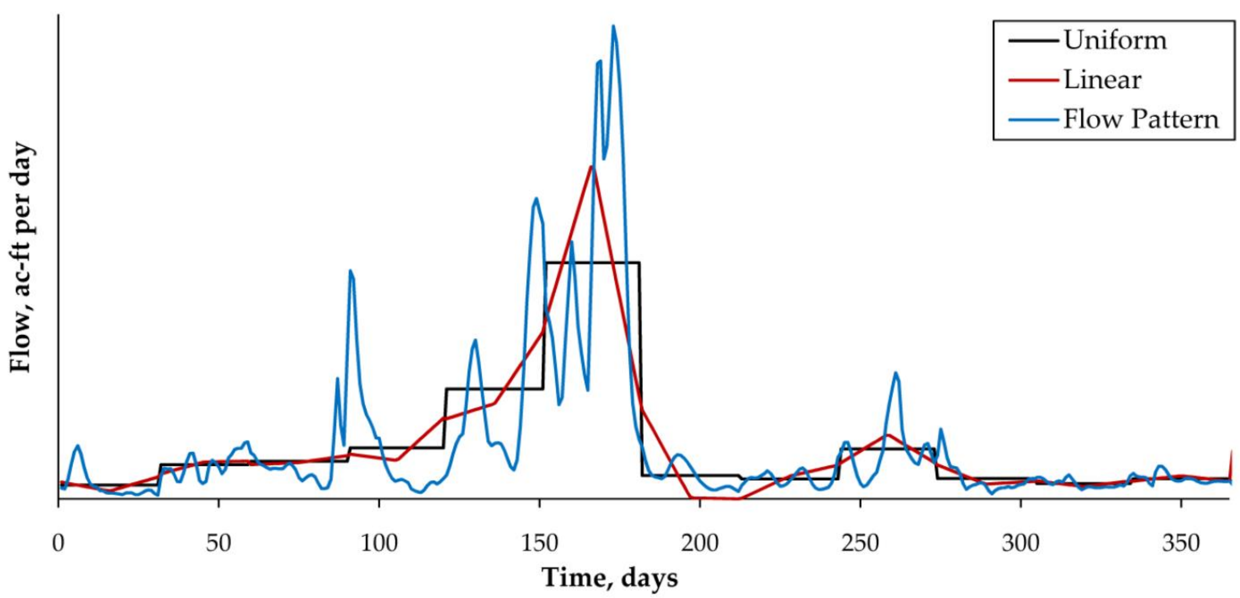


Figure 53. Comparison of uniform, linear spline interpolation, and normalized flow pattern monthly to daily flow disaggregation methods (Hoffpauir, 2011)

Another modeling group within DWR MSO has developed daily data for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) Fine-Grid model (CA DWR, 2022b). The C2VSIM model simulates water movement through the linked land surface, groundwater, and surface water flow systems in California's Central Valley. It is an application of the Integrated Water Flow Model (IWFM). It is not a system model like CalLite or CalSim, but its daily hydrologic inputs could be mapped for use in a daily CalSim model.

3.3.3 Reservoir Operations

Reservoir operational zones are driven by storage levels. Level 1 is the dead pool storage at the low end and level 6 is the physical reservoir capacity. In between, the levels are either static or timeseries variables that represent rule curves that change seasonally. These inputs are either obtained from the DCR 2017 CalSim II study then disaggregated from monthly to daily or calculated directly using daily data. Figure 28 shows how the storage levels for each reservoir zone and their bases.

Table 11. North of Delta reservoir level values or timeseries and calculation method.

Reservoir	Variable	Value (TAF)	Timeseries calculation method
Shasta	S_SHSTALevel1 (Deadpool)	550	
	S_SHSTALevel2	Timeseries	Using 2017 DCR fixed values for the whole month
	S_SHSTALevel3	2500	
	S_SHSTALevel4	Timeseries	Using 2017 DCR fixed values for the whole month
	S_SHSTALevel5 (Flood control pool)	Timeseries	1977 USACE Water Control Manual
	S_SHSTALevel6 (Capacity)	4552	
Oroville	S_Orovllevel1 (Deadpool)	29.6	
	S_Orovllevel2	852	
	S_Orovllevel3	min(2470, S_OrovlLevel4)	Using 2017 DCR fixed values for the whole month
	S_Orovllevel4	Dynamic	
	S_Orovllevel5 (Flood control pool)	Timeseries	1970 USACE Water Control Manual
	S_Orovllevel6 (Capacity)	3558	
Folsom	S_Folsmlevel1 (Deadpool)	90	
	S_Folsmlevel2	Timeseries	
	S_Folsmlevel3	Timeseries	
	S_Folsmlevel4	Timeseries	
	S_Folsmlevel5 (Flood control pool)	Timeseries	2004 Reclamation-SAFCA Interim Water Control Manual (SUPERSEDED)
	S_Folsmlevel6 (Capacity)	975	

Figure 54 to Figure 56 show the daily storage level timeseries for Shasta, Oroville, and Folsom used in the thesis model. Except for the level 5 timeseries, the timeseries were uniformly distributed from the monthly values in CalSim II to daily values in the thesis model. The main lessons come from comparing differences from one level to another. The level 1 and 2 timeseries are constant. Zone 1 must be at least the deadpool storage. Zone 2 could theoretically be up to the difference between level 2 and level 1 and can be thought of as a buffer before dead pool. Zone 3 is conservation storage, which is bounded by the difference between level 3 adjusted and level 2. Only about 500 TAF is allowed in zone 3. This is most likely because of the flood control season. However, from May to August, the gap between level 3 adjusted and level 2 increased. This could be due to the snowmelt and fill season. The objective would be to fill zone 3 as much as is feasible considering downstream objectives.

Zone 4, another conservation zone, is the difference between level 4 and level 3 adjusted. During the fall and winter months, level 4 and level 5 (flood control rule curve) usually overlap. Meaning that zone 4 can only store water as is feasible under flood control operations. Zone 5, the flood zone, is the difference between level 5 and level 4. During the winter season (usually October to May), level 5 and level 4 overlap. From around June to September, there is allowable space for zone 5 water as shown by the difference between level 5 and 4 timeseries. Lastly, zone 6, the overtopping zone, is any water above the reservoir capacity or level 5 timeseries. There is almost never water in this zone due to the highly negative weight of zone 6. In summary, the level timeseries dictate how much water can be stored in each reservoir zone.

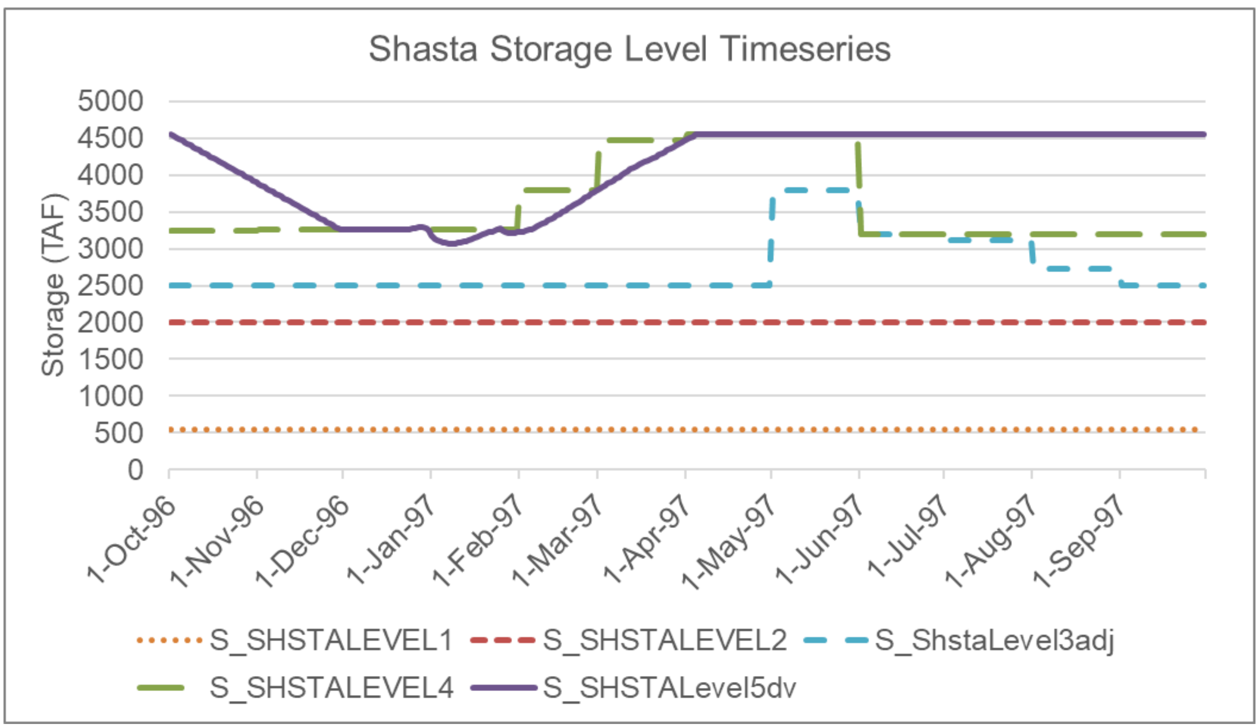


Figure 54. Thesis model daily Shasta storage level (TAF) timeseries

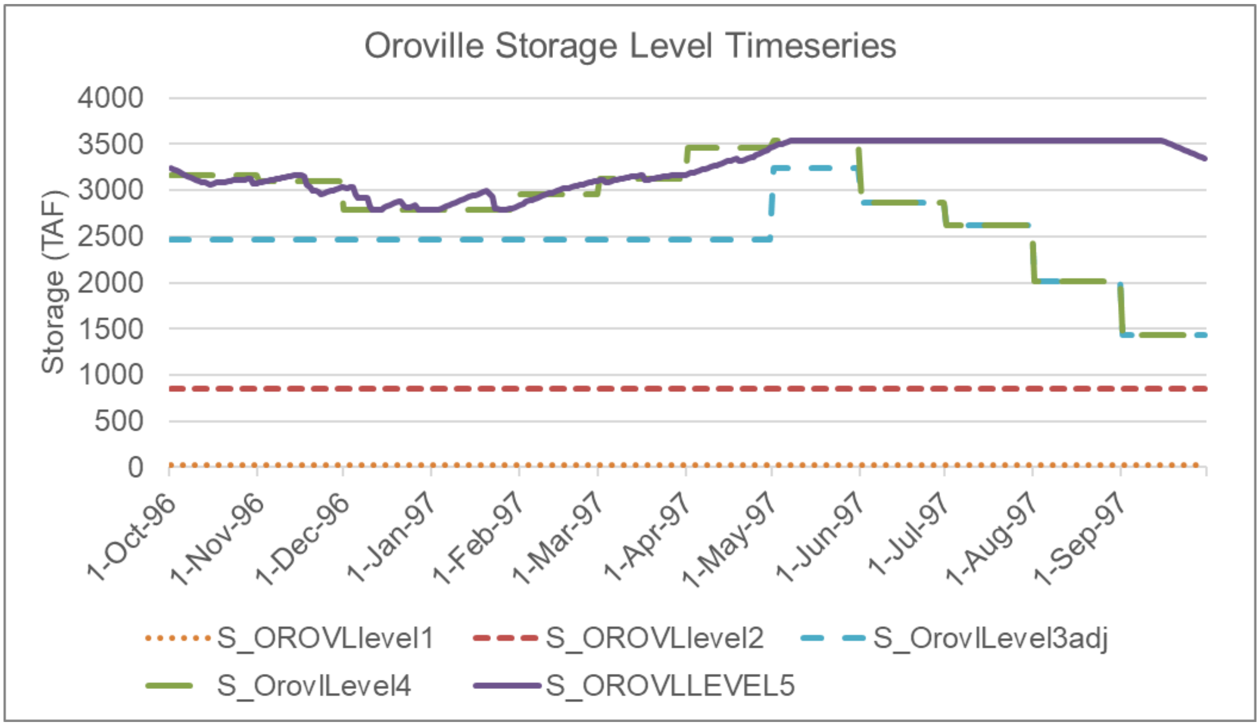


Figure 55. Thesis model daily Oroville storage level (TAF) timeseries

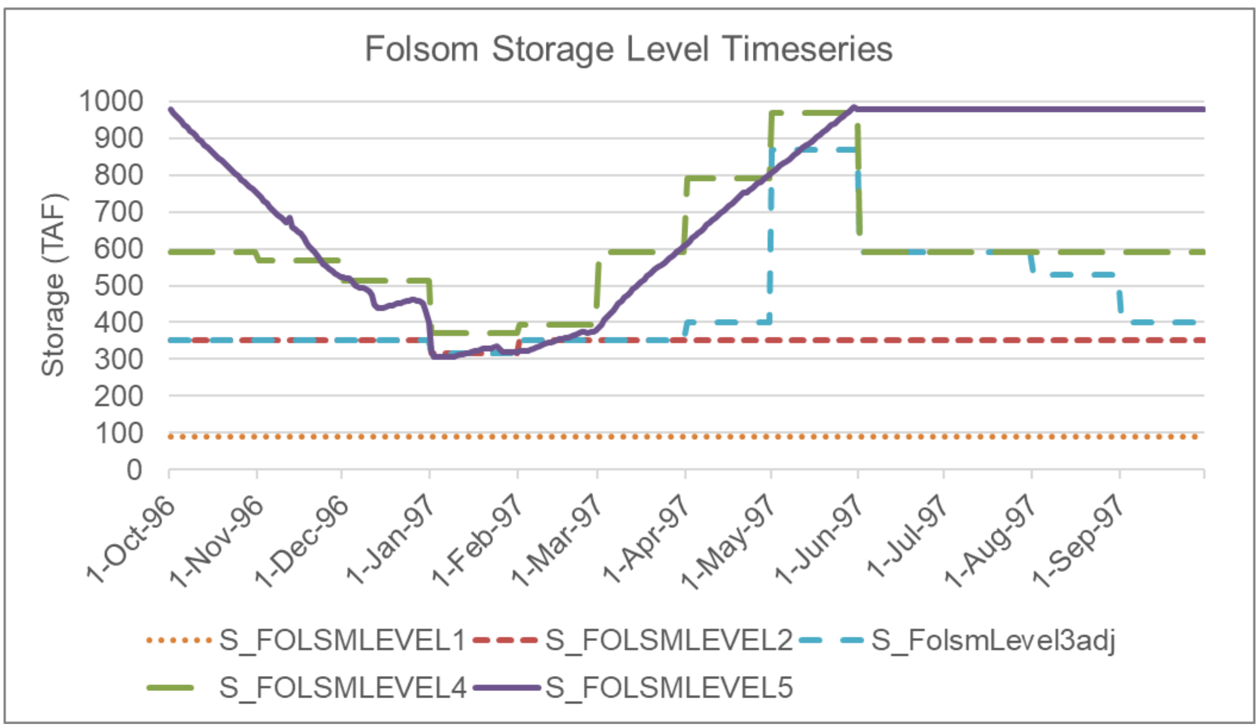


Figure 56. Thesis model daily Folsom storage level (TAF) timeseries

3.3.4 Flood Control

This section explains how the flood control rule curve timeseries were calculated for Shasta, Oroville, and Folsom. Table 12 summarizes the main resources used. Figure 28 shows that the level 5 timeseries, the flood control rule curve, is used to determine zone 5 in reservoirs. In this study, zone 5 is the flood control pool.

Table 12. Main references for flood control rule curves for the major NOD reservoirs

Facility	Reference
Shasta Dam	1977 WCM (Knowles and Cronkite-Ratcliff, 2018; USACE, 1977)
Oroville Dam	1970 WCM (Knowles and Cronkite-Ratcliff, 2018; USACE, 1970)
Folsom Dam	Superseded 2004 USBR and SAFCA Interim Agreement (J. Forbis, USACE, personal communication, May 2022)

3.3.4.1 *Shasta*

Shasta Dam is operated so tailwater flow at Keswick Dam should be below 79,000 cfs, the Sacramento River at Bend Bridge gaging station near Red Bluff flow should be below 100,000 cfs, and storage space in Shasta should follow the 1977 Water Control Diagram (WCD) from the USACE. The Keswick node in the study is simplified as a flow node and not treated as a dam, so the 79,000 cfs restriction is omitted. Only the flow restriction at Bend Bridge is applied. The flood control rule curve (also known as Level 5 CalSim timeseries) at Shasta was recreated using historical data using Knowles and Cronkite-Ratcliff's (2018) report.

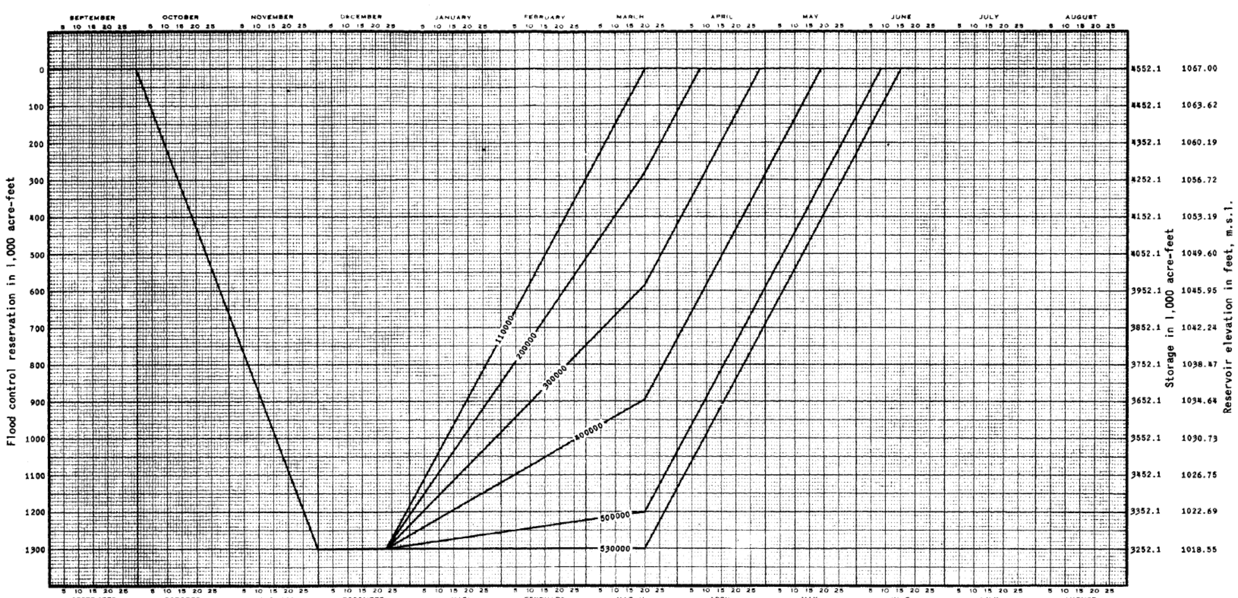


Figure 57. Shasta 1977 WCD

3.3.4.2 *Oroville*

Oroville Dam flood control operations should prevent Feather River flows at Oroville, Feather River above the mouth of the Yuba River, Feather River below the mouth of the Yuba River, and Feather River below the mouth of the Bear River from exceeding 150,000 cfs, 180,000 cfs, 300,000 cfs, and 320,000 cfs, respectively (Jones, 1999). Oroville storage also should operate to the 1970 WCD (USACE, 1970). The flood control rule curve at Oroville was recreated using historical data using Knowles and Cronkite-Ratcliff's (2018) report.

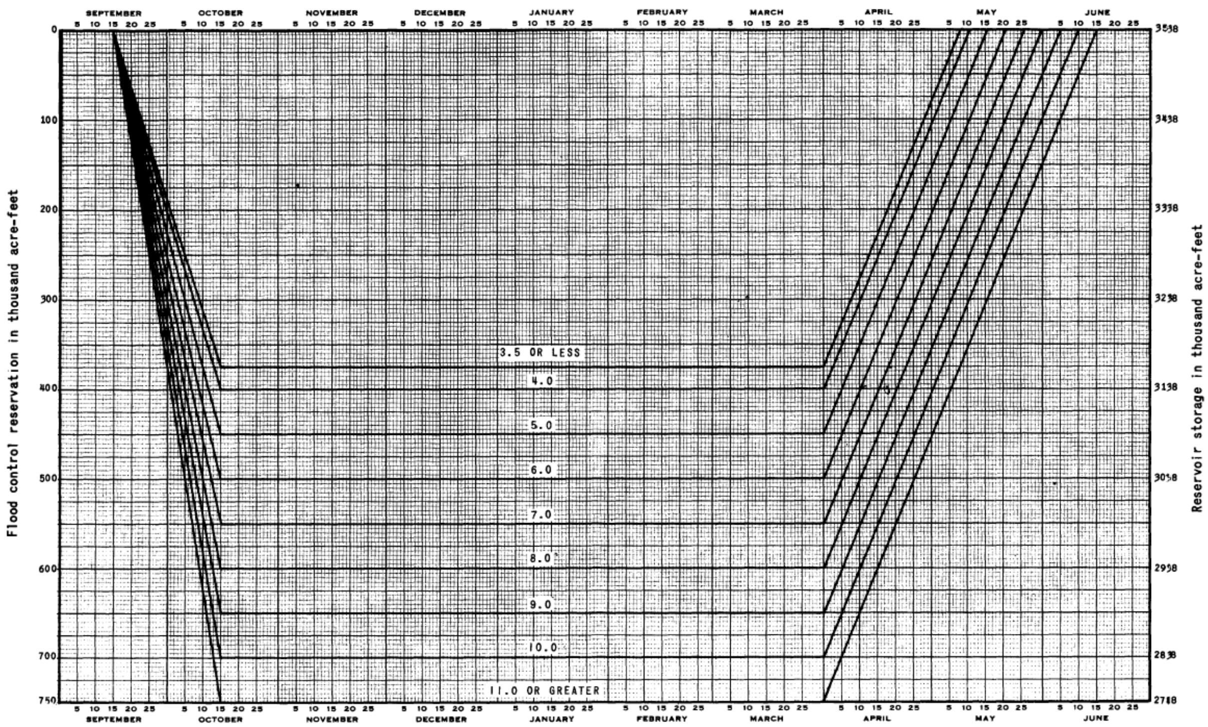


Figure 58. Oroville 1970 Water Control Diagram (USACE, 1970)

3.3.4.3 *Folsom*

Folsom flood control operation guidance is that flows in the American River should not exceed 115,000 cfs. The Water Control Manual assumed here was that of the 2004 Reclamation and SAFCA Interim Agreement which provides variable flood storage space in Folsom Lake. There was a 1993 SAFCA WCD as well but the main difference was Folsom storage capacity. In 1993, the Folsom storage capacity was 975 TAF while in 2004, the capacity was 977 TAF. The flood control rule curve at Folsom was recreated using historical data using the superseded 2004 WCD (J. Forbis from USACE, personal communication, April 2022). The flood storage zone volume is determined using basin wetness parameters and storage in upstream reservoirs.

There is a newer 2019 WCM. This was developed after a series of investigations and several flood risk management projects in and near the American River watershed, also known as the Joint Federal Project (JFP) which includes the additional release capacity from a new spillway (Goharian et al., 2020). Construction of the JFP was completed in 2017. Congress then directed the USACE to update the WCM for Folsom Dam to fully realize the benefits of the completed Folsom Dam modifications (now JFP). The USACE also was directed to reduce variable space allocation from the interim operating agreement between 400,000 AF and 670,000 AF to a range between 400,000 AF and 600,000 AF. USACE also evaluated the feasibility of incorporating NWS weather forecasts into Folsom Dam and Lake's WCM (USACE, 2019). The reason for not using this newer manual was to be as similar as possible to flood control operations with WY 1997 presented in this study.

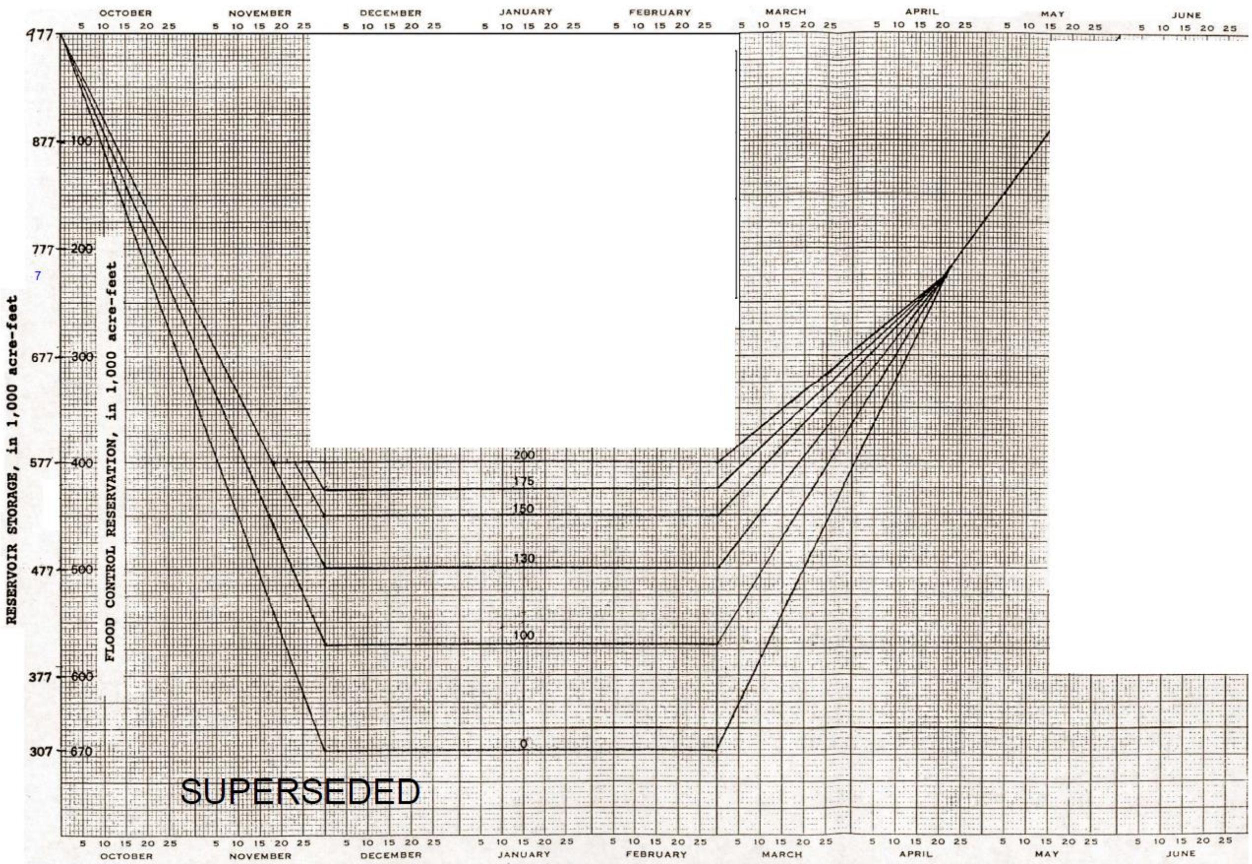


Figure 59. Superseded Folsom 2004 WCD

3.3.5 Minimum In-stream Flow Requirements

Table 13 lists the NOD flow requirements in the Sacramento, Feather, and American Rivers. In the model, channel arcs are split between MIF and “EXC” arcs. MIF arcs are weighted high (usually around 5000) so that the model prioritizes making the appropriate reservoir releases to meet the MIF sub-arc. (Refer back to section Weights and Penalties for the exact MIF weights). Unlike in CAM (Equation (53)), the CalLite/CalSim requirements are less than or equal to constraints (Equation (52)); There is no relaxation arc (slack variable) with a very high penalty to reduce the requirement if the model cannot meet it .

$$ChannelArc_{MIF} < Requirement_{MIF} \tag{52}$$

$$ChannelArc_{MIF} > \ Requirement_{MIF} - RelaxationArc \tag{53}$$

Table 13. North of Delta MIFR in daily CalLite

Region	Location	Description
Upper Sacramento R.	Sacramento River below Keswick Dam	SWRCB WR 90-5, predetermined Central Valley Project Improvement Act (CVPIA) 3406(b)(2) flows
Upper Sacramento R.	Sacramento River below Red Bluff	SWRCB WR 90-5, varies depending on Shasta index
Upper Sacramento R.	Sacramento River at Wilkins Slough	5,000 cfs for navigation
Feather R.	Feather River below Thermalito and at the Mouth	1983 DWR, Department of Fish and Game (DFG) Agreement
American R.	Below Nimbus Dam	Nimbus standard pre-CVPIA MIF values for b(2) accounting
American R.	At H St Bridge	SWRCB D-893

3.3.6 Delta Inflow Demand

To simulate forecasted Delta inflow demand, historical Freeport flows from DAYFLOW were used for perfect foresight to drive future day 3 model flows at Freeport. This is similar to how previous WRIMS-based models (Chen, 2011; Fung, 2011) simulated Delta inflow demand by using the Sacramento River at Hood timeseries (C_Hood or C400).

Two types of goals are used. The first type of model objective (Figure 60) focuses on meeting current timestep Freeport demand, represented by a timeseries of historical Freeport flows. The "lhs > rhs penalty 1000" means that if the Freeport flow exceeds the historical flows, each additional flow beyond the RHS incurs 1000 units of penalty per TAF of exceedence. "lhs < rhs penalty 9999" means that if the model Freeport is lower than the historical values, then each TAF of flow under the target incurs a 9999 penalty on the objective function. So the model is more encouraged to at least meet the target. There is a penalty (1000 units per cfs) for going above to discourage the model from excessive releases to meet the Freeport demand. The penalty of being under-target in each timestep is much higher so the model seeks to meet the demand downstream.

```
goal(fm) setFreeport {lhs C_Freeport($m) rhs C_Freeport_Hist($m)
    lhs>rhs penalty 1000
    lhs<rhs penalty 9999
}
```

Figure 60. STO Freeport demand goal

The second type of goal to meet Delta inflow demand is only functional with MTO. The algorithm was introduced in section 3.1.4.3 and reiterated below:

1. Define decision variables
    a. Shortage in meeting Delta inflow requirement
    b. Summation of shortage
2. Calculate shortage in meeting Delta inflow requirement
    a. Shortage = Delta inflow requirement – Simulated Freeport flow
3. Calculate cumulative shortage per MTO sub-period
    a. Cumulative shortage = cumulative shortage (-1) + shortage
    b. Reset counter when new MTO sub-periods starts
4. Set goal to minimize future end of MTO sub-period shortages
    a. If end of MTO sub-period cumulative shortage is 0, then there is no penalty
    b. Else, accrue penalty of 5000 per cfs of cumulative shortage

The purpose of the second type of goal is to use MTO mode to refine operations. Conceptually, the goal is to make the model less myopic by not just focusing on the current timestep, but also the future timesteps. With this second type of goal, the model needs to determine optimal releases to meet the Delta inflow demand not just for the current timestep, but for multiple days.

Table 14 shows the frequency of Delta inflow shortages when routing only is enabled and MTO is not in a preliminary scenario set. The shortage column shows that there are 17 days in which shortages occurred. On the other hand, Table 15 shows the frequency of Delta inflow shortages and cumulative shortages at the end of an MTO period with both routing and MTO are enabled. There were only 10 days of shortages with MTO enabled. The table serves to visualize the second type of goal to meet Delta inflow demand when MTO is turned on which was introduced in the previous paragraph.

Table 15 differs with Table 14 in that cumulative shortages within an MTO sub-period and an end of MTO sub-period future penalty are calculated. A larger end of MTO sub-period penalty is detrimental to the objective value so the solver seeks to make release decisions to minimize shortages not only in the current timestep, but also by the end of the sub-period. The end of MTO period penalty on July 6, July 12, July 18, July 24, and July 31 is determined by taking the cumulative shortage at those dates, then multiplying that by 5000 as specified in the algorithm provided earlier.

The main takeaway between the routing only and the routing and MTO on scenarios is that the average shortages in July 1997 can be reduced when the second kind of goal is implemented. Table 14 shows that the average shortages in July 1997 with routing only enabled is 1251 cfs. The shortage column shows that there are 17 days in which there were shortages. Meanwhile, Table 15 only has 669 cfs of shortages on average and there were only 10 days when shortages occurred. In summary, MTO mode allows future targets (minimize shortages, end of period storage, etc.) and lets the solver determine optimal releases to meet those targets.

Table 14. Example routing on only scenario Delta inflow demand shortages in meeting historical Freeport flows in July 1997.

Date	Routing only Freeport flows	Historical Freeport flows	Shortage	Cumulative shortage
1-Jul-97	20100	20100	0	0
2-Jul-97	20300	20300	0	0
3-Jul-97	13420	20300	6880	6880
4-Jul-97	18149	20400	2251	9131
5-Jul-97	18111	20700	2589	11720
6-Jul-97	17614	20500	2886	14606
7-Jul-97	20200	20200	0	0
8-Jul-97	17388	19900	2512	2512
9-Jul-97	19611	19700	89	2601
10-Jul-97	19062	20000	938	3538
11-Jul-97	17717	20300	2583	6122
12-Jul-97	19152	20700	1548	7669
13-Jul-97	19173	20800	1627	0
14-Jul-97	21713	21000	0	0
15-Jul-97	26735	21100	0	0
16-Jul-97	22301	20900	0	0
17-Jul-97	20900	20900	0	0
18-Jul-97	16690	21200	4510	4510
19-Jul-97	18818	21200	2382	0

20-Jul-97	21115	21200	85	85
21-Jul-97	21500	21500	0	85
22-Jul-97	21500	21500	0	85
23-Jul-97	16359	21900	5541	5626
24-Jul-97	21514	21700	186	5812
25-Jul-97	21677	21700	23	0
26-Jul-97	21300	21300	0	0
27-Jul-97	23508	21300	0	0
28-Jul-97	21300	21300	0	0
29-Jul-97	21000	21000	0	0
30-Jul-97	18460	20600	2140	2140
31-Jul-97	20800	20800	0	2140
Average			**1251**	

Table 15. Example routing and MTO on scenario Delta inflow demand shortages in meeting historical Freeport flows in July 1997.

MTO sub-period	Date	Routing and MTO Freeport flows	Historical Freeport flows	Shortage	Cumulative shortage	End of MTO period penalty
1	1-Jul-97	20100	20100	0	0	
	2-Jul-97	20300	20300	0	0	
	3-Jul-97	21911	20300	0	0	
	4-Jul-97	18745	20400	1655	1655	
	5-Jul-97	17820	20700	2880	4536	
	6-Jul-97	17013	20500	3487	8023	40113526
2	7-Jul-97	20200	20200	0	0	
	8-Jul-97	19900	19900	0	0	
	9-Jul-97	19700	19700	0	0	
	10-Jul-97	20000	20000	0	0	
	11-Jul-97	20300	20300	0	0	
	12-Jul-97	20700	20700	0	0	0
3	13-Jul-97	20800	20800	0	0	
	14-Jul-97	21000	21000	0	0	
	15-Jul-97	21100	21100	0	0	
	16-Jul-97	20900	20900	0	0	
	17-Jul-97	20900	20900	0	0	
	18-Jul-97	21200	21200	0	0	0
4	19-Jul-97	19304	21200	1896	1896	
	20-Jul-97	19578	21200	1622	3518	
	21-Jul-97	20527	21500	973	4491	
	22-Jul-97	19892	21500	1608	6099	
	23-Jul-97	18597	21900	3303	9402	
	24-Jul-97	21700	21700	0	9402	47008540
5	25-Jul-97	21700	21700	0	0	
	26-Jul-97	21300	21300	0	0	
	27-Jul-97	21300	21300	0	0	
	28-Jul-97	19114	21300	2186	2186	
	29-Jul-97	21000	21000	0	2186	
	30-Jul-97	19485	20600	1115	3300	
	31-Jul-97	20800	20800	0	3300	16502169
Average				**669**		

3.4 Further MTO Scenario Adjustments

There are two modifications implemented in the RMTO scenario to prevent Folsom deadpool storage conditions. Earlier iterations of RMTO resulted in excessive reliance of Folsom storage to meet Delta inflow demand resulting in multiple deadpool storage days (Figure 118). Shasta EOS storage also was very high in the pre-adjusted MTO scenario (Figure 114). The two code modifications to level out Shasta storage and prevent Folsom deadpool storage days are as follows:

1. Setting current day Shasta releases to future historical Wilkins Slough flow
2. Increasing Folsom conservation storage zone weights

3.4.1 Shasta Releases to Future Wilkins Slough Flow

This prevents Shasta storage from getting too full (Figure 114) since it forces the model to make current day Shasta releases to be the Wilkins Slough historical flow 2 days into the future. In the future, this should be replaced with a set of goals, weights, or penalties that more elegantly use MTO syntax so that the model does not let Shasta hold all the water and rely on Folsom excessively.

3.4.2 Folsom Storage Zone Weights

Folsom storage zone weights in the conservation zone were increased by 500 units relative to the original (Table 7). This is to prevent excessive releases from Folsom leading to deadpool storage conditions in the summer (Figure 118). This code change is a temporary workaround until a proper and comprehensive recalibration of weights and penalties is performed for a daily timestep model.

Table 16. Folsom storage zone decision variable weights in the model – MTO mode

Decision variable	Weight	Description
S_Folsm_1	40000*taf_cfs	Deadpool storage zone
S_Folsm_2	593*taf_cfs	Conservation storage
S_Folsm_3	588*taf_cfs	Conservation storage
S_Folsm_4	584*taf_cfs	Conservation storage
S_Folsm_5	550*taf_cfs	Conservation storage
S_Folsm_6	-10000*taf_cfs	Storage above flood control rule curve

Chapter 4 Results and Discussion

This thesis compares WY 1997 model results with historical storages and flows. This year was chosen based on historical data availability within the CalSim II period of record from WY 1921-2003. This allows the comparison with historical and CalSim II 2017 DCR results. 1997 was chosen because one of California's most devastating flood events happened in January 1997. The 1997 flood event pushed the Sacramento flood control limit and caused many failures in the system (Jones, 2013). Simulating this year will show performance of the routing parameters during wetter years. A limitation of this thesis is that a drier year is not simulated. Using drier hydrology is needed to show the limitations of using fixed Muskingum routing parameters which does not consider varying flow conditions. Future work would use hydrology from a drier year between WY 1997-2003 so that a CalSim II comparison could be done. A good candidate is WY 2001 since it has the driest Sac Valley Index (SVI) from 1997-2003 (Table 17).

Table 17. Official Water Year Classifications based on May 1 Runoff Forecasts (CDEC)

WY	Sac Valley Index	WYT	San Joaquin Valley Index	WYT
1995	12.4	W	5.5	W
1996	9.7	W	3.9	W
1997	11	W	4.2	W
1998	12.4	W	4.9	W
1999	10	W	3.4	AN
2000	9.2	W	3.3	AN
2001	5.9	D	2.3	D
2002	6.5	D	2.3	D
2003	8	AN	2.7	BN
2004	7.7	BN	2.2	D
2005	7.4	BN	4.2	W
2006	13	W	5.5	W
2007	6.2	D	1.9	C
2008	5.4	C	2.1	C
2009	5.5	D	2.4	D
2010	6.9	BN	3.5	AN
2011	10	W	5.1	W
2012	6.9	BN	2.2	D
2013	5.8	D	1.6	C
2014	4	C	1.1	C
2015	4	C	0.7	C
2016	7.1	BN	2.4	D
2017	14.9	W	6.2	W
2018	7.2	BN	3	BN
2019	10.2	W	4.2	W
2020	6	D	2.2	D
2021	4	C	1.3	C

There will be two groups of simulated vs historical comparisons. The first group compares the three daily simulation results with historical. The second group compares monthly results from the Base and Routing on MTO scenario with a CalSim II study and historical data. Since the thesis scenarios are daily, they are converted from daily to monthly by taking the monthly average of flows and the end-of-month storages.

4.1 Daily Cases

The first group compares three daily timestep cases with historical data (data sources are listed on Appendix B - Historical Data Sources). Results are shown for selected parameters from Figure 61 to Figure 71.

1. Base case – No routing and STO
2. Routing on and STO
3. Routing on and MTO

The three daily cases are also evaluated on three other categories:

1. MIF requirements statistics
2. Reservoir conditions – Dead pool and flood control encroachment statistics
3. Delta inflow demand statistics

MIF requirement statistics show how often the model exceeds, meets, and violates meeting flows at various control points in the Sacramento Valley. Reservoir conditions tables show the frequency of reservoir storage going into deadpool and frequency of being at or over the flood control rule curve. Delta inflow demand statistics are like the MIF requirement tables in that it shows how often the model can exceed, meet, and violate the Delta inflow requirement represented as historical Sacramento River at Freeport timeseries.

4.1.1 Base vs. Routing STO

4.1.1.1 *Folsom Reservoir Over-reliance due to Shortest Travel Time*

The routing on STO case (dashed purple line) is starkly different for Shasta and Folsom operations compared to the base case (no routing STO). Shasta storage (Figure 62) with routing has much higher storage. By the end of September, simulated and historical storages are nearly identical. However, Folsom storage (Figure 66) with routing is consistently close to dead pool from July onward.

When routing is included, the model tends to rely on Folsom more to meet Delta inflow demand. This is because Folsom reservoir releases enter the Delta soonest. In general, operators assume that Folsom releases reach the Delta on the same day. Coordinated operations of the CVP/SWP indicate that Folsom tends to be the first option to meet Delta demands. The USBR (2020) explains some of the decision-making process of meeting in-basin uses as defined in the COA:

"When more reaction time is available, reservoir release changes are used adjust to changing in-basin conditions. If Reclamation decides the reasonable course of action is to increase upstream reservoir releases, then the response may be to increase Folsom Reservoir releases first because the released water will reach the Delta before flows released from other CVP and SWP reservoirs."

In-basin uses are legal uses of water in the Sacramento basin including water to meet Delta regulations such as D-1641. Another way to meet Delta inflow requirements for Delta outflow is to reduce exports instead of pulling water from Shasta or Oroville which will take more than one day to arrive in the Delta. Reclamation and DWR keep a daily water accounting of their share of obligations. Reclamation and DWR operate their respective facilities according to the COA. The COA defines the project facilities and their water supplies. It formulates how the projects can coordinate operations. The COA also provides formulas for sharing joint responsibilities to fulfill Delta standards and other legal uses of water. The COA sharing and balancing logic is currently not included in this study. This is because the COA equations from CalSim II require Delta and South of Delta decision variables such as surplus outflow, CVP exports, SWP exports, Contra Costa, and North Bay Aqueduct diversions.

Reservoir balancing between CVP facilities could prevent excessive reliance on one facility. The balancing logic was obtained from the CalSim II run using the storage level timeseries as explained in the method section. However, this logic was used on a monthly model without routing. Refining the CVP reservoir balancing logic is another avenue to prevent Folsom from reaching early dead pool storage.

The absence of the COA balancing and sharing equations and use of a monthly-model based CVP balancing logic enables a larger decision variable space which could be suboptimal, such as Folsom reservoir being relied on consistently due to its shorter travel time to the Delta. Developing more constraints and policies could calibrate the model to maintain more reasonable conservation space in Folsom. The goal is to have the model show more even distribution of responsibility between Shasta and Folsom reservoirs. Currently, the weights on reservoir zones between Shasta and Folsom are the same for each timestep. Theoretically, this should mean that the model would be indifferent to releasing water from Shasta and Folsom since the reservoir zones have the same weights. The model releasing 10 TAF from Shasta vs 10 TAF from Folsom to meet Delta inflow should theoretically decrease the objective function by the same amount with either source.

The issue now arises when considering reservoir release travel time. Shasta releases do not reach the Delta on the same day. Travel time is usually around five days (about three days during high flow events). For example, Figure 1 estimates that it takes about 72.5 hours for Shasta releases to reach Sacramento River at Verona. It takes another 10 hours for the Sacramento River at Verona flows to reach Freeport according to Table 1.

With routing enabled but only using single time step optimization, the model cannot make "smarter" decisions by looking to the future to know how much to release given travel times and future demands. The model is myopic and only cares about the current timestep. For example on Day 1, the model needs to provide 10,000 cfs at Freeport. Assume that the main sources are Shasta and Folsom (Oroville is excluded from this hypothetical case). Ideally, Shasta would provide 5,000 cfs and Folsom would provide 5,000 cfs assuming no depletions and demands upstream to Freeport. However, when travel times and attenuation are considered, if 5,000 cfs is released from Shasta, that amount would not arrive at Freeport in the same time step. Depending on the flow conditions, it will take 3-5 days for the 5,000 cfs upstream releases to reach the Delta. As a result, there is practically no benefit to releasing from Shasta to meet downstream MIF requirements that take longer than one day to arrive. The model should have made the appropriate releases 3-5 days before this Day 1 scenario. However, the model scenario only optimizes one time step at a time instead of optimizing for a 5-7 day period. Therefore with routing enabled but without multi time step optimization, Shasta tends to keep more in storage.

On the other hand, Folsom releases made on the same day are expected to arrive in the Delta. In the solver’s perspective whose goal it is to meet Delta inflow demand, it will almost exclusively rely on Folsom unless there are flood control releases from Shasta and Oroville which means those two reservoirs can contribute more to Delta demand even under routing constraints. The reservoir zone weights at Folsom alone are insufficient to prevent the model from unduly draining Folsom storage.

In terms of Oroville, the model releases just enough to meet MIF requirements at the Feather River once the flood season ends around late February. A possible explanation for this is once high flows have ceased at the Feather River, the solver cannot rely as much on Oroville to meet Delta inflow demand. Around late February as well, the model makes abrupt high releases at Folsom which might be an attempt to meet the Delta inflow demand in the same time step. These higher than usual releases at Folsom to meet Delta demand were detrimental to maintaining storage at Folsom since the peak of the inflow season in WY 1997 ended around mid-February. Instead of slowly building Folsom storage from February to June, Folsom releases were higher than historical which meant that the peak storage around mid-May was only around 500 TAF. Starting in mid-May, Folsom releases started to increase significantly again, contributing to intermittent dead pool storage conditions at Folsom starting in July 1997.

The reasons for higher Folsom releases starting in mid-May was once again related to the limitation of STO when implementing channel routing. If Folsom releases were forced to match historical levels, it would be beneficial for the LP objective value because there will be higher storage at Folsom. However, the model uses more Oroville storage to meet Delta inflow demand downstream. For example, 2 TAF were saved in Folsom by forcing releases to be the same as historical in one time step. But for Oroville, 13 TAF of additional water was released to meet the same Delta demand of 10,400 cfs at Freeport. The model was forced to rely on Oroville releases to meet downstream demand. However, due to travel time and attenuation, the model determines that it can only meet the Delta downstream demand by excessively releasing from Oroville, an attempt to overcome the channel routing constraints. In actual operations, the appropriate Oroville releases would have been made 2-3 days ago so Folsom does not bear the sole burden of meeting Delta inflow requirements.

4.1.1.2 *Fluctuating Flows and Reach Storage Model Treatment*

Dead pool storage conditions at Folsom reservoir starting in July 1997 was the main reason for the erratic release pattern and magnitudes at Oroville. The model weights inhibit Folsom reservoir from decreasing below dead pool storage at 90 TAF. However, the model objective remains that Delta inflow demands at Freeport be met. Since Folsom is at deadpool, the next candidate is Oroville to meet Delta demands because it is the next closest facility. The 2016 water travel time estimates show that Oroville releases during high flow conditions (80,0000-160,000 cfs of Oroville releases) take 38.5 hours to reach Freeport (or about 1.6 days). Otherwise, the rule of thumb estimate of Oroville travel time to the Delta is about 3 days.

By the summer, routing travel time and attenuation limit how much of current day Oroville releases will reach the Delta. For the solver to overcome this limitation, it will make excessively high releases in one timestep so that Oroville releases will travel down the Feather River faster and reach the Delta as much as possible. On the other days Oroville is not releasing as much, the model is relying on reach storage at Gridley to meet Delta demand which is not realistic. However, since there are weights on keeping Oroville water as much as is feasible, then the solver will look for other stored water. Reach storage is a good candidate because these are currently unweighted. A permanent solution to prevent the model from treating reach storage as downstream storage is yet to be found. Fung (2011) encountered the same issue when performing optimization for Delta inflows in his study and explained the phenomenon below:

> "When the flows fluctuate, it means that the solver is choosing a solution where a large amount of water is released upstream, which may satisfy the downstream demand for a few days. In those next few days, a low flow is needed to meet the new demand because a large amount was released prior. Then when all the water is fully routed and exits the system a new large pulse is needed to repeat the process. Although the hydrographs are not ideal, they are correct solutions."

Fung (2011) proposed some options to correct for fluctuating releases such as 1) setting more weights or penalties on the objective function, 2) changing the routing coefficients, 3) the time step, or the 4) forecasting period. A relatively small negative weight can be set on the reach storage arc so that the model is not incentivized to treat this reach storage as actual water supply storage (like Keswick Dam or Thermalito Diversion Dam). Another option is to penalize changes in release rates or reach storage to dampen fluctuations. However, adding weights and penalties on variables and goal statements involves much trial and error since the interactions between the other weights and penalties needs to be evaluated. Ferreira's (2007) dissertation determines updated weights and penalties in a selected CalSim model. Changing the routing coefficients or method, time step, and/or forecasting period can be pursued in the future.

Another workaround is to set penalties on reach storage changing with respect to the previous timestep. This was done on Gridley reach storage which reduced the incidents of erratic release patterns in the summer. This uses a similar concept to penalizing changes in releases from one time step to another to minimize releases changes mentioned above. But more research is needed to determine the optimal penalty with respect to the current storage zone weights so the model appropriately draws down Oroville storage rather than pulling water from reach storage, a variable added to simulate Muskingum channel routing. In summary, more constraints on the reach storage or change in releases can help prevent the model from releasing high flows in some days with the expectation that reach storage will supply water for a few days, then release high pulses of flow again later.

4.1.1.3 *Base Case Performance*

Lastly, when comparing the model simulations with historical, the base case better matches the observed storages. This may lead the reader to think that implementing routing and MTO subsequently is unneeded. This is misleading because the base case, although more "accurate", does not properly reflect actual operations. The base case mainly relies on the accretion-depletion terms to do the "routing". This is how the California Food-Energy-Water System (CALFEWS) simulation model structured their model (Zeff et al., 2021). CALFEWS describes the adaptive surface and groundwater management in the Central Valley while keeping California's food-energy-water system in mind. CALFEWS simulates water storage and conveyance networks in the Central Valley using a daily timestep. Routing of water from different reservoirs to the Delta is not modeled. CALFEWS instead uses the incremental flows, which are synonymous with accretion-depletion terms in this thesis, between nodes to represent the difference in flow between gauges and upstream reservoir releases made on the same day. It assumes an operator is skilled in managing the routing network throughout the Sacramento-San Joaquin system (H. Zeff, personal communication, May 4, 2021). An important distinction between CALFEWS and the model in this study is that CALFEWS does not use linear programming. As a result, CALFEWS does not have penalties or system-wide objectives to solver for. It is more of a rule-based simulation model.

A summary of the key findings comparing the base case and routing on STO case is:

- **The model tends to rely on the closest storage facility to meet downstream demands in a case with channel routing and only STO**. In a California NOD application, the solver almost always relies on Folsom reservoir to meet Delta inflow demands (represented through historical Sacramento River at Freeport timeseries). Exceptions are when Shasta and Oroville release significant amounts for flood operations. During these times, flows are high enough that travel times from these northernmost facilities are expedited so Shasta and Oroville contribute some water towards Delta inflow demand. Otherwise, if Delta demand is 10,000 cfs in the current timestep but travel times from Shasta take five days while it takes three days for Oroville, then the model sees no benefit pulling from Shasta or Oroville because the water would not be arriving at the Delta in the same time step and thus provide no value for the LP objective value. The model needs to consider an optimization period beyond just the current timestep to better represent real world reservoir operations. The multi time step optimization period should be at least five days to accommodate times when Shasta releases might be at their lowest and take the longest to reach the Delta from upstream. Additional constraints such as those representing the COA responsibility sharing and updating the reservoir balancing logic can also help distribute the CVP NOD reservoir releases better.
- **Appropriate weights and penalties will need to be recalibrated and applied to reach storage to prevent the model from viewing it as a downstream storage facility**. Reach storage decision variables were introduced to simulate the storing and release of wedge storage as flows travel through the river. They are not meant to act as secondary water supply sources so that the model can flood the system in one timestep, causing high wedge storage accumulation, then minimize reservoir releases because it sees that it can pull water from the reach wedge storage.

- **The base case matches observed data better compared to the routing on STO and routing on MTO cases because the accretion-depletion terms at each node act as a pseudo-reach storage to mimic routing.** For simulation or rule-based models like CALFEWS, this assumption of no routing with a daily timestep may be sufficient. But for MILP-based models like CalLite or CalSim, channel routing will need to be incorporated explicitly to represent reality better.

4.1.2 Routing STO vs Routing MTO

This section evaluates key differences between the routing STO (RSTO, dashed purple line) and routing MTO (RMTO, dashed red line) results. Overall, there are no major differences in reservoir storages and releases. For Shasta, RMTO has a slightly higher end of September (EOS) storage compared to historical (blue line). However, Oroville's end of season storage is lower compared to the routing STO scenario. Folsom has a noticeable difference from RSTO to RMTO in that deadpool storage conditions in July in RSTO are prevented in RMTO. However, the EOS storage for RMTO Folsom is more than 100 TAF higher than historical.

This section describes operational differences in the ability to meet MIF requirements, the status of reservoir conditions such as dead pool and flood control encroachment, and the ability to meet Delta inflow demand. Table 18 to Table 20 show MIF requirement statistics for the three model cases. The base case has no incidents of "below MIF" violations. With routing enabled but using STO only, shortages in meeting Wilkins Slough MIF increased from zero to 67 days. Table 21 shows detailed MIF statistics for Wilkins Slough. Once MTO was implemented (Table 20) with the shortage minimization goal, shortages decreased from 67 to zero days. In summary, MTO can improve model operations.

Table 22 to Table 24 shows statistics on dead pool storage and flood control encroachment incidents at Shasta, Oroville, and Folsom reservoirs. Dead pool storage should only occur in extremely dry conditions. As a result, if dead pool storage occurs in this very wet WY 1997 simulation, there are significant model limitations. Flood control encroachment occurs when storage exceeds the flood control rule curve. WY 1997 had one of the largest storms on record. So some encroachments are expected. Table 22 shows that routing increases dead pool storage at Folsom. Table 24 shows that these incidents start in July and through September. With MTO, dead pool storage incidents were prevented. Table 23 shows minimal differences in encroachment incidents between Shasta and Oroville in the base scenario. However, Folsom used to have more incidents in the base at 64 days. With routing, this decreased to 24 days. This is most likely tied to routing increasing model reliance on Folsom. With MTO enabled, encroachment incidents increased by 13 days (24 to 37).

Table 25 and Table 26 show statistics on the model's ability to meet Delta inflow demand through a timeseries. Table 25 shows once again no shortages ("LT demand") in the base cycle. This is expected because there is no routing so any releases in the current timestep should reach Freeport. However, routing only results in 71 days Freeport demand shortages. With MTO and the shortage minimization goal, shortages decreased by 38 days (Scenario 3-2). Ideally, there should be minimal shortages in meeting the Freeport demand since WY 1997 is a wet year. Further work is needed to determine a more optimal MTO goal that makes the model more efficient in meeting Delta inflow requirements.

To understand further the storage balancing and deadpool behaviors, there are two types of plots provided. The first plot is the total Shasta, Oroville, and Folsom (S+O+F) simulated storage versus the simulated individual reservoir storage. This helps show how soon or late reservoirs fill and empty. The second type of plot is the total S+O+F historical versus simulated storage to determine if the scenarios are making the appropriate amount of cumulative releases and if the three scenarios have consistent total storage despite the imbalances between individual reservoirs.

Figure 72 shows the base (routing and MTO off) scenario S+O+F storage vs individual reservoirs. Figure 73 shows results for the routing on scenario while Figure 74 shows results for the routing and MTO on setup. Overall, these plots show a strong tendency to draw down Folsom first. The problem is worst off for the routing on scenario though it appears also in the other scenarios. The routing MTO scenario shows improvements because the storage zone weights for Folsom were significantly increased to discourage the model from drawing down Folsom too fast.

Lastly, Figure 75 shows the historical vs simulated S+O+F storage. Total storage between historical and all simulated scenarios remain very similar until early in December 1996. This is mainly due to the more risk averse flood control operations in the model. The higher flood control releases reduce the peak storage which then propagates differences between actual and simulated from January 1997 onward. Reservoir releases vary between the scenarios from spring to summer. Overall, the routing STO EOS storage is closest to historical whereas the routing MTO EOS combined storage is about 1000 TAF lower than historical. In summary, the higher penalties imposed on flood control encroachment can result in lower storage storages along with a model's perfect foresight ability. In reality, human judgment plays a role which cannot be represented in an MILP model. A more thorough recalibration of the goals, weights, and penalties, however, can help reduce the discrepancies between total NOD storage between the routing MTO scenario and historical, though a perfect replication is not expected.

4.1.3 Timeseries Plots

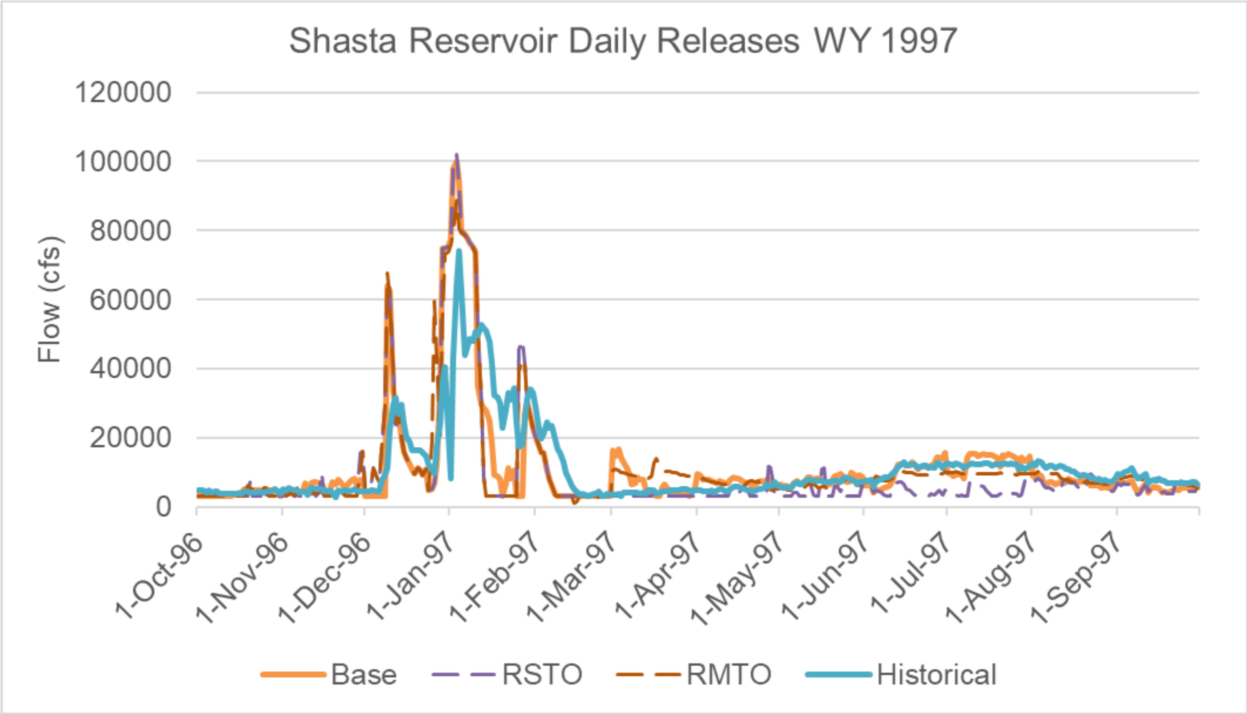


Figure 61. Daily Shasta reservoir releases for simulations and historical data in WY 1997

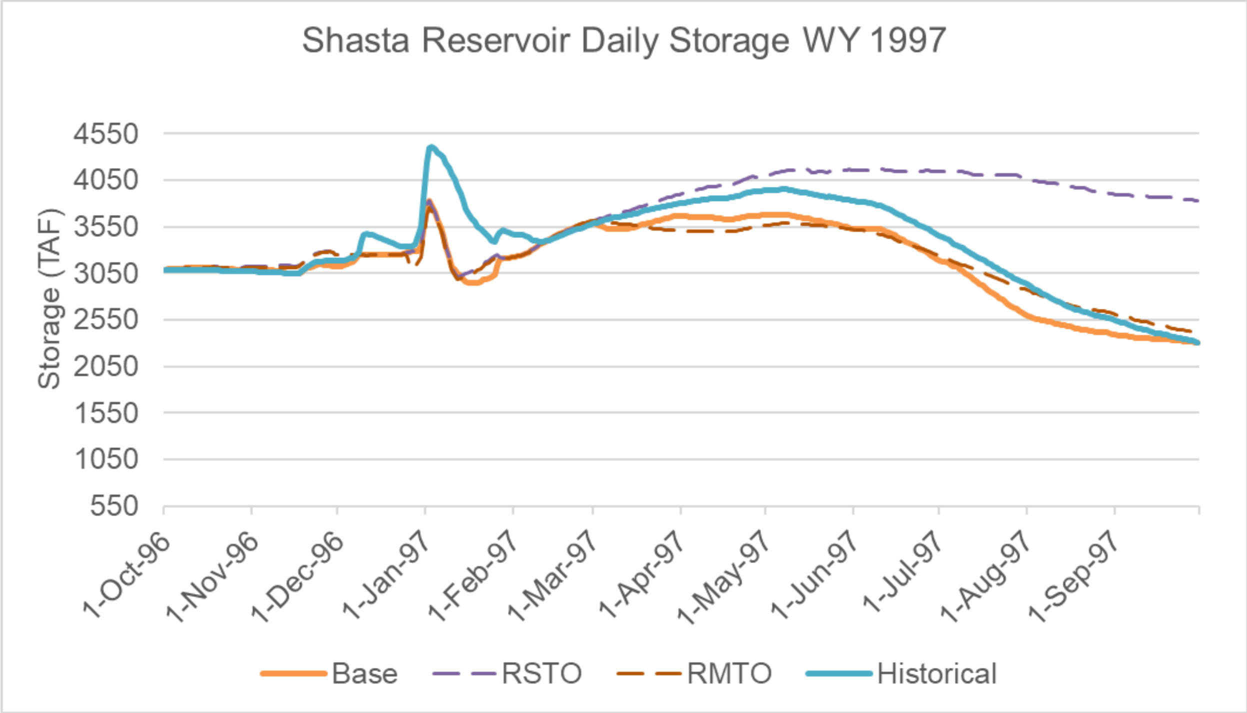


Figure 62. Daily Shasta reservoir storage for simulations and historical data in WY 1997

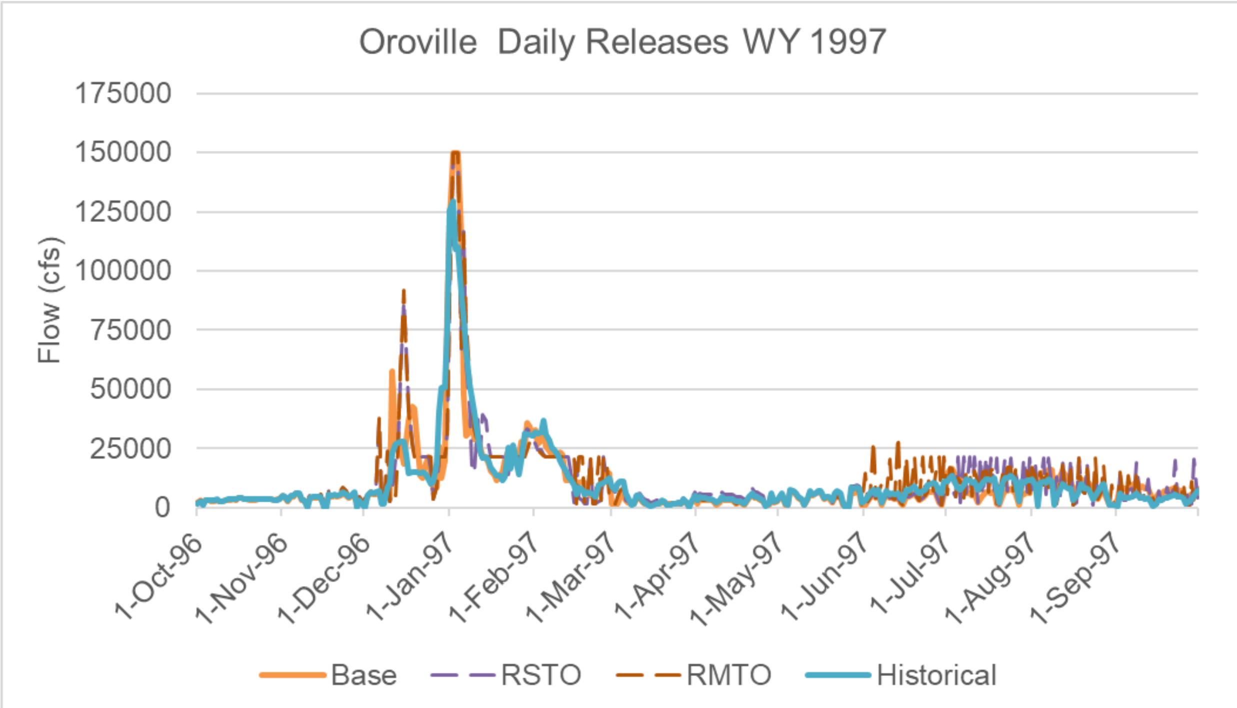


Figure 63. Daily Oroville reservoir releases for simulations and historical data in WY 1997

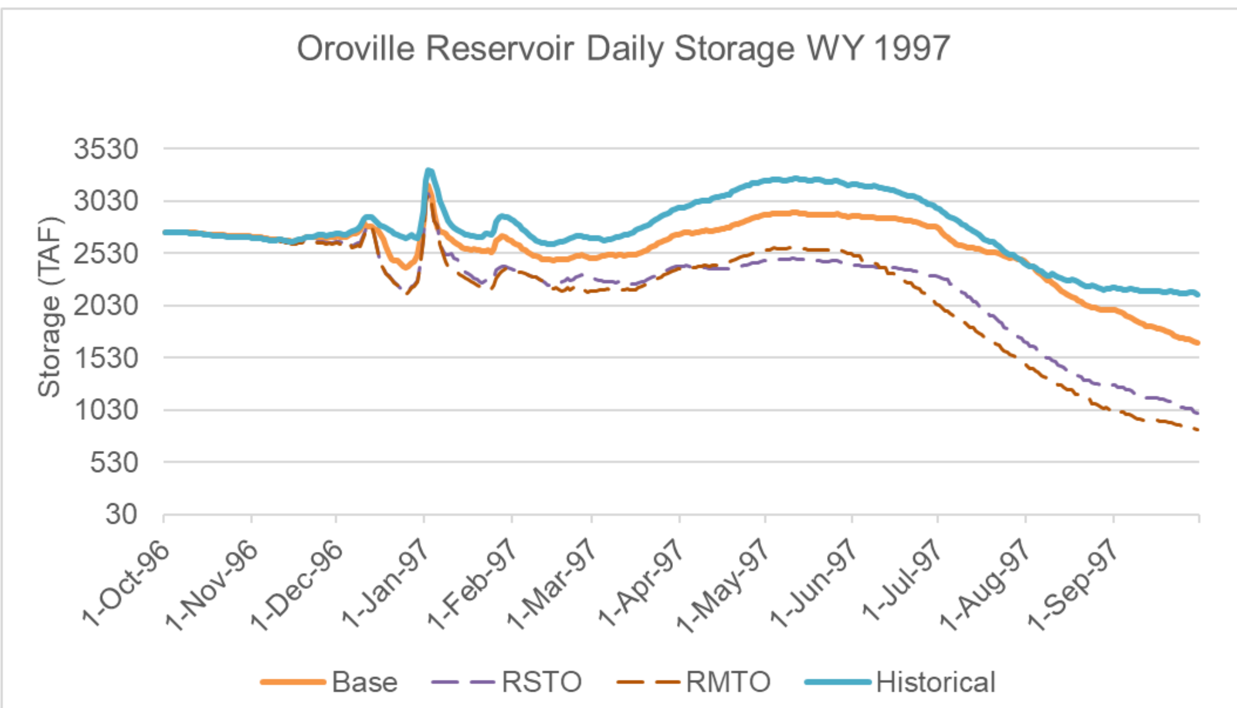


Figure 64. Daily Oroville reservoir storage for simulations and historical data in WY 1997

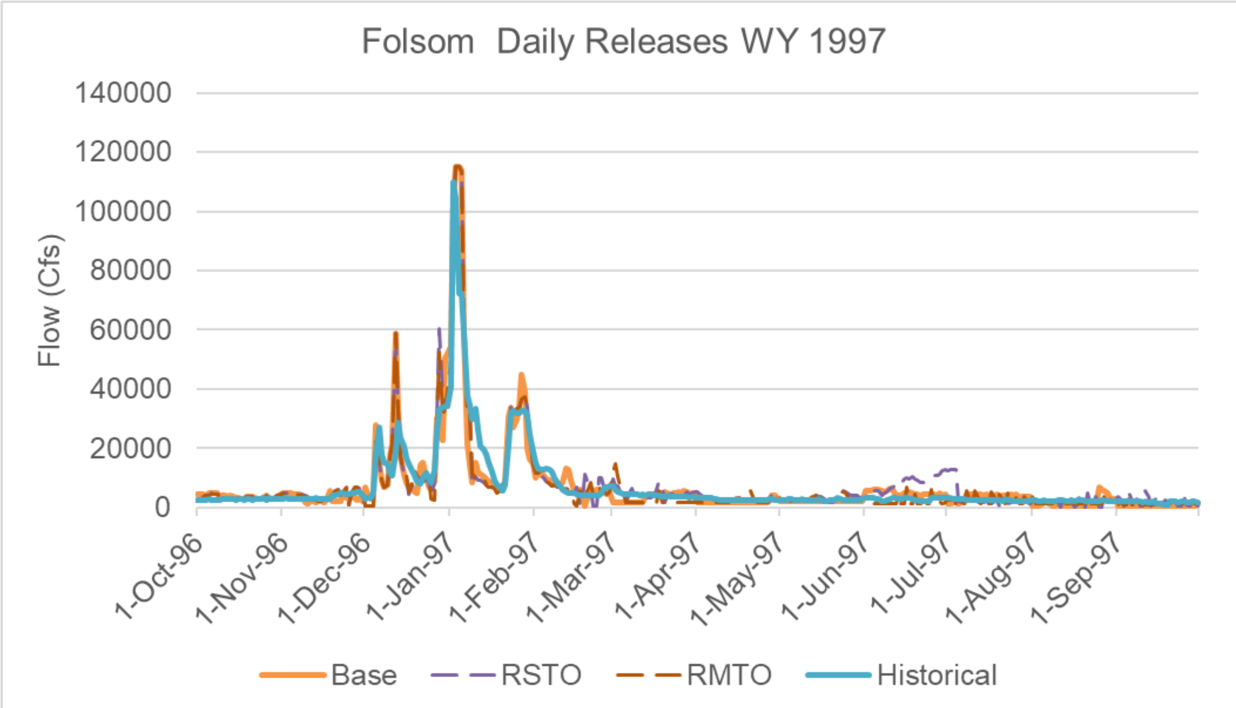


Figure 65. Daily Folsom reservoir releases for simulations and historical data in WY 1997

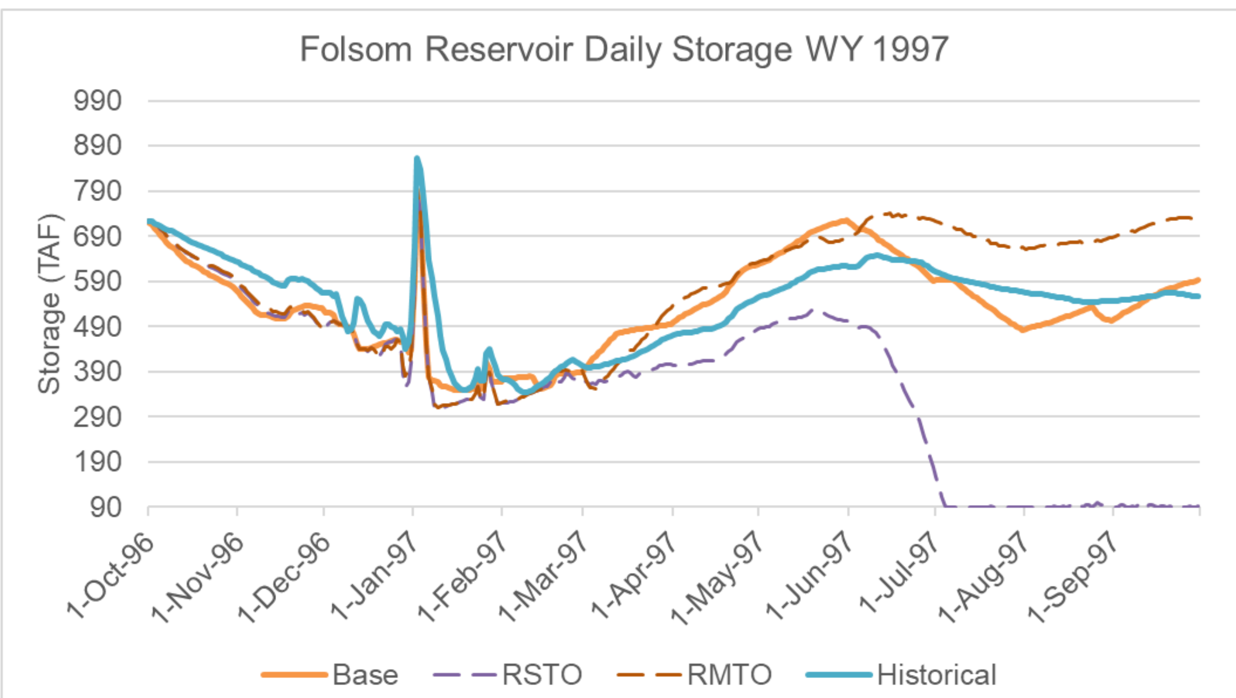


Figure 66. Daily Folsom reservoir storage for simulations and historical data in WY 1997

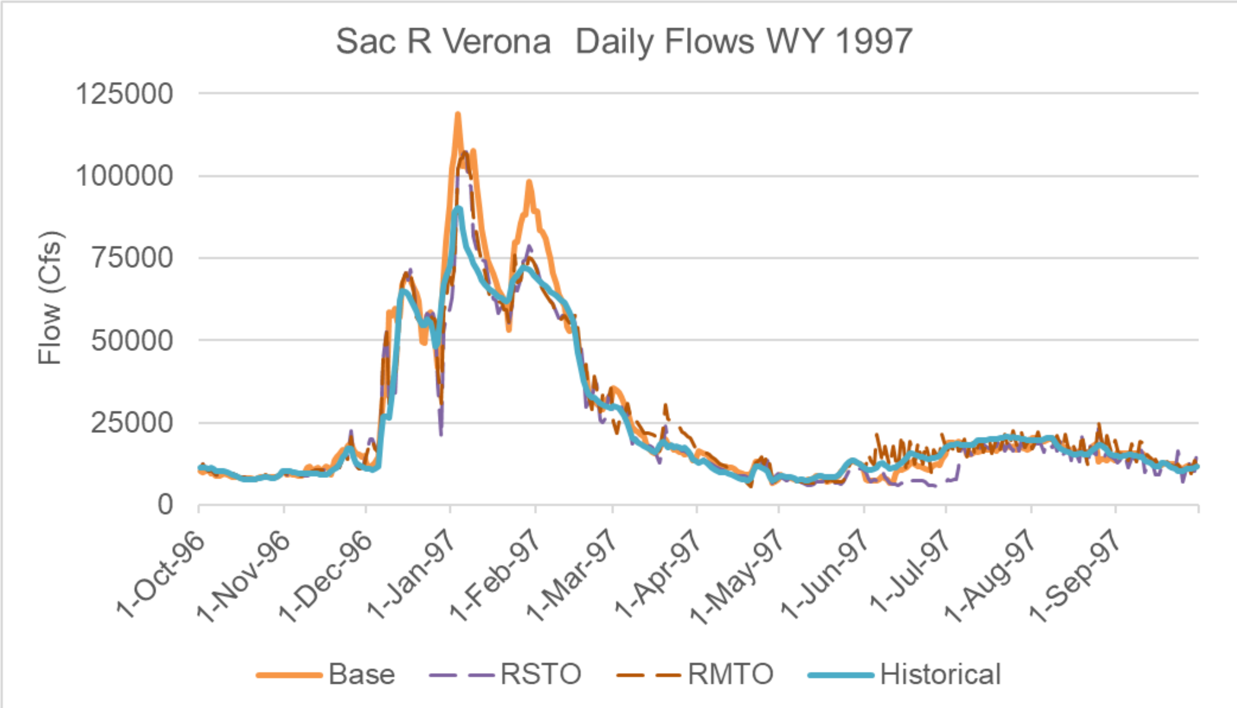


Figure 67. Daily Sacramento River at Verona flow for simulations and historical data in WY 1997

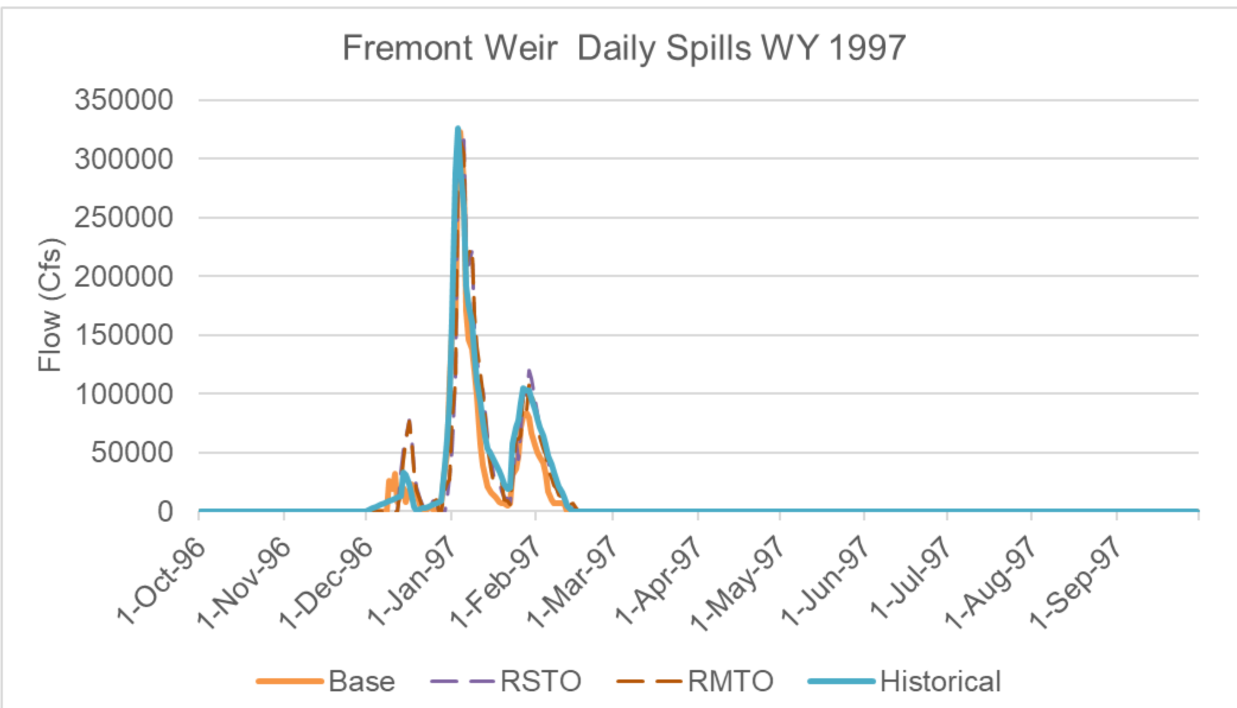


Figure 68. Daily Fremont weir spills for simulations and historical data in WY 1997

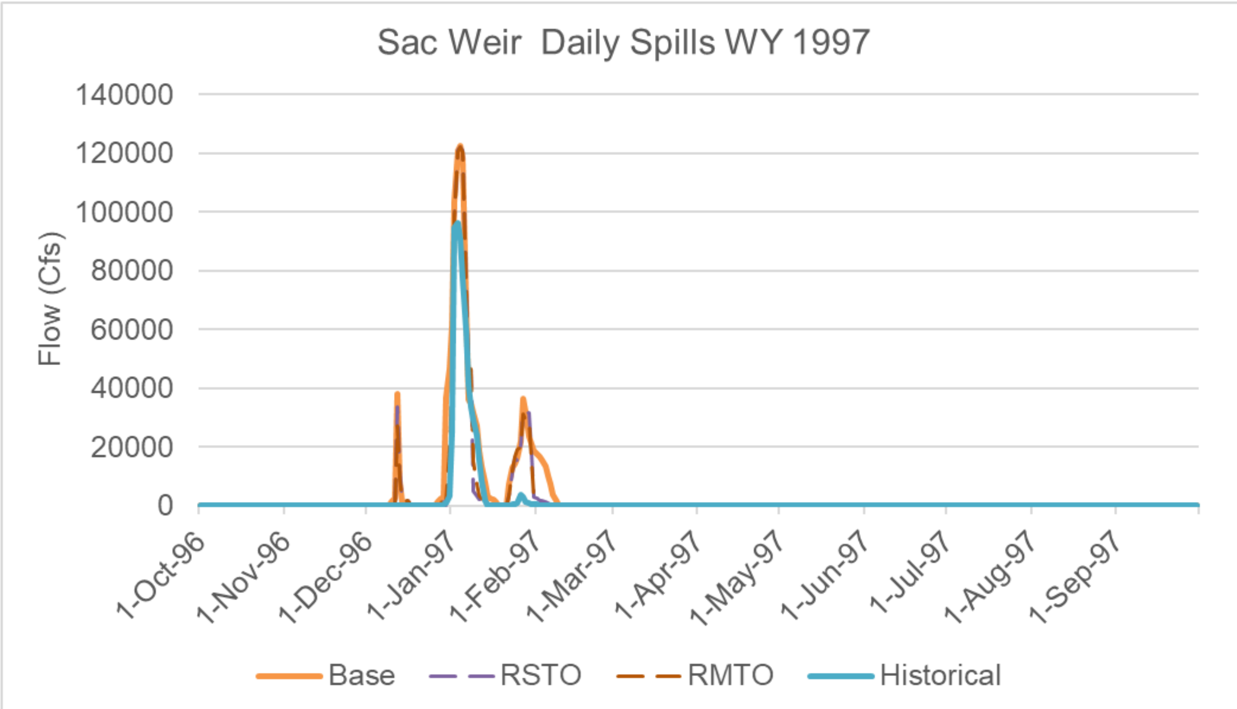


Figure 69. Daily Sacramento weir spills for simulations and historical data in WY 1997

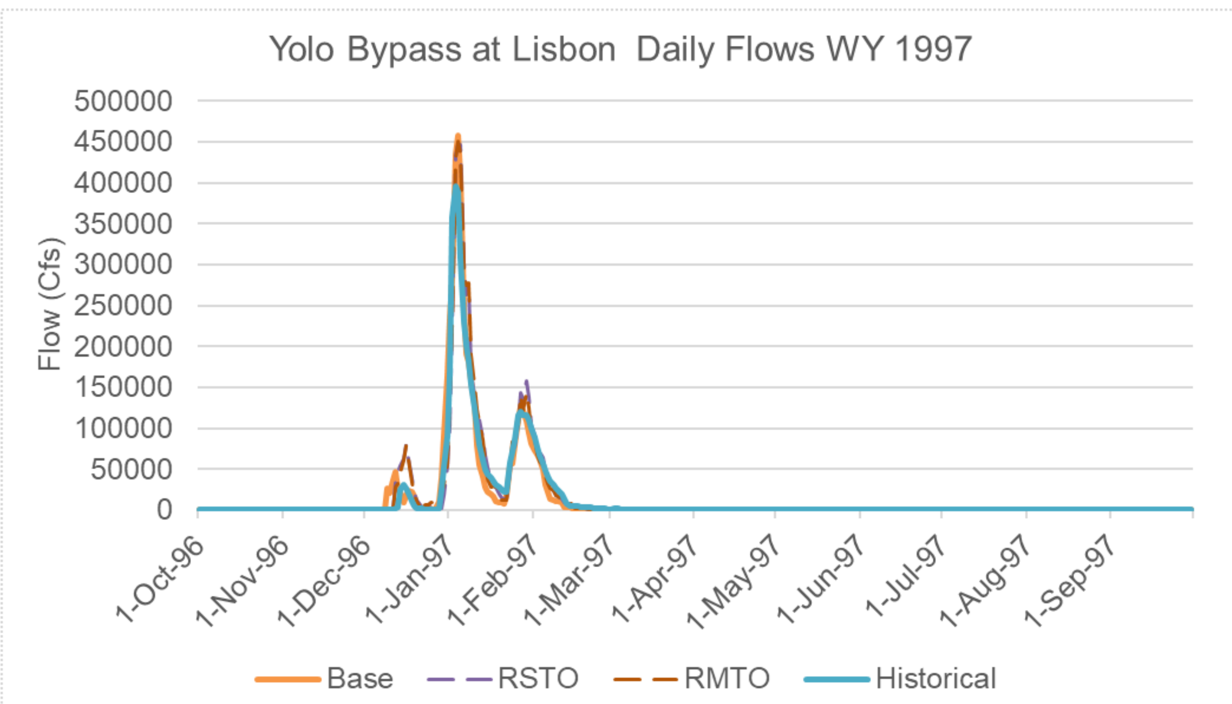


Figure 70. Daily Yolo Bypass at Lisbon flow for simulations and historical data in WY 1997

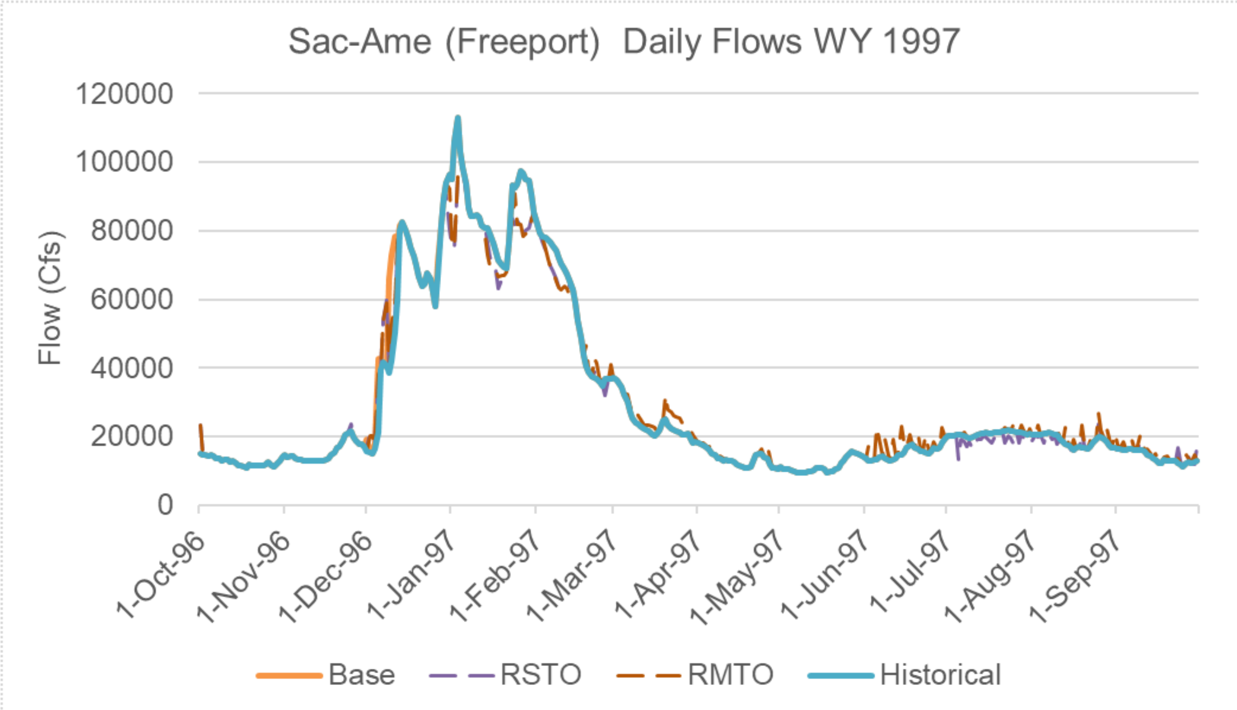


Figure 71. Daily Sacramento River at Freeport flow for simulations and historical data in WY 1997

4.1.4 MIF Requirements Tables

Table 18. Daily MIF requirement statistics for base case (no routing and STO) in WY 1997

River	Control Point	Above MIF	At MIF	Below MIF	Avg MIF shortages (cfs)	Max MIF shortages (cfs)
Sacramento	Below Keswick	365	0	0	0	0
Sacramento	Red Bluff	365	0	0	0	0
Sacramento	Wilkins Slough	258	107	0	0	0
Feather	Thermalito/ Gridley	184	181	0	0	0
Feather	At Mouth	365	0	0	0	0
American	Nimbus	249	116	0	0	0
American	H St	365	0	0	0	0

Table 19. Daily MIF requirement statistics for routing on and STO in WY 1997

River	Control Point	Above MIF	At MIF	Below MIF	Avg MIF shortages (cfs)	Max MIF shortages (cfs)
Sacramento	Below Keswick	362	3	0	0	0
Sacramento	Red Bluff	365	0	0	0	0
Sacramento	Wilkins Slough	184	114	**67**	**85**	**862**
Feather	Thermalito/ Gridley	243	122	0	0	0
Feather	At Mouth	365	0	0	0	0
American	Nimbus	336	29	0	0	0
American	H St	351	14	0	0	0

Table 20. Daily MIF requirement statistics for routing on and MTO in WY 1997

River	Control Point	Above MIF	At MIF	Below MIF	Avg MIF shortages (cfs)	Max MIF shortages (cfs)
Sacramento	Below Keswick	358	7	0	0	0
Sacramento	Red Bluff	365	0	0	0	0
Sacramento	Wilkins Slough	300	65	0	0	0
Feather	Thermalito/ Gridley	263	102	0	0	0
Feather	At Mouth	365	0	0	0	0
American	Nimbus	229	136	0	0	0
American	H St	365	0	0	0	0

Table 21. Daily Wilkins Slough MIF requirement statistics in WY 1997

Wilkins Slough stats	Base	RSTO	RMTO	Scenario 2-1	Scenario 3-2
Above MIF	258	184	300	-74	116
At MIF	107	114	65	7	-49
Below MIF	0	**67**	0	67	-67
Avg MIF shortages	0	**85**	0	85	-85
Max MIF shortages	0	**862**	0	862	-862

4.1.5 Reservoir Status Tables

Table 22. Daily Dead pool storage incidents for Shasta, Oroville, and Folsom in WY 1997

Reservoir	Base	RSTO	RMTO	Scenario 2-1	Scenario 3-2
Shasta	0	0	0	0	0
Oroville	0	0	0	0	0
Folsom	0	55	0	55	-55

Table 23. Daily Flood control encroachment incidents (Storage > flood control rule curve) for Shasta, Oroville, and Folsom in WY 1997

Reservoir	Base	RSTO	RMTO	Scenario 2-1	Scenario 3-2
Shasta	13	14	11	1	-3
Oroville	5	4	4	-1	0
Folsom	64	24	37	-40	13

Table 24. Monthly distribution of dead pool storage incidents for Folsom in WY 1997

Month	Base	RSTO	RMTO
October	0	0	0
November	0	0	0
December	0	0	0
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0	0	0
June	0	0	0
July	0	26	0
August	0	16	0
September	0	13	0

4.1.6 Meeting Delta Inflow Demand Tables

Table 25. Daily frequency of simulations in meeting Delta inflow demand in WY 1997

Criteria	Base	RSTO	RMTO	Scenario 2-1	Scenario 3-2
LT demand	0	71	33	71	-38
EQ demand	355	258	209	-97	-49
GT demand	10	36	123	26	87

Table 26. Monthly distribution of simulations not meeting Delta inflow demand in WY 1997

Month	Base	RSTO	RMTO	Scenario 2-1	Scenario 3-2
October	0	0	0	0	0
November	0	0	0	0	0
December	0	4	1	4	-3
January	0	21	21	21	0
February	0	13	11	13	-2
March	0	0	0	0	0
April	0	0	0	0	0
May	0	0	0	0	0
June	0	0	0	0	0
July	0	23	0	23	-23
August	0	9	0	9	-9
September	0	1	0	1	-1

4.1.7 Total Simulated and Historical NOD Storage

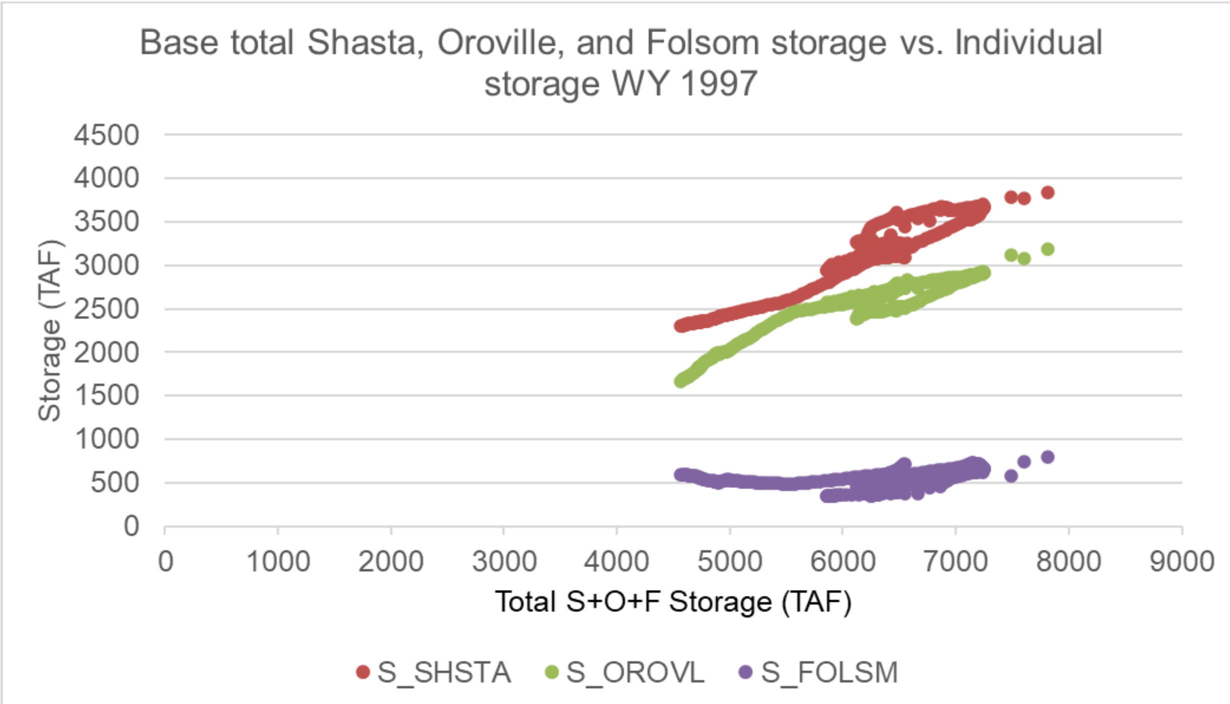


Figure 72. Base (no routing STO) total Shasta, Oroville, and Folsom storage vs. Individual storage scatterplot in WY 1997

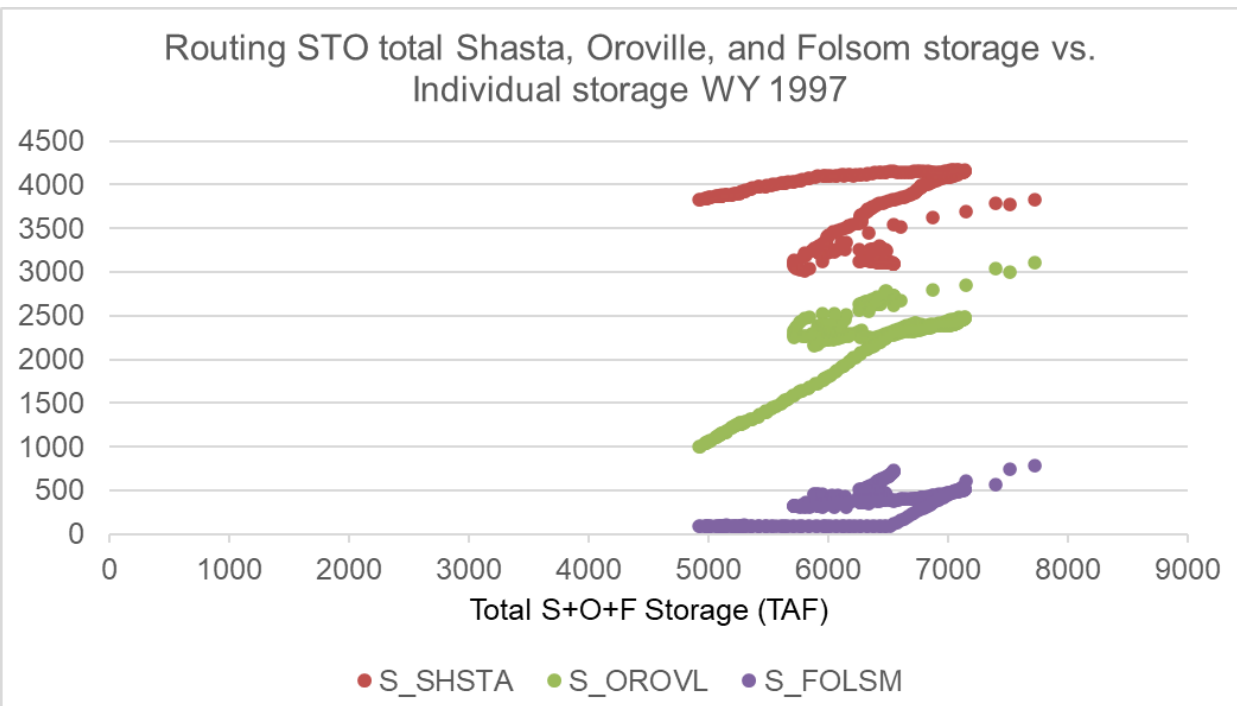


Figure 73. Routing STO total Shasta, Oroville, and Folsom storage vs. Individual storage scatterplot in WY 1997

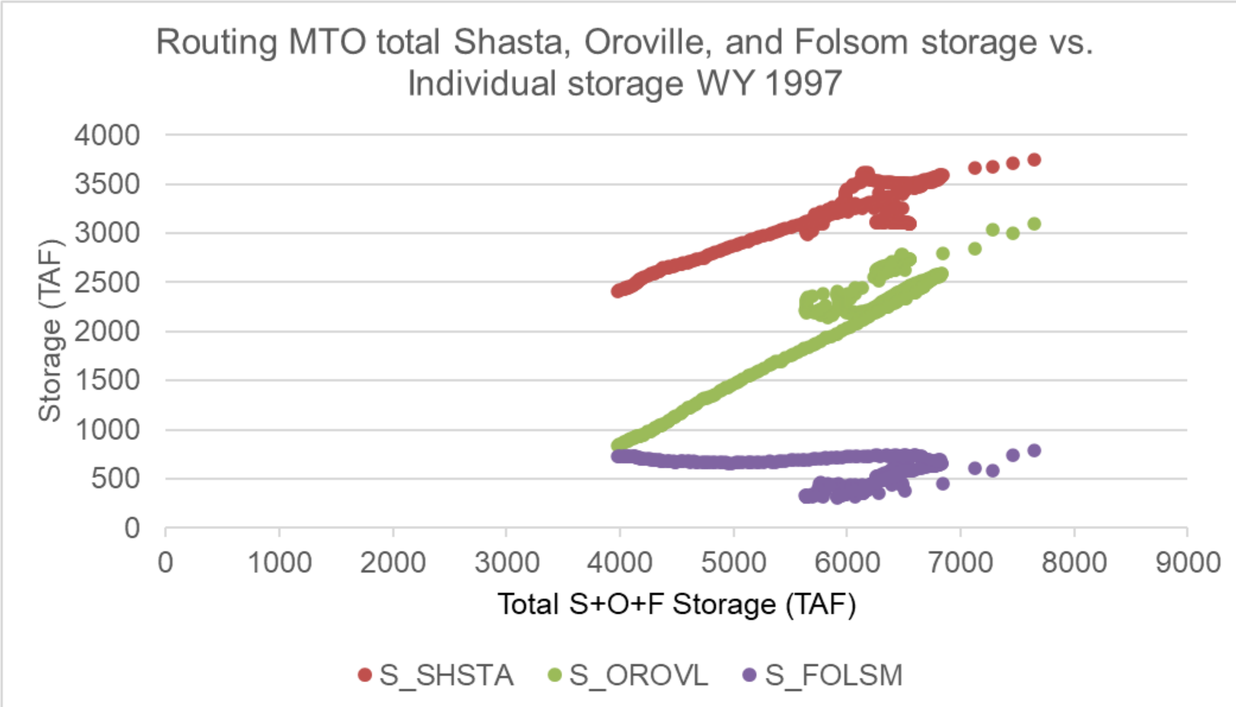


Figure 74. Routing MTO total Shasta, Oroville, and Folsom storage vs. Individual storage scatterplot in WY 1997

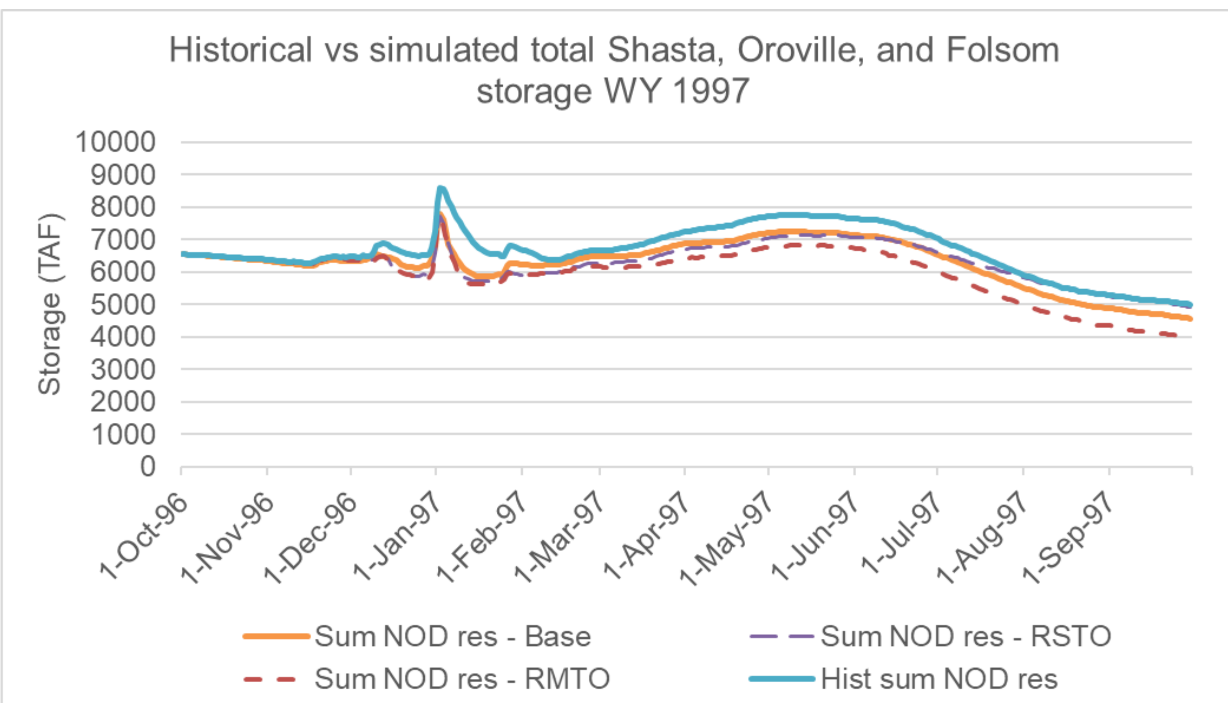


Figure 75. Simulated and historical daily total NOD reservoir storage in WY 1997

4.2 CalSim II and Historical Monthly Comparison

This section compares the routing on and MTO (RMTO) daily model simulation with the 2017 DCR CalSim II and historical data. The goal is to see how the RMTO case, when converted to a monthly average, compares to the monthly CalSim II model and historical. Timeseries plots and scatterplots (Figure 76 to Figure 78) between simulated and historical will be presented. The timeseries are formatted so October values are on the x-axis position on October 31. The scatterplots compare the simulations (RMTO or 2017 DCR CalSim II) on the x-axis with historical on the y-axis.

The base case (no routing and STO only), although shown to be closer to the daily historical data comparison in the previous section, is not included in this section. The base case looks more "accurate" but does not represent reality since routing is not implemented. The accretion-depletion terms at each node act as a pseudo-reach storage node that adds or removes flow, mimicking routing attenuation.

Issues in model simulations are apparent when reviewing storage timeseries and scatterplots. Figure 76 shows that the model tends to rebalance the reservoirs to keep more in Folsom and less in Oroville by EOS. Shasta reservoir in RMTO is releasing more water starting in the spring. EOS Shasta carryover storage for RMTO and historical end up similar to around 2500 TAF. For Oroville, RMTO storage is consistently lower starting from January 1997. EOS carryover storage is only 1000 TAF compared to over 2000 TAF from historical. The reason for a much lower Oroville storage was due to a series of sensitivity studies and experiments to prevent Folsom storage from reaching deadpool storage in the summer. The current workaround implemented does not have the optimal balance between the three reservoirs which results in lower Oroville storage but higher Folsom EOS storage. For now, this is an acceptable tradeoff because before the adjustments, Folsom storage was getting into deadpool storage conditions which should never happen especially in a wet year like WY 1997.

Next, CSII Folsom reservoir seems to have a higher fill rate from March to June since the peak is almost at capacity. However, RMTO's Folsom fill rate is higher compared to observed starting from April. Peak storage for RMTO Folsom was near 700 TAF in July. RMTO Folsom EOS storage ends up higher compared to historical by a noticeable margin. Only the RMTO Shasta r-squared had a positive value above 0.5. The rest were negative for R_MTO and CSII, indicating poor performance in mimicking observed operations. This does not mean that the thesis and CSII models are not insightful. These models are not purely for simulation. They are driven by weights and penalties that represent operational priorities which may not exactly replicate reality. Also, more future work is needed in the thesis model to address limitations such as achieving a reasonable balance in the NOD reservoirs with routing and MTO.

Monthly releases between RMTO and CSII show good performance as shown in Figure 77. Differences in storage accumulate over time, but release differences are not cumulative, and so appear more similar across models. In r-squared terms, RMTO and CSII Shasta releases perform similarly. RMTO Oroville releases r-squared is higher (0.97) compared to CSII's (0.86). However, this is misleading because the Oroville EOS storage is lower in RMTO. The monthly average releases show that RMTO Oroville reservoir is releasing more compared to historical releases during the early winter months and summer. RMTO Folsom releases r-squared is also higher (0.99) compared to CSII's (0.96). Again, this is misleading because it does not show the impact of lower releases in the spring and summer resulted in higher Folsom EOS storage.

Figure 78 shows that Fremont weir spills match well with observed for both RMTO and CSII while Sacramento weir spills tend to be overestimated in both model simulations. Fremont weir spill r-squared for RMTO has the slight advantage of a 1.0 value when looking at monthly averaged spills compared to CSII (0.97). However, RMTO overestimates Sacramento weir spills more resulting in lower r-squared (0.77) compared to CSII's (0.89). One reason for worse performance for RMTO could be that the weir spill logic in general should be refined for a daily model. The current approach was taken from the monthly CalSim/CalLite run. The other reason for Sacramento weir spill overestimation is differences between how Sacramento weir spill is operated and what the model assumes.

CA DWR (2010) summarized how the Sacramento Weir works. It is the only manually operated weir that, consisting of 48 gates that divert floodwater to the Yolo Bypass. Each gate has 38 vertical wooden plank needles. The number of gates to be opened is determined by the National Weather Service (NWS) and DWR river forecasting team to: 1) Prevent the stage at the I Street gage from exceeding 29 feet, or 2) hold the stage at the downstream end of the weir to 27.5 feet. The weir gates are closed as rapidly as is feasible once the weir stage drops below 25 feet.

The section below shows the model assumption comments for CalLite/CalSim Sacramento Weir operations from the file "weir_steps_monthops.wresl."

"Sacramento Weir Flow to Yolo Bypass

- The Sacramento Weir is the only weir with operating gates (48). The weir rating curve assumes all 48 gates are open.
- It appears that PROSIM also assumes the gates always remain open. This operation will cause spills more frequently than would normally occur. Under actual current operation, the gates remain closed during normal (non-flood) operation and are not opened until stages at the "I" Street gage exceed or are forecasted to exceed 27.5 feet. The 48 gates are then opened, as needed, to prevent stages greater than 29.0 ft. However, the complication is that the gates must remain open until stages in the river and bypass drop below the weir crest (river flows less than 37,000 cfs), when the gates can be raised.
- When the Sacramento Weir gates are opened during a flood, water flows upstream from the American River to the weir. Therefore, the weir arc is included at the junction of the American River (Node 166).
- The weir logic, below, is a very simplified representation of weir gate operation, refinements may be required during model calibration."

In summary, Sacramento weir spills are overestimated in the model due to differences in assumptions in how many gates should be open and when the gates should be closed.

Delta inflow terms at Yolo Bypass – Lisbon and Sacramento River – Freeport perform well mainly because of model objectives as shown in the lower half of Figure 78. Also, flows to Yolo Bypass depend on weir spills. Since the simulation weir spills match observed well (except for Sacramento weir which tends to be overestimated), the r-squared for Yolo Bypass with

R_MTO has excellent performance (0.98 r-squared), same with CSII (0.99 r-squared). Freeport flow R_MTO also has a high r-squared of 0.99 because one of the model objectives is to ensure Freeport simulated flow matches the observed as much as possible. The excellent performance of Freeport simulated flows show that the model can achieve this. However, how the model achieves this can vary significantly as shown by the suboptimal performance of upstream reservoir storage. As mentioned in the previous section, additional model constraints, weights and penalties can encourage the model to act more consistently in operations.

4.2.1 Timeseries and Scatterplots

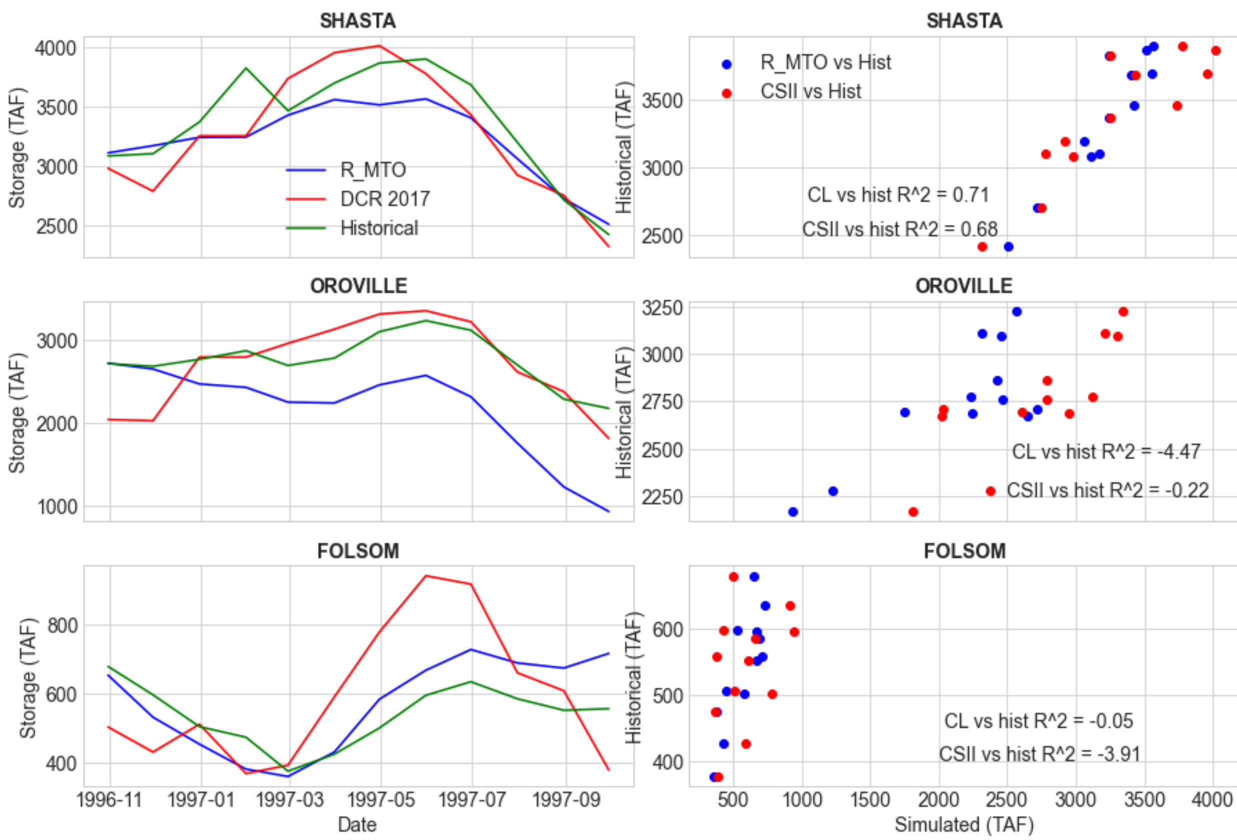


Figure 76. Monthly timeseries and scatterplots of Shasta, Oroville, and Folsom storage for routing and MTO on, 2017 DCR CalSim II run, and historical in WY 1997

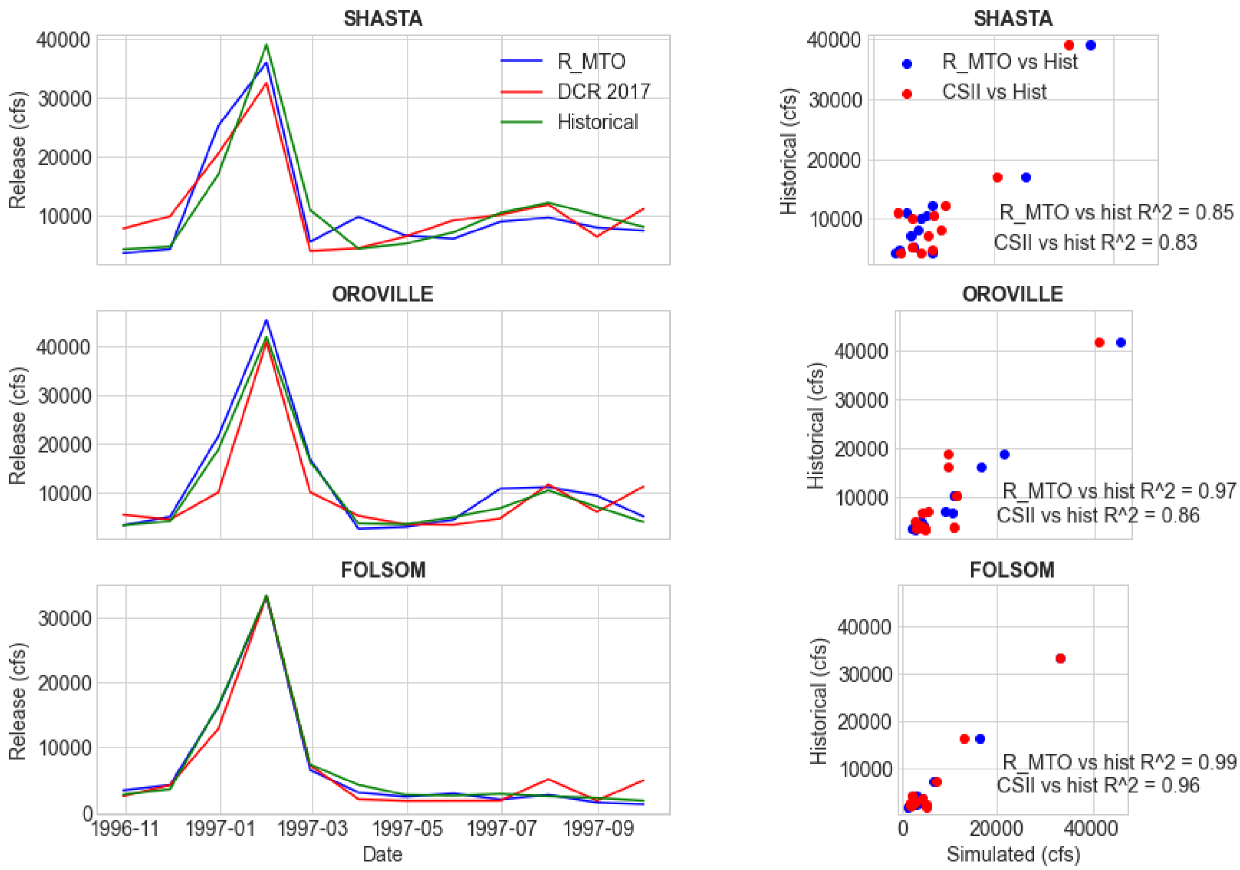


Figure 77. Monthly timeseries and scatterplots of Shasta, Oroville, and Folsom releases for routing and MTO on, 2017 DCR CalSim II run, and historical in WY 1997

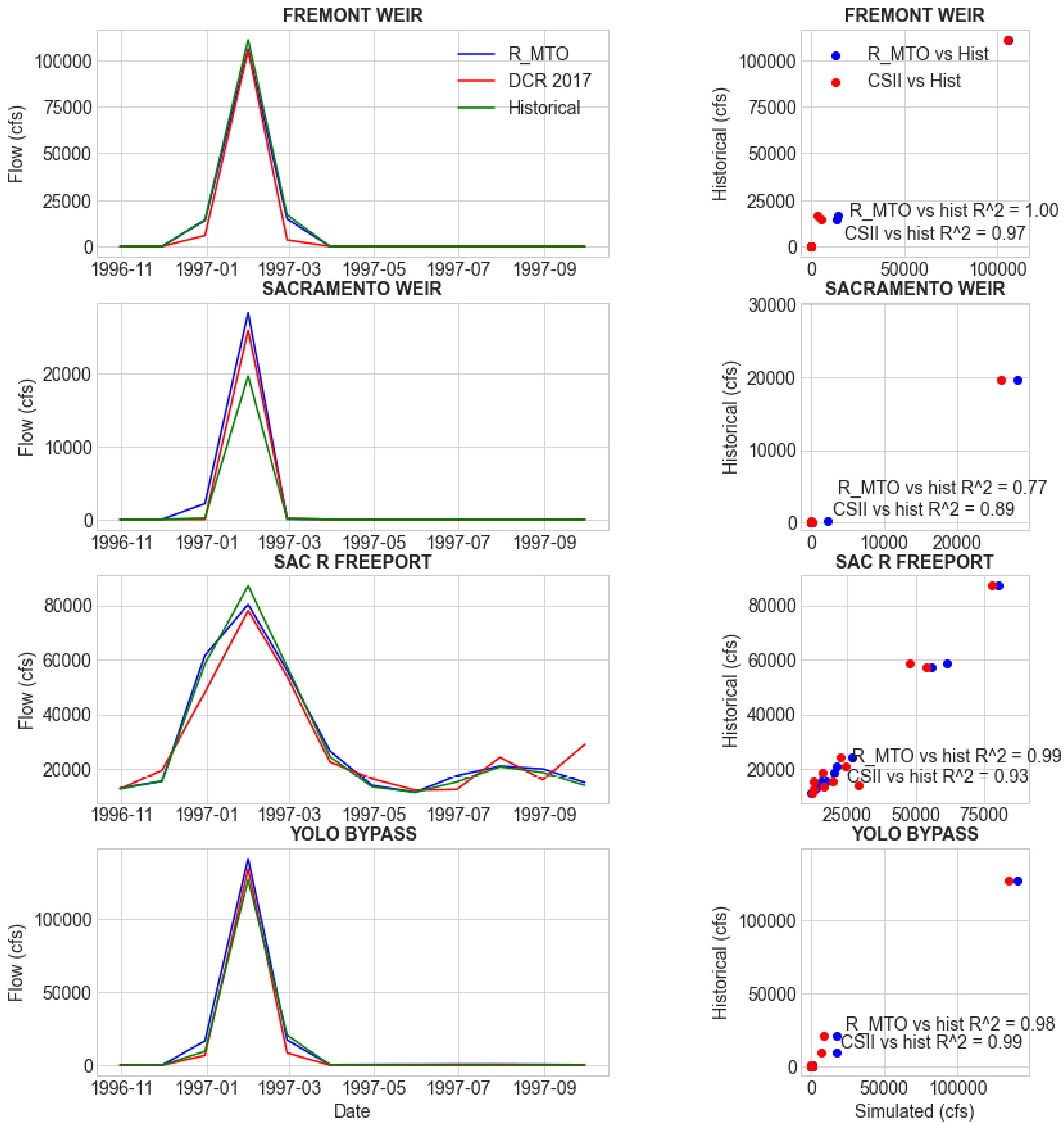


Figure 78. Monthly timeseries and scatterplots of Fremont weir and Sacramento weir spills, Sacramento River at Freeport flows, and Yolo Bypass at Lisbon flows for routing and MTO on, 2017 DCR CalSim II run, and historical in WY 1997

Chapter 5 Conclusions

5.1 Key Findings

A daily version of planning models like CalLite can represent more accurately finer time step operations such as flood control, weir spills, and meeting Delta and environmental requirements which occur in daily to weekly time frames. Monthly timesteps can underestimate operations such as flood control releases and weir spills. Channel routing is needed for a daily model for a system the size of the Central Valley. This study implemented a Muskingum hydrologic routing method along with MTO to address previous concerns on using routing with STO. MTO, which involves an ability to access, forecast, and evaluate future decision variables, is needed in large systems such as California's NOD region where travel times from upstream reservoirs to the lower system exceed one day. The model described in this study is simplified from CalLite. The efforts and lessons from this study can aid a larger effort to develop a daily CalLite model using a CalSim 3 model as a base. The main findings are:

1. Simulating channel routing in a MILP, network model within WRIMS2 requires adding intermediate channel storage nodes that temporarily store and delay routed water as it flows from one node to another.
2. With routing enabled, the model mostly relies on the reservoir with the shortest travel time to the Delta inflow demand location (at Freeport), in this case Folsom reservoir. The solver then produces undesirable Folsom storage operations with extended dead pool zone storage in the summer. More constraints or different penalty weights are needed to better simulate coordinated operations between the CVP and SWP daily through the COA. An updated CVP reservoir balancing scheme that considers travel times and future targets can improve storage distribution between Shasta and Folsom as is done in actual operations. Currently the storage zones between Shasta and Folsom are identical in all timesteps. The model is then indifferent in theory on which storage zone to draw from. A workaround in the MTO simulation was to increase the Folsom conservation storage zone weights so the model will avoid excessive Folsom releases.
3. When introducing a reach storage arc for channel routing, additional constraints are needed to ensure the model does not treat the reach storage arc as an actual reservoir. When weights are present on storage zones and MTO is used, the model might find it advantageous to release a huge pulse of water in one day then let the reach storage provide the water for downstream needs because the reach storage has no weights or penalties by default. Though this is not an ideal solution, it may produce a higher objective value over the MTO period.
4. The base scenario (no routing and STO only) showed the best performance when reviewing the daily operations. However, this base case does not adequately represent reality as routing is not considered. Releases from Shasta on the same day are assumed to travel just in time to meet Delta inflow demands downstream with the help of AD terms. MTO which facilitates the model making appropriate releases days in advance to handle routing travel time constraints is not represented although this is how the model can better mimic how operators make real-time decisions.
5. Using MTO with routing enabled produces better performance in terms of reducing violations in meeting MIF requirements at Wilkins Slough, Delta inflow demand represented through Freeport timeseries, and reducing incidents of dead pool storage at

Folsom. Part of this is done through minimizing cumulative shortages (demand or requirement minus actual flow) over an MTO sub-period.

6. The MTO periods are fixed in increments of six-day periods, so the model is always optimizing from the current up to the 5th future timestep. In other words, the MTO period is not moving forward but fixed to a specific end day. For a daily model, the rolling MTO period might be more appropriate and closely represent how operators meet daily to assess system conditions and make decisions for the upcoming days.
7. Enabling MTO in this study increased run time by 171% (from 7 seconds to 19 seconds) for only 365 days within WY 1997. The model and constraints level of detail will have to be monitored to prevent runtime from exponentially increasing. Using the same one year runtime from this study, an 84-year period with STO and a daily timestep would produce an estimated runtime of 588 minutes or almost 10 hours. If MTO is enabled, the runtime would jump to 1596 minutes or 26.6 hours, more than double the estimate when just using STO. This study also only has two cycles (sub-models, iterations) and does not include the Delta and South-of-Delta. Overall, keeping runtime reasonable using a daily model will be a significant undertaking. Fortunately, WRIMS2 has the feature of variable timestep simulation in which monthly models can be coupled with daily ones (Xie, 2014). During drier seasons, the model could be set up so that the daily cycle is off. During wetter periods, the daily cycle with routing and MTO will be included. This hybrid approach of only enabling the daily mode in appropriate situations will prevent model runtime from significantly increasing, so that usage will be more practical.

5.2 Limitations and Future Work

5.2.1 Model Coverage

The NOD schematic has many simplifications. Compared to the HEC-FCLP model, the Sacramento River flood control structures such as Moulton Weir, Colusa Weir, Tisdale Weir, and Sutter Bypass are not simulated. Only the Fremont and Sacramento Weirs are modeled. This is mainly because the thesis model is based on the CalLite schematic and code. One future objective is to have a daily timestep model in CalLite as a simplified model of CalSim II or CalSim 3. Simplifications are needed to speed up model run-time. CalSim II and CalSim 3 simulate the Moulton Weir, Colusa Weir, Tisdale Weir, and Sutter Bypass. However, to reduce run-time, some nodes in CalSim II were removed and accounted for in CalLite as accretion-depletion terms. The thesis model schematic largely remains consistent with the original CalLite schematic except for new nodes on the Upper Sacramento River and Yolo Bypass to include flood control points and also to follow the Muskingum criteria (see 3.3.1 Model Schematic Design).

The model domain does not include the Delta and South of Delta which are central to overall CVP/SWP operations. The "true" Delta demand is not yet represented properly in this study. One reason for a daily California planning model is to better represent Delta requirements such as meeting salinity requirements which is measured in terms of rolling averages over days. Project allocation procedures are also not simulated which can result in sub-optimal reservoir operations because the projects are not accounting for meeting CVP and SWP demands. Future work would include the Delta and South of Delta incorporating the non-linearity involved with MTO especially if the ANN method were used. The DWR MSO Delta Modeling Group is conducting research with UC Davis researchers in the Department of Computer Science, Department of Electrical and Computer Engineering, and Department of Mathematics to develop a machine learning salinity forecasting-capable model (Qi et al., 2022).

5.2.2 Channel Routing

The Muskingum routing method was used in this study. This method has been applied in many models. However, there are limitations to this approach. First, the routing parameter values used originated from a HEC-FCLP model of the Sacramento Valley developed near the late 1990s. In simulating a wet year like 1997, these might be sufficient. But when running a long-term simulation such as WY 1922-2003 for example, these parameter values might not be appropriate. Next, the routing parameters for K and X are fixed. The Muskingum routing coefficients are not updated as flow conditions change.

Future work could incorporate the variable Lag and K method using the CNRFC's parameters within their CHPS model which USBR and DWR use for their reservoir operations forecasting. The routing parameters for lag and attenuation are related by flow values. Ilich (2008) also noted that MTO mode should strive to use variable coefficient routing methods which update the coefficients if the preceding flows were very low or resembling flood event flows. This is why the WEB.BM (Ilich, 2022) routing method employed within MTO mode uses the SSARR routing model that uses a relationship between time to storage and flow Q.

5.2.3 Hydrologic Inputs

Simplifications in the model schematic necessitate using incremental flows or AD terms. AD terms may already include the depletions to water diversions, so simulating deliveries may not be needed. But missing historical flow data in the lower Feather River and lower Sacramento River means that accretions or depletions are not always reliable. Also, some relationships that determine basin overflows are not available, so depletions at Ord Ferry might be overestimated. AD terms drive reservoir operations so if depletions are overestimated, then the reservoir will be releasing much more than observed to ensure flows are non-negative. Future work would involve gathering comprehensive data or approximate relationships to find reasonable AD terms for the Sac-American River confluence, Feather River below Yuba City, Sacramento River at Ord Ferry, and others.

This study also uses perfect foresight for inflows. Inflows are not forecasted which is done in CAM through a DLL. Future work could be to develop a way to forecast future days of inflows to reservoirs to couple with MTO, perhaps using a two-stage linear program formulation in the MTO to represent multiple short-term forecasts. CalSim II/CalLite assumes static land use, fixed water supply contracts, and regulatory requirements in each simulation year. Then the historical hydrology such as stream flows are modified for impacts of land use change and upstream flow regulations (Draper and Bourez, 2004). However, for ease of implementation, this thesis just used historical inflows as is.

Additionally, a comprehensive water balance was not conducted in which various inflow and outflow terms such as groundwater pumping, recharge, evapotranspiration, etc. are explicitly accounted for (Figure 79). For CalSim II, the Central Valley was split into seven in the Sacramento Valley floor while two DSAs represented the Delta. DSAs were boundaries within the Central Valley to facilitate the water balance calculation.

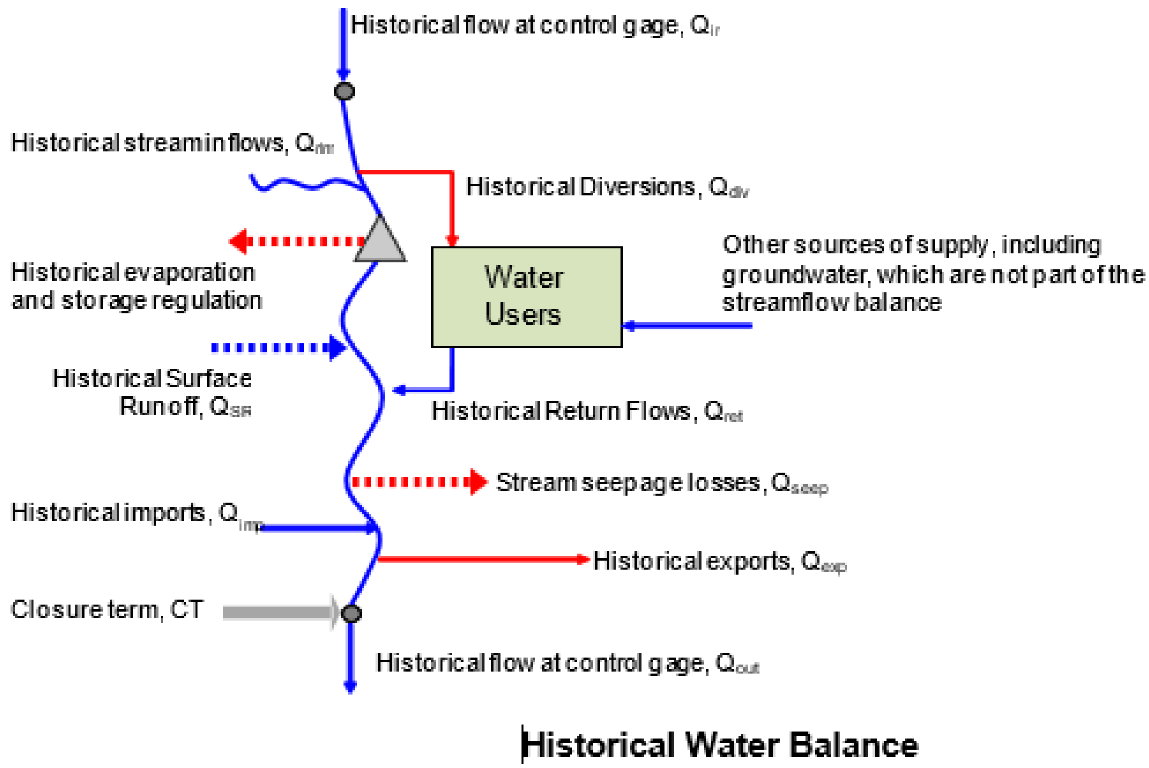


Figure 79. Historical water balance example (A. Draper, personal communication, August 21, 2019).

Local inflows were determined for each valley floor DSA and were calculated as a closure term using a hydrologic mass balance (Draper and Bourez, 2004). The local inflows, also synonymous with accretions, represent direct precipitation runoff and any inflows from locations not represented explicitly within CalSim II and thus cannot be associated with a specific stream (CA DWR, 2003). This method of calculating accretions (or depletions) is much for complex and explicit which is a huge contrast to the current approach depicted in Appendix A - Accretion-Depletion Term Calculations and Estimation which basically takes flow from a CDEC or USGS station and subtracts flow from another station. Ideally, such a process would be done within a daily WRIMS-based California water resources planning model based on this thesis.

5.2.4 Recalibration and Adjustments

Calibrating the weights and penalties of the original CalSim/CalSim II monthly timestep models took years with the expertise of dedicated modelers. A similar effort of recalibrating and adjusting to the weighting structure, goal statements and penalties applied will be needed. For example, without additional adjustments, the routing MTO scenario results in very high EOS Shasta storage (Figure 114) and multiple deadpool storage days in Folsom (Figure 118). Preliminary adjustments are implemented as described in section 3.4 Further MTO Scenario Adjustments. These code changes prevent unrealistic behaviors such as Folsom deadpool storage incidents starting in the summer during a wet year. They also show what a model with routing and MTO is capable of. However, the model presented in this thesis will need extensive peer review and assistance in developing an updated set of weights and penalties (Ferreira, 2007; Israel and Lund, 1999) appropriate for a daily timestep California NOD or even Central Valley-wide model.

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Appendix A - Accretion-Depletion Term Calculations and Estimation

AD term	Method
AD_Kswck	Keswick Reservoir (CDEC, reservoir outflow) - Spring Creek Powerplant at Keswick, CA (mean discharge) - Shasta Dam (CDEC, reservoir outflow)
AD_BendBr	Sacramento River at Bend Bridge (CDEC) - Keswick Reservoir (CDEC, reservoir outflow)
AD_RedBluff	Red Bluff diversion dam release (USBR CVO, Kristin White) – Sacramento River at Bend Bridge (CDEC)
AD_OrdFry	Ord ferry flow (CDEC) – Red Bluff diversion dam release (USBR CVO, Kristin White) – Black Butte release (CDEC) The East Bank Overflow (EBO) should ideally be added. However, the relationship of Ord Ferry flow and EBO is currently unavailable. As a result, accretions at Ord Ferry might be underestimated because the overflows are not being added back
AD_Wilkns	Sacramento River below Wilkins Slough (CDEC, flow, mean daily) – Ord Ferry flow (CDEC)
AD_Grdley	Feather River near Gridley (CDEC, flow, mean daily) - Oroville Dam (CDEC, reservoir outflow)
AD_Mrysvl	Yuba River near Marysville, USGS - Yuba River near Smartville, USGS
AD_Nclaus	Bear River near Wheatland (flow, mean daily) (similar to Jones 1999)
AD_YubaCt	Estimated discharge at Feather River at Yuba City by using internal NOAA Weather Forecast Office (WFO) stage-discharge relationship. This is only for estimation purposes. DWR does not officially have a stage-discharge relationship for Yuba City and Nicolaus. Feather River at Yuba City - Feather River near Gridley
AD_SacFea	Sacramento River at Verona (CDEC, flow, mean daily) - Sacramento River below Wilkins Slough - Feather River near Nicolaus + Fremont Weir Spill (CDEC, flow, mean daily)
AD_Wdlnd	Cache Creek at Yolo (CDEC, flow, mean daily)
AD_Lisbon	YOLO BYPASS AT LISBON (flow, river discharge) - Yolo Bypass near Woodland (flow, mean daily) - Sacramento Weir Spill to Yolo Bypass (USGS, discharge, mean)
AD_SacAme	Not used due to lack of data at Sacramento River at I St.
AD_Nimbus	Lake Natoma release (CDEC) - Folsom Dam (CDEC)
AD_HSt	Not calculated due to lack of data

Appendix B - Historical Data Sources

This section summarizes the data sources used to review the simulation results, provide initial conditions, rim inflow timeseries, and calculate accretion-depletion terms. CDEC is the initial data source preferred. If data is incomplete or unavailable, then USGS' National Water Information System (NWIS) was the next option. With regards to the Delta, DAYFLOW is the preferred data source. For example, Sacramento River – Freeport and Yolo Bypass – Lisbon data are QSAC and QYOLO respectively. For more information on DAYFLOW data sources and calculations, please see: https://data.ca.gov/dataset/dayflow/resource/a756df43-5dc7-417a-a538-1fcace7de562

Parameter	CalLite arc	Historical data source
Shasta storage	S_SHSTA	CDEC - SHA SHASTA DAM (USBR) Sensor Number 15
Oroville storage	S_OROVL	CDEC - ORO OROVILLE DAM Sensor Number 15
Folsom storage	S_FOLSM	CDEC - FOL FOLSOM LAKE Sensor Number 15
Sacramento River below Keswick flow	C_KSWCK	CDEC – KES KESWICK RESERVOIR Sensor Number 23
Sacramento River at Bend Bridge	C_BENDBR	CDEC - BND SACRAMENTO RIVER AT BEND BRIDGE Sensor Number 41
Red Bluff Diversion Dam release to Sacramento River	C_REDBLF	Requested from USBR CVO
Sacramento River at Vina Bridge	C_VINBRD	CDEC – VIN SACRAMENTO RIVER AT VINA BRIDGE-MAIN CH Sensor Number 41
Sacramento River at Ord Ferry	C_ORDFRY	CDEC – ORD SACRAMENTO R AT ORD FERRY-MAIN CHANNEL Sensor Number 41
Sacramento River at Colusa	C_COLUSA	CDEC – COL SACRAMENTO RIVER AT COLUSA Sensor Number 41

Sacramento River below Wilkins Slough flow	C_WILKNS	CDEC - WLK SACRAMENTO RIVER BELOW WILKINS SLOUGH Sensor Number 41
Feather River near Gridley	C_GRDLEY	CDEC - GRL FEATHER RIVER NEAR GRIDLEY Sensor Number 41
Feather River at Yuba City	C_YUBACT	N/A Obtained estimated rating curve used internally within the local Weather Forecast Office (WFO) at YUBC1. However, DWR does not provide a rating curve due to backwater effects when Yuba River is experiencing high flows downstream. As a result, the previous rating curve provided at the WFO website was removed to be consistent with the CNRFC YUBC1 station (K. Lerman, CNRFC, personal communication, July 11, 2022)
Feather River near Nicolaus	C_NCLAUS	Historical flow data is unavailable at CDEC- NIC most likely due to backwater flooding effects and for the same reason why Yuba City does not have flow data.
Yuba River inflow to Feather River	C_MRYSVL	CDEC - MRY Yuba River near Marysville Sensor 41
Sacramento River at Verona	C_SACFEA	CDEC - VON SACRAMENTO RIVER AT VERONA Sensor Number 41
Folsom reservoir outflow	C_FOLSM	CDEC - FOL FOLSOM LAKE Sensor Number 23
American River below Lake Natoma	C_NIMBUS	CDEC – NAT LAKE NATOMA (NIMBUS DAM) Sensor Number 23
American River at H Street Bridge	C_HST	Historical flow data is unavailable at CDEC- HST
Sacramento-American Confluence	C_SACAME	CDEC – ST SACRAMENTO RIVER AT I STREET BRIDGE Sensor Number 20

Fremont weir spill	D_FREWEIR	This station has a lot of data entries which say “BRT” or below rating table. As a result, most of the values are 0. Freeport flow comparisons were deemed more useful. CDEC - FRE SACRAMENTO R @ FREMONT WEIR(CREST 32.0') Sensor Number 41 USGS 11391021 FREMONT WEIR SPILL TO YOLO BYPASS NR VERONA CA only has data from 1947 to 1975
Sacramento weir spill	D_SACWEIR	USGS 11426000 SACRAMENTO WEIR SPILL TO YOLO BYPASS NR SAC CA Discharge(Mean)
Yolo Bypass near Woodland	C_WDLAND	USGS 11453000 YOLO BYPASS NR WOODLAND CA Discharge(Mean) CDEC – YBY was not used because daily mean flow data was only available from June-July 1998
Yolo Bypass inflow to Delta	C_LISBON	DAYFLOW - QYOLO
Sacramento River at Freeport	C_FREEPORT	DAYFLOW - QSAC

Appendix C – Other State Variable Inputs and Sources

Timeseries name	Source	Additional identifiers
C_Wilkns_Ups_Hist	CDEC	WLK 41
I_Folsm	CDEC	FOL 76
I_Orovl	CDEC	ORO 76
I_Shsta	CDEC	SHA 76
S_Folsmlevel5	CDEC	FMV, UNV, HHL 15
S_Orovllevel5	CDEC	PPT for ORO, SBY, BRS, SVL, QCY, CAM, DES, CNY
S_Shstalevel5	CDEC	SHA 76
E_FOLSM	CDEC	DCR 2017
E_OROVL	CDEC	DCR 2017
E_SHSTA	CDEC	DCR 2017
minflow_C_Grdley	CSII study	DCR 2017
minflow_C_Kswck	CSII study	DCR 2017
minflow_C_YubaCt	CSII study	DCR 2017
minflowFeaMouth	CSII study	DCR 2017
S_Folsmlevel2	CSII study	DCR 2017
S_FolsmLevel3adj	CSII study	DCR 2017
S_OrovlLevel3adj	CSII study	DCR 2017
S_Shstalevel2	CSII study	DCR 2017
S_ShstaLevel3adj	CSII study	DCR 2017
S_Folsmlevel4	CSII study	DCR 2017
S_OrovlLevel4	CSII study	DCR 2017
S_Shstalevel4	CSII study	DCR 2017
C_Freeport_Hist	DAYFLOW	QSAC
I_Yuba	USGS	11418000

Appendix D – Data QAQC and Estimation Methods

Objectives

California Data Exchange Center (CDEC) and United States Geological Survey National Water Information System (USGS NWIS) were the two main data sources for the study's model input. CDEC and USGS NWIS data was reviewed to determine the frequency of missing, negative, and zero value data to prepare data for model input or validation. The period of record was from Sep 1996 to Sep 2022.

Flow and Storage Data

Missing Data

Source	Parameter type	Data clean up method
CDEC	Storage	Replace using linear interpolation
CDEC	Reservoir inflow	Replace using linear interpolation
CDEC	Reservoir outflow (except Kelly Ridge)	Replace using linear interpolation
CDEC	Kelly Ridge reservoir outflow	Replace using linear interpolation
CDEC	Flow (except Fremont Weir)	Replace using linear interpolation
CDEC	Fremont Weir	Replace with zeroes
CDEC	Reservoir evaporation	Replace using linear interpolation
USGS	BEAR R NR WHEATLAND CA **11424000**	N/A
USGS	CLEAR C NR IGO CA **11372000**	N/A
USGS	CACHE C A YOLO CA **11452500**	N/A
USGS	YUBA R BL ENGLEBRIGHT DAM NR SMARTSVILLE CA **11418000**	Replace using linear interpolation
USGS	YUBA R NR MARYSVILLE CA **11421000**	N/A
USGS	YOLO BYPASS NR WOODLAND CA **11453000**	Replace with zeroes
USGS	SACRAMENTO WEIR SPILL TO YOLO BYPASS NR SAC CA **11426000**	Replace with zeroes
USGS	SPRING C PH A KESWICK CA **11371600**	Replace with zeroes

Figure 82 shows that there is a lot of missing data for Fremont Weir spills. CDEC does not report zero values for Fremont Weir when it is not spilling. The values are just left blank. For this dataset, missing values will be replaced as zeroes. Oroville reservoir evaporation contained missing data. Linear interpolation will be used to fill in the data gaps.

The rest of the stations vary in their frequency of missing data. Kelly Ridge outflow had multiple days of missing data from 1998-1999 but not much after that. Black Butte reservoir outflow also was the next station with the most missing data. Figure 83 shows a plot of the lowest to highest missing data ratio with Fremont weir spill station as the highest.

There were also a handful of columns that had missing initial data. This meant that linear interpolation was not going to handle these rows. As a result, backward interpolation was used.

In [42]:

```
df_pp[df_pp.columns[df_pp.isna().any()]].head(10)
#df[df.columns[df.isna().any()]]

```

Out[42]:

DATE TIME	ORO_resinf	VIN_flow
1996-09-01	NaN	NaN
1996-09-02	2536.0	NaN
1996-09-03	2760.0	NaN
1996-09-04	2002.0	NaN
1996-09-05	1686.0	NaN
1996-09-06	2314.0	9711.0
1996-09-07	2905.0	10335.0
1996-09-08	2583.0	10688.0
1996-09-09	2577.0	10597.0
1996-09-10	2198.0	10339.0

Figure 80. Columns which have NaNs in the beginning of the dataset (Oroville reservoir inflow and Vina Bridge flow)

```
df_pp = df_pp.interpolate(method ='linear', limit_direction ='backward')

```

Figure 81. Function that uses backward fill for linear interpolation

Four USGS NWIS stations contained missing data:

1. 11371600 – Keswick
2. 11426000 – Sacramento Weir
3. 11418000 – Yuba River below Englebright
4. 11453000 – Yolo Bypass

Except for Yuba River below Englebright, all the missing data in the stations were replaced with zeroes. Data at Yuba River below Englebright was replaced through linear interpolation.

CDEC

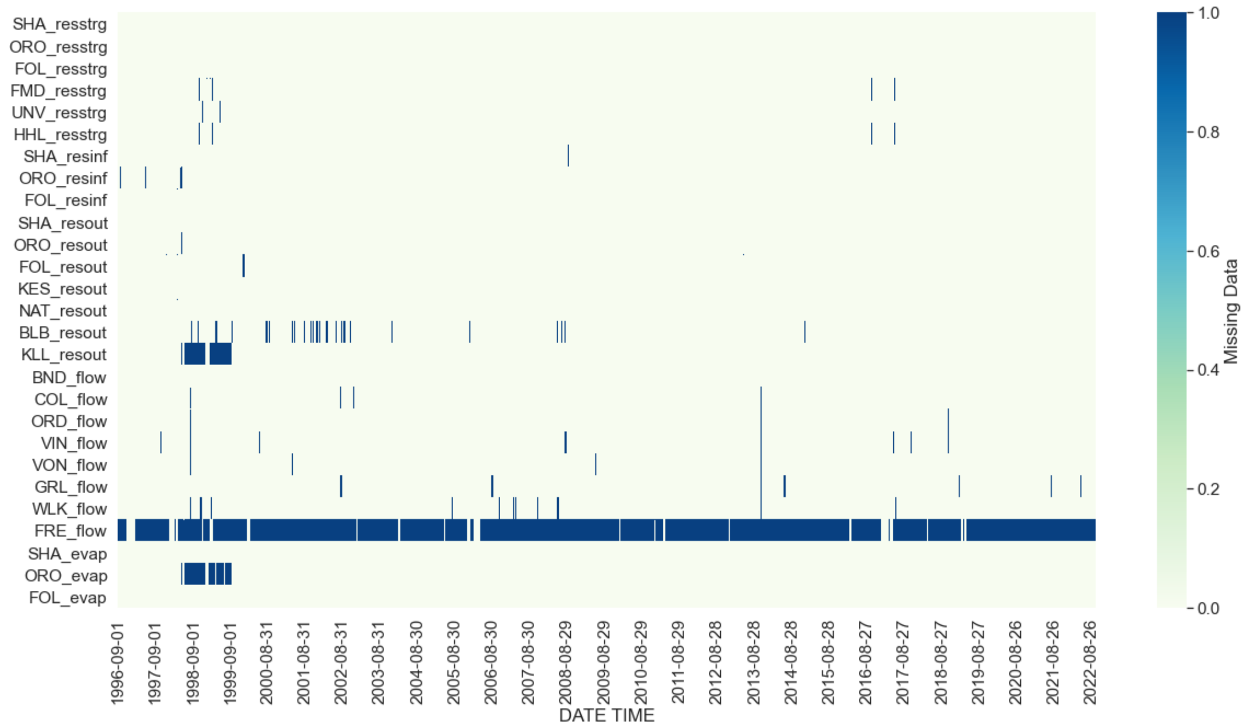

Figure 82. Heatmap showing the occurrences of missing data from selected CDEC stations from Sep 1996 to Sep 2022

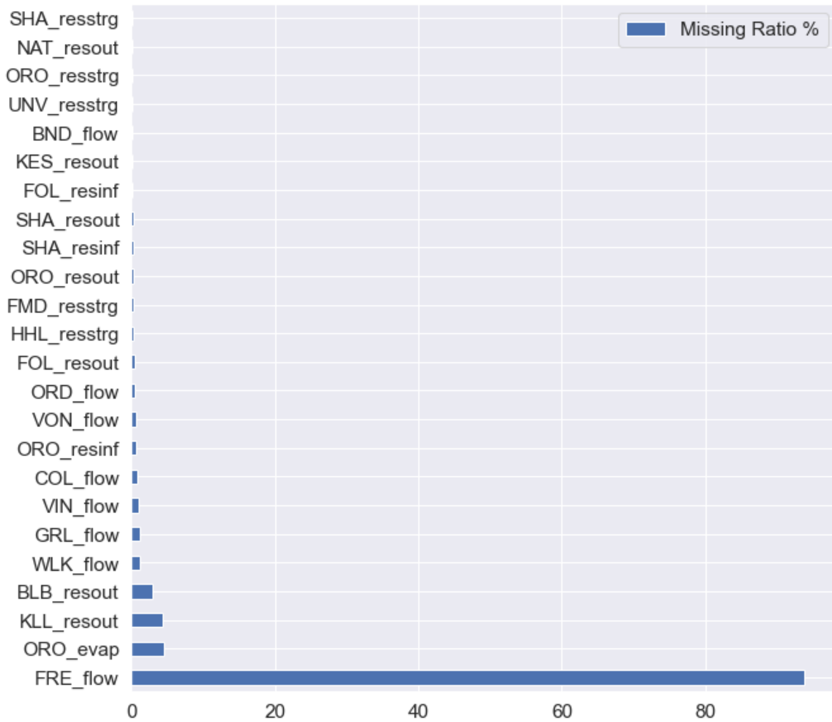

Figure 83. Selected CDEC stations with high lowest (top) and highest (bottom) missing data ratio from Sep 1996 to Sep 2022.

USGS NWIS

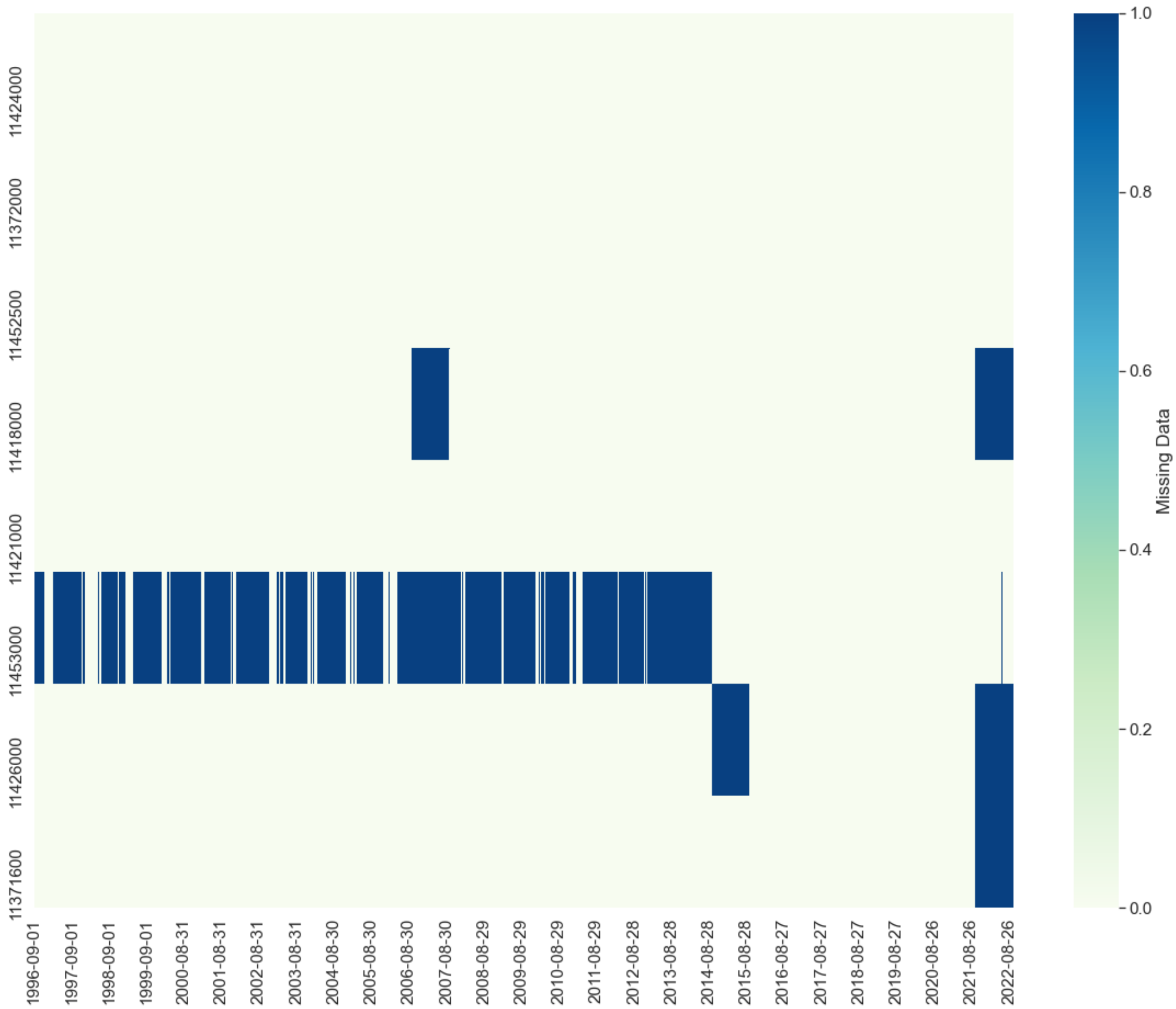

Figure 84. Heatmap showing the occurrences of missing data from selected USGS NWIS stations from Sep 1996 to Sep 2022

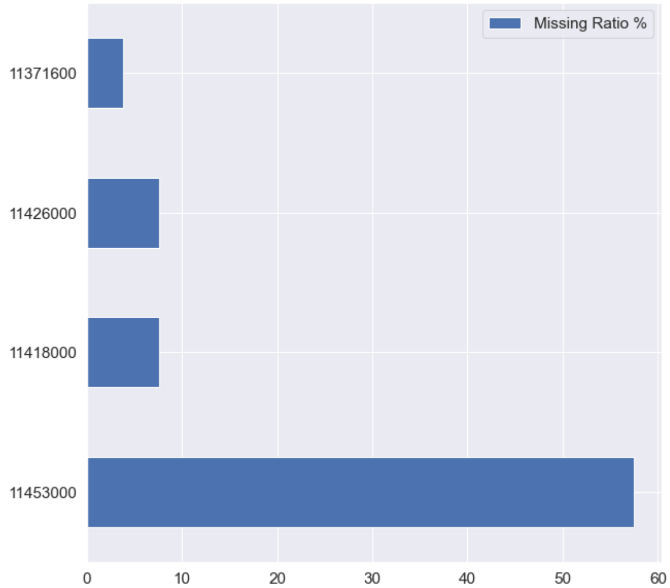

Figure 85. Selected USGS NWIS stations with high lowest (top) and highest (bottom) missing data ratio from Sep 1996 to Sep 2022.

Outliers

CDEC

Figure 88 shows a boxplot of the selected reservoir storage stations. There are no notable outliers to be handled. Figure 89 shows a boxplot of daily reservoir inflow from Shasta, Oroville, and Folsom. There are some outliers. However, these could be due to huge storms in 1997, 2006, and 2017. Figure 90 shows through visual inspection of the timeseries plot that there are no unusual outliers aside from the major storms in 1997, 2006, and 2017. In contrast to this is seen in Figure 91 in which one data point in the Black Butte reservoir outflow is exceedingly high compared to the rest of the station. A visual inspection through Figure 92 shows that both Black Butte (BLB) and Kelly Ridge (KLL) reservoir outflow have one outlier to be handled. The BLB and KLL outliers were replaced with the median. Figure 97 and Figure 98 show the updated station boxplots when the outliers were replaced.

Next, Figure 93 shows the boxplot of selected flow stations. All stations have some degree of outliers which could be due to some key storms in 1997, 2006, and 2017 as shown in Figure 94. Lastly, Figure 95 shows the boxplot for reservoir evaporation at Shasta, Oroville, and Folsom. Figure 96 shows that the highest evaporation for Shasta and Folsom occurred in winter 2022 water year which was categorized as a Dry Sacramento Valley water year type. The highest evaporation for Oroville occurred around the latter part of 2012 which was categorized as a Below Normal Sacramento Valley water year type.

USGS

Figure 86 shows the boxplot of the selected USGS stations. There are multiple outliers in these stations, most notably station 11453000 (Yolo Bypass near Woodland). Through visual inspection from Figure 87, the outliers could have been simply from the major storms in the period of record as mentioned in the CDEC section. As a result, no outlier processing will be done for the selected USGS stations.

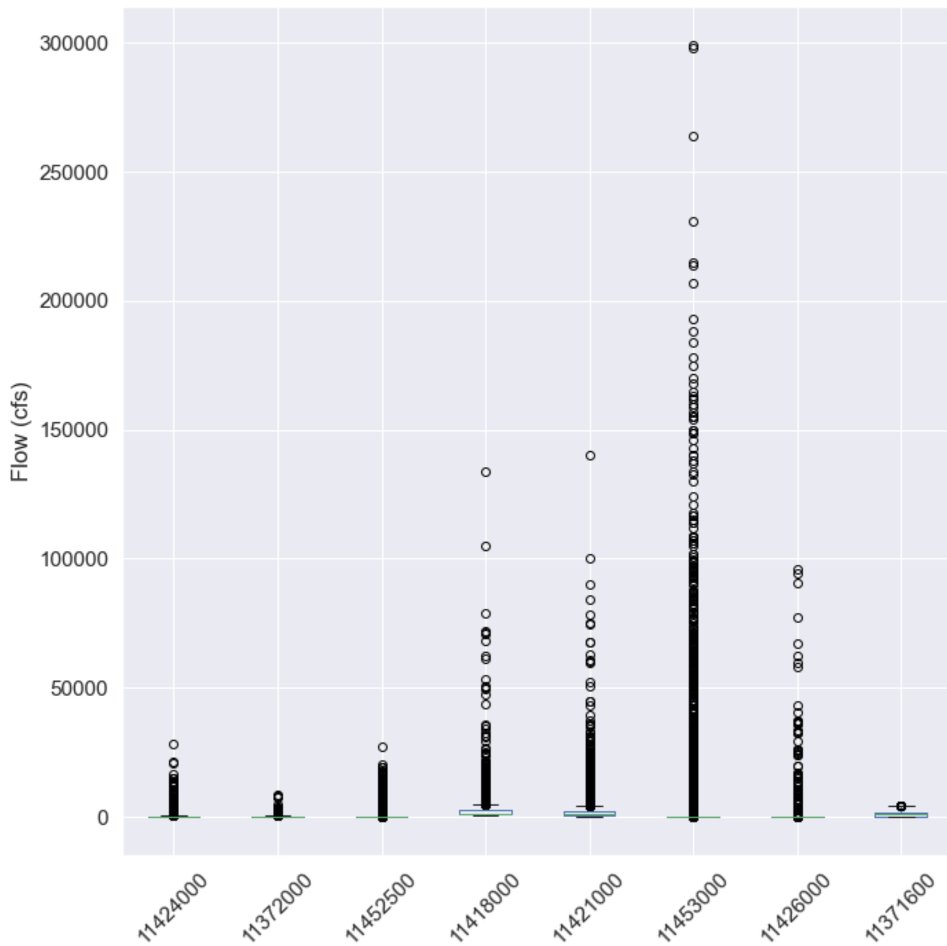

Figure 86. Boxplot of daily flows for selected USGS stations from Sep 1996-Sep 2022 before post-processing.

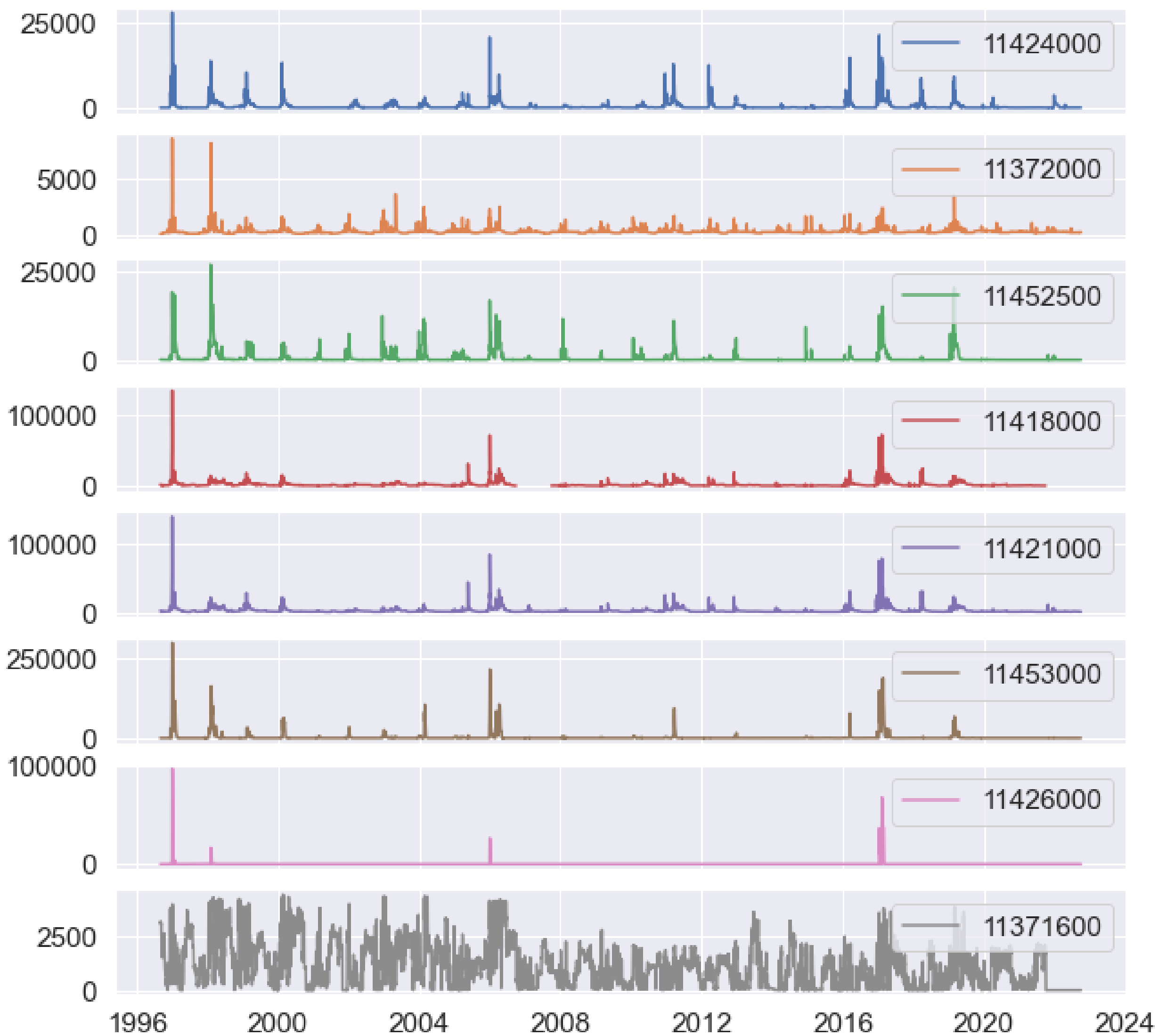

Figure 87. Daily timeseries of daily flows (cfs) for selected USGS stations from Sep 1996-Sep 2022 before post-processing.

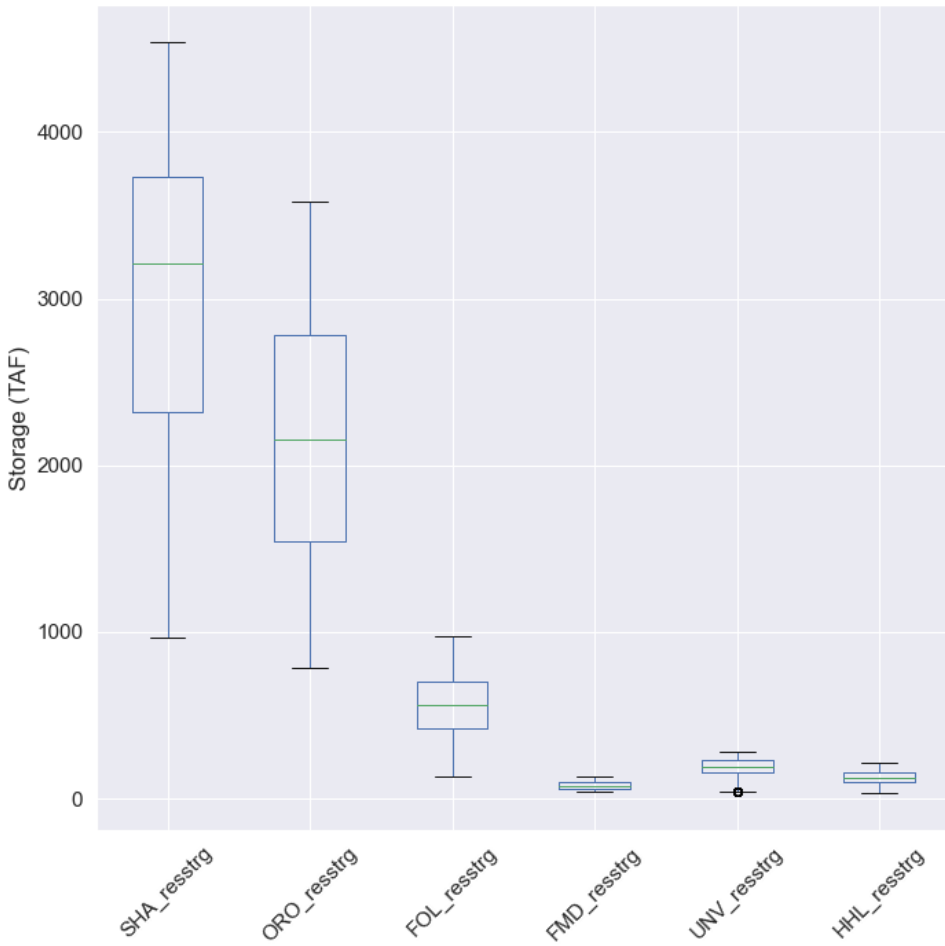

Figure 88. Boxplot of daily reservoir storage for selected CDEC stations from Sep 1996-Sep 2022 before post-processing.

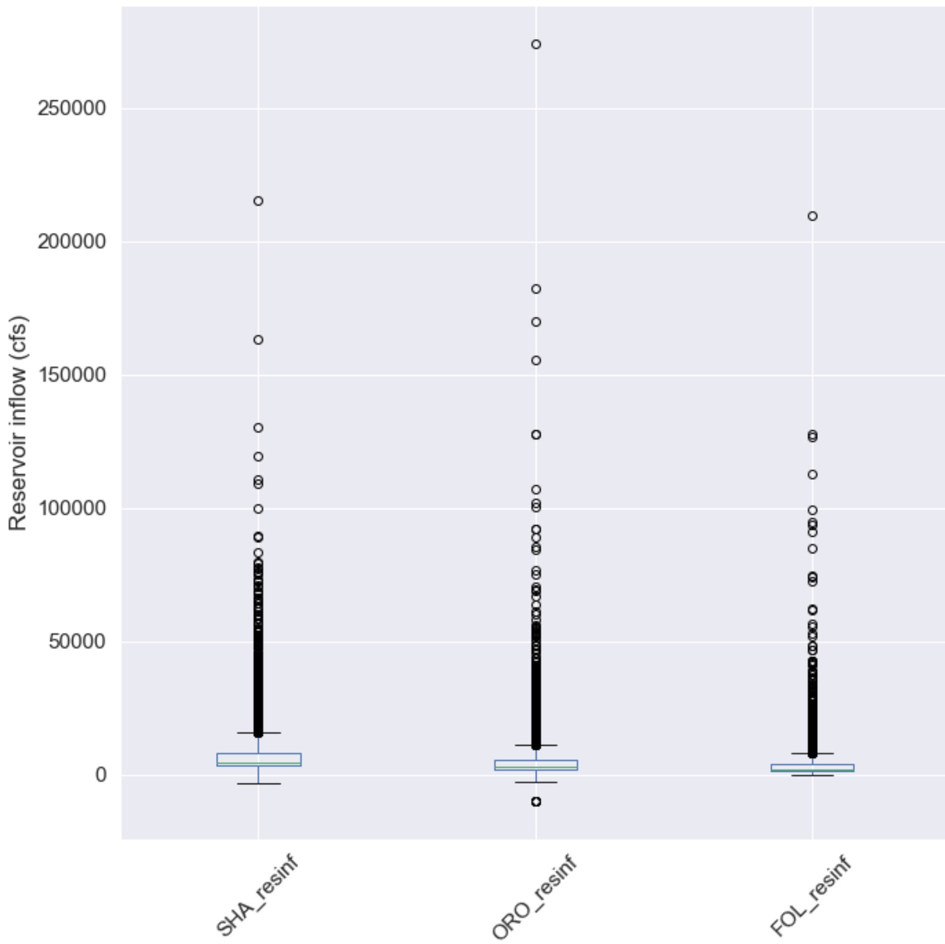

Figure 89. Boxplot of daily reservoir inflow (cfs) for selected CDEC stations from Sep 1996-Sep 2022 before post-processing.

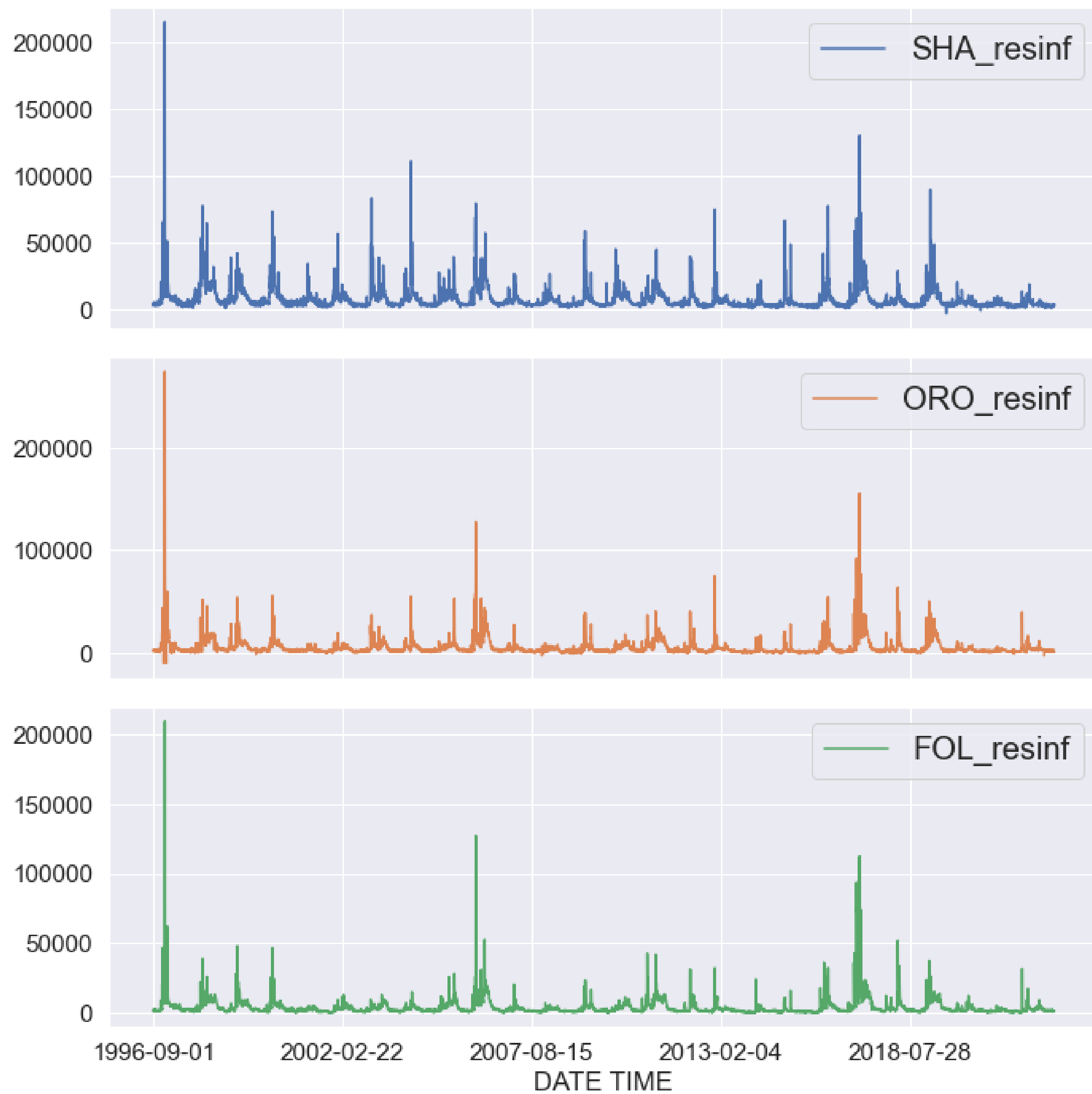

Figure 90. Daily timeseries of daily reservoir inflow (cfs) for selected CDEC stations from Sep 1996-Sep 2022 before post-processing.

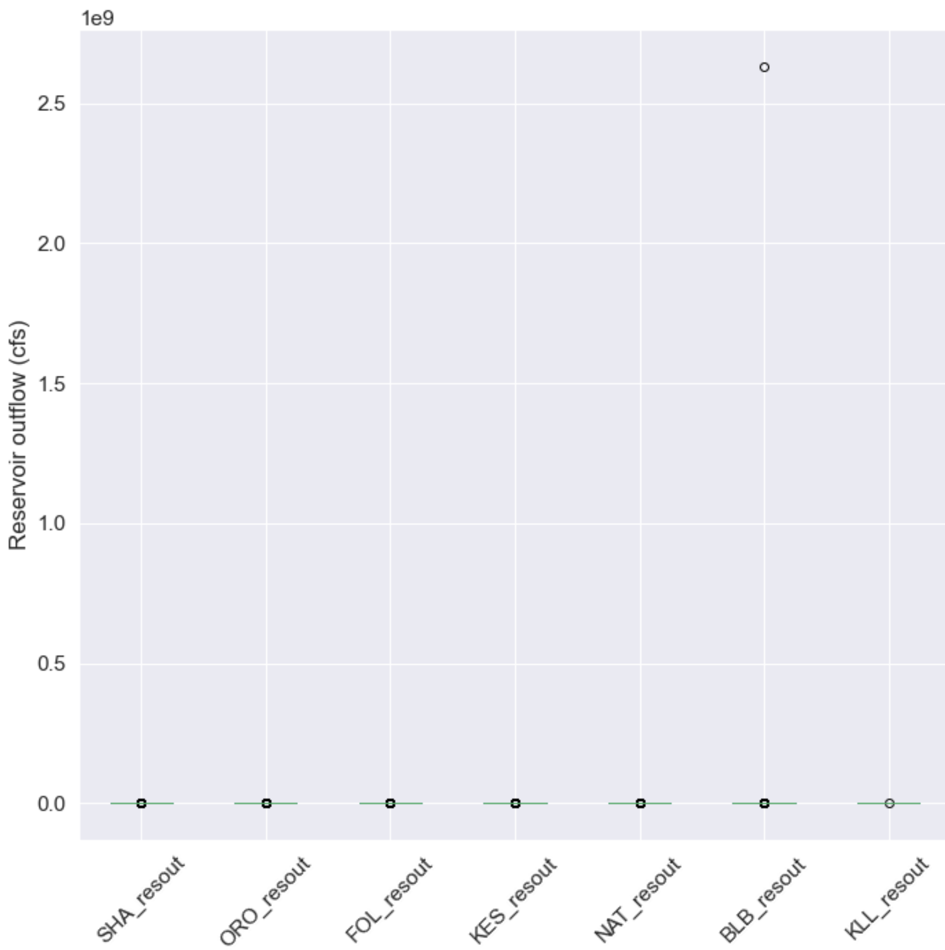

Figure 91. Boxplot of daily reservoir outflow (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

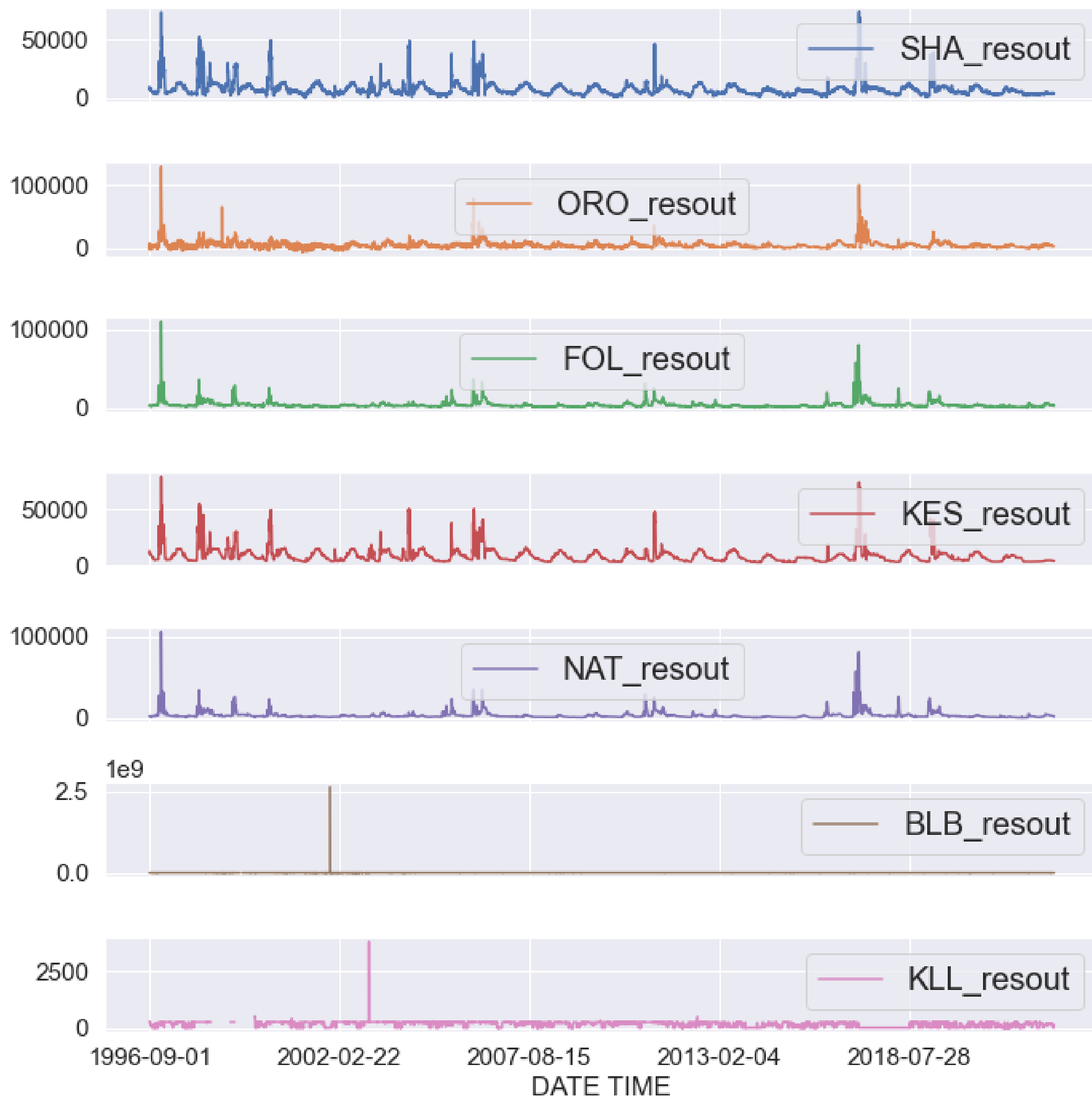

Figure 92. Daily timeseries of daily reservoir outflow (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

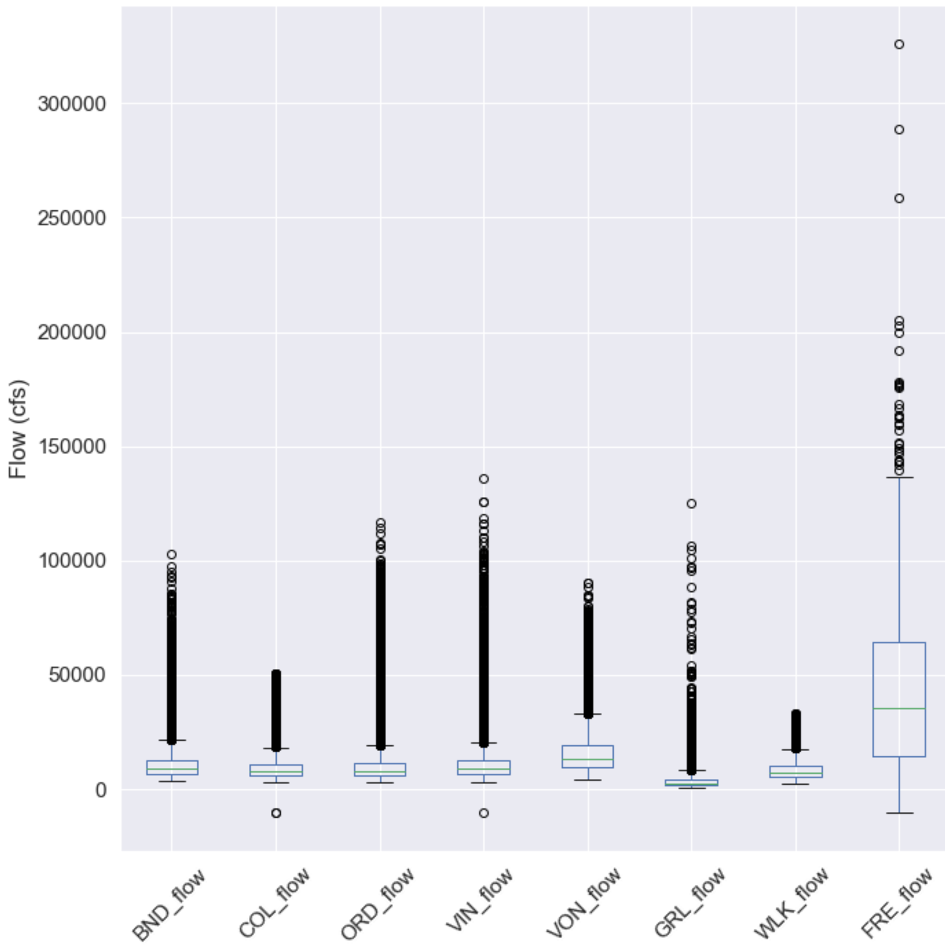

Figure 93. Boxplot of daily flow (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

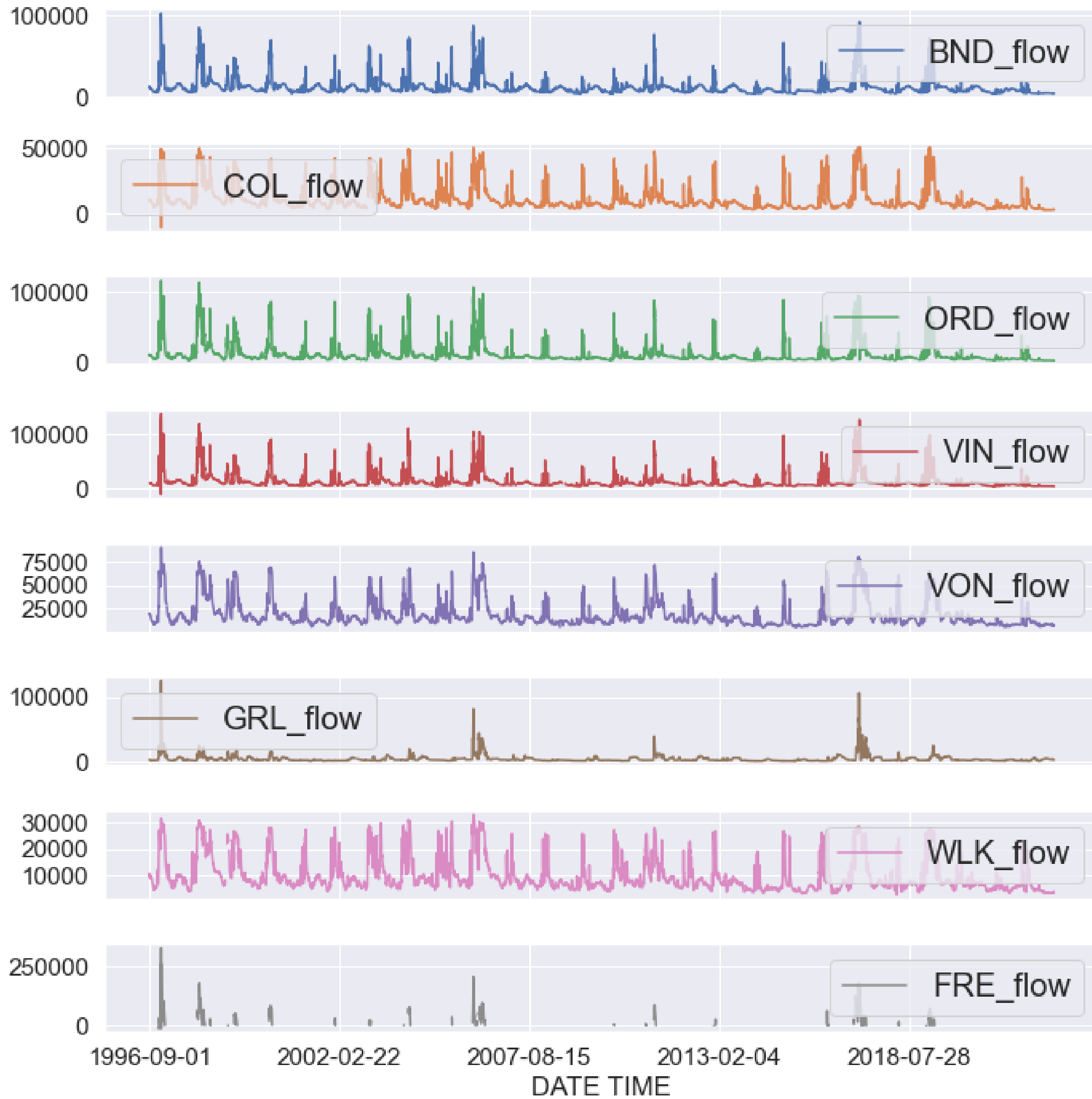

Figure 94. Daily timeseries of daily flow (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

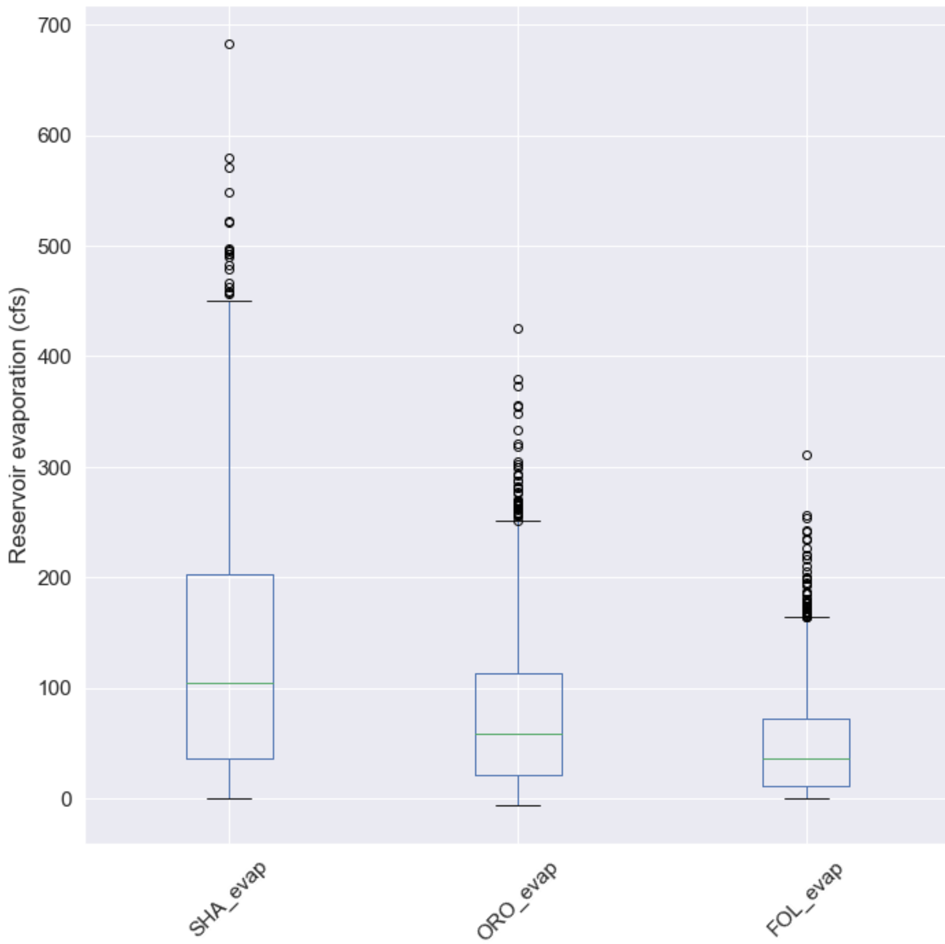

Figure 95. Boxplot of daily reservoir evaporation (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

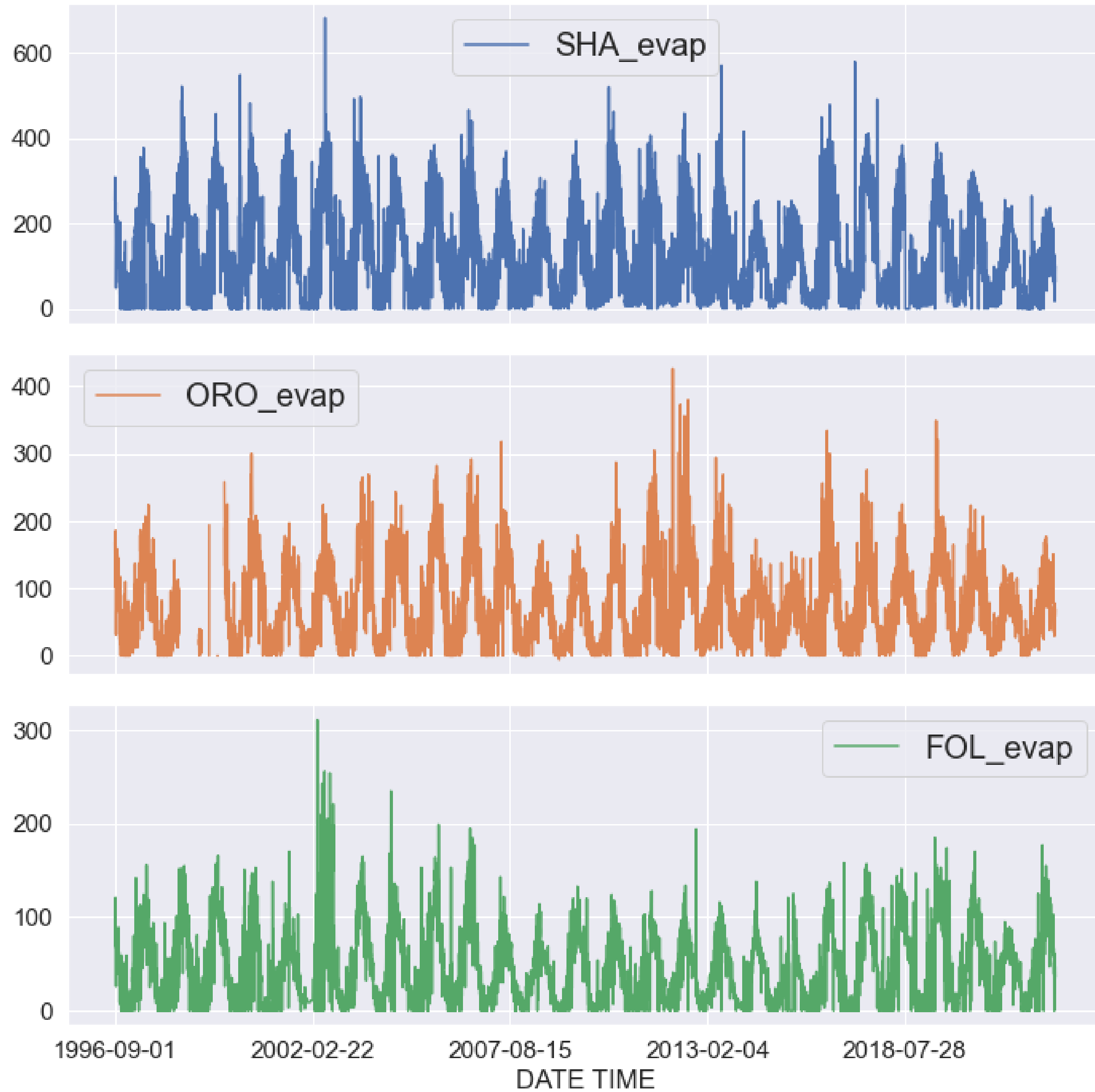

Figure 96. Daily timeseries of daily reservoir evaporation (cfs) for selected CDEC stations from Sep 1996-Oct 2022 before post-processing.

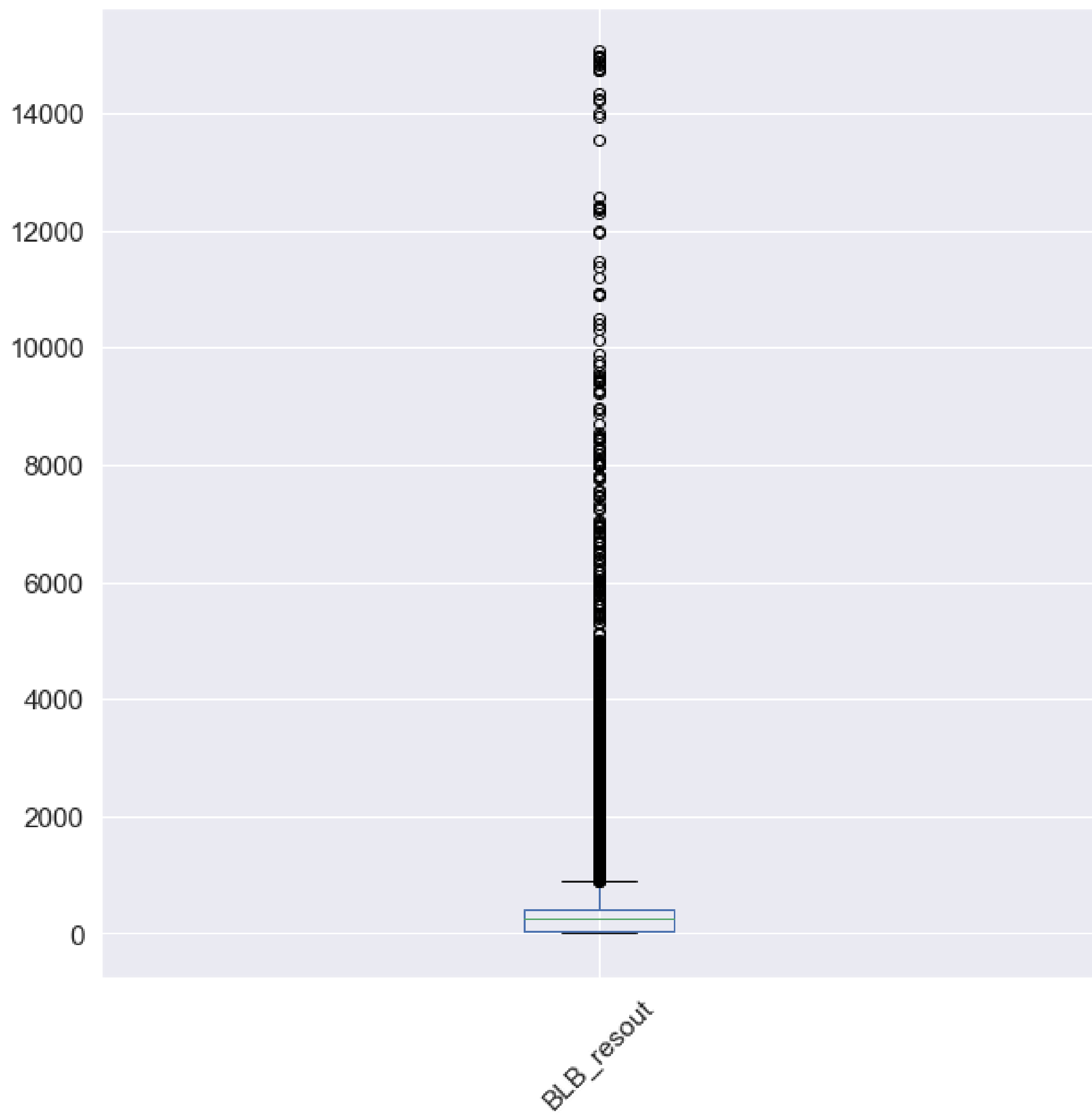

Figure 97. Boxplot of Black Butte reservoir outflow after replacing outliers with the median

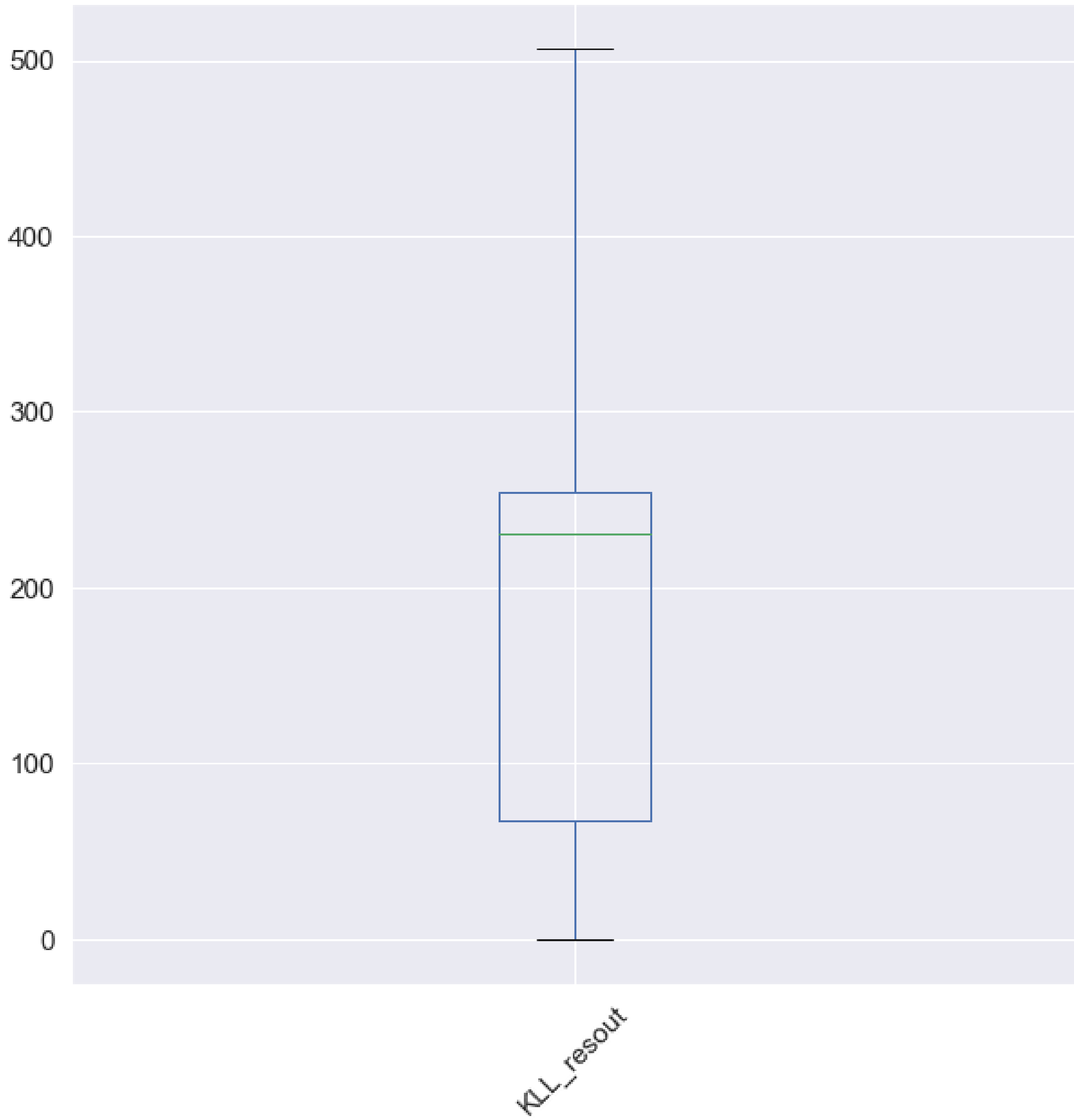

Figure 98. Boxplot of Kelly Ridge powerplant outflow after replacing outliers with the median

Negative Data

CDEC	Parameter type	Data clean up method
CDEC	Reservoir inflow	Replace using linear interpolation
CDEC	Reservoir outflow	Replace using linear interpolation
CDEC	Flow	Replace using linear interpolation
CDEC	Reservoir evaporation	N/A
USGS	BEAR R NR WHEATLAND CA **11424000**	N/A
USGS	CLEAR C NR IGO CA **11372000**	N/A
USGS	CACHE C A YOLO CA **11452500**	N/A
USGS	YUBA R BL ENGLEBRIGHT DAM NR SMARTSVILLE CA **11418000**	N/A
USGS	YUBA R NR MARYSVILLE CA **11421000**	N/A
USGS	YOLO BYPASS NR WOODLAND CA **11453000**	N/A
USGS	SACRAMENTO WEIR SPILL TO YOLO BYPASS NR SAC CA **11426000**	N/A
USGS	SPRING C PH A KESWICK CA **11371600**	N/A

Figure 99 shows which stations and variables contained negative data. Figure 100 shows that Oroville reservoir outflow had the highest ratio of negative data. For CDEC columns with negative values, they were replaced through linear interpolation. For example, negative Oroville releases are data errors after communication with CDEC staff (D. Parker, personal communication, November 2, 2022). For this process, negative CDEC values are assumed data entry or gage errors. There were no negative data in the selected USGS NWIS dataset as shown in Figure 101.

CDEC

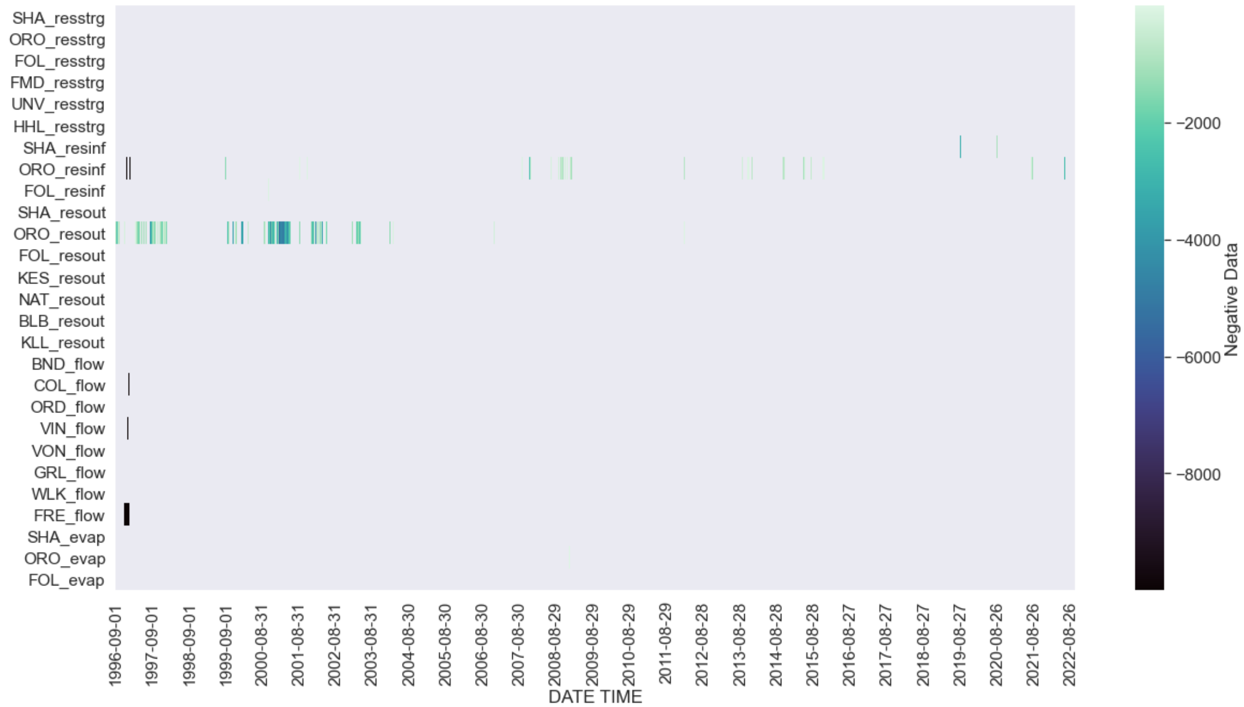

Figure 99. Heatmap showing the occurrences of negative data from selected CDEC stations from Sep 1996 to Sep 2022

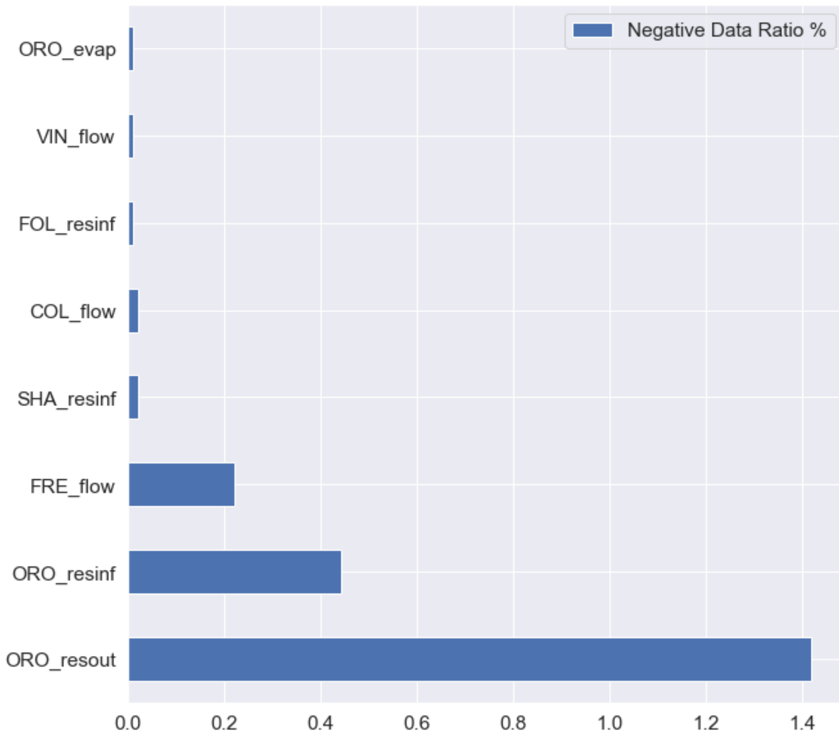

Figure 100. Selected CDEC stations with high lowest (top) and highest (bottom) negative data ratio from Sep 1996 to Sep 2022.

USGS NWIS

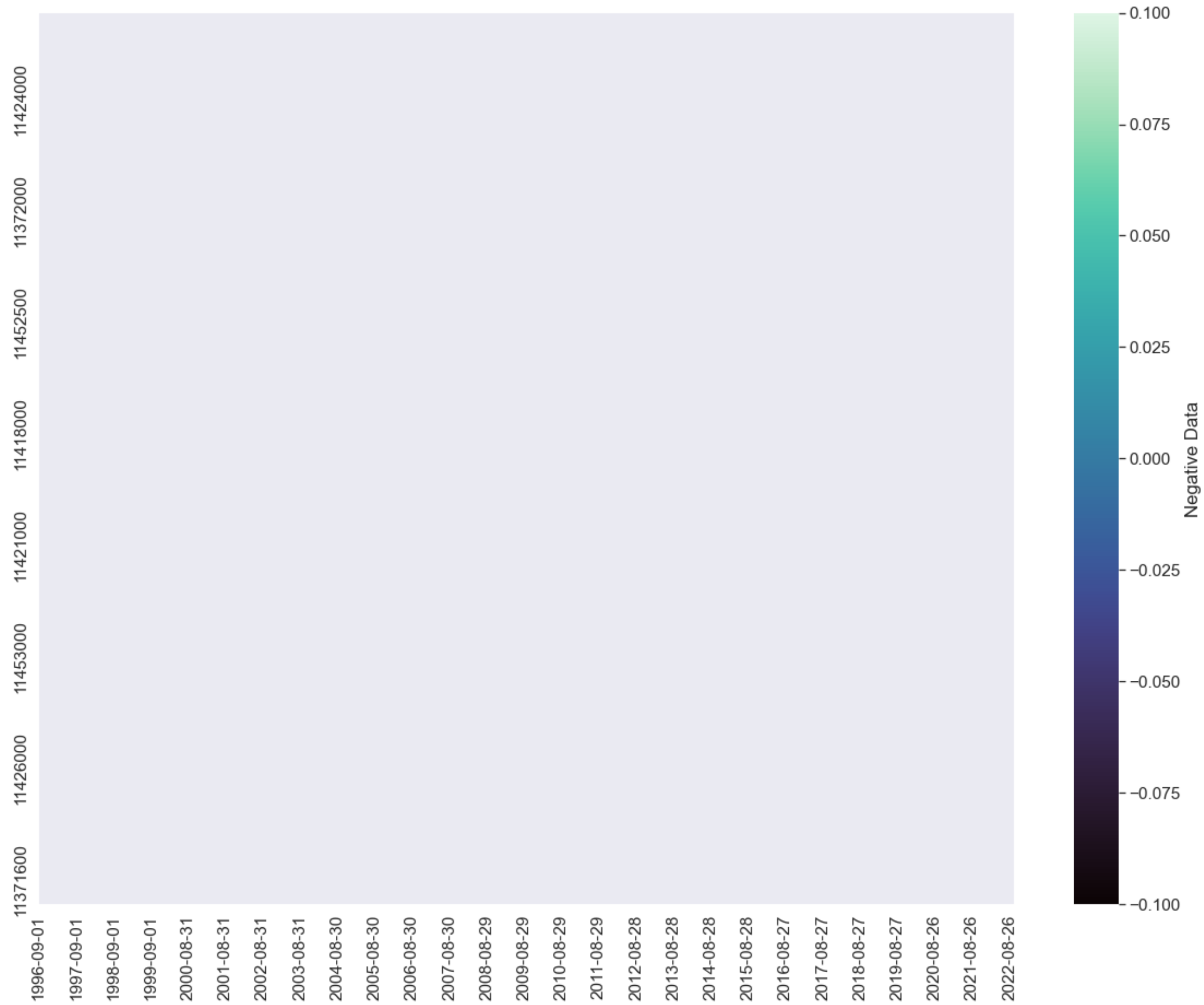

Figure 101. Heatmap showing the occurrences of negative data from selected USGS NWIS stations from Sep 1996 to Sep 2022

Zeroes Data

CDEC	Parameter type	Data clean up method
CDEC	Storage	N/A
CDEC	Reservoir inflow	N/A
CDEC	Reservoir outflow	N/A
CDEC	Flow	N/A
CDEC	Reservoir evaporation	N/A
USGS	BEAR R NR WHEATLAND CA **11424000**	N/A
USGS	CLEAR C NR IGO CA **11372000**	N/A
USGS	CACHE C A YOLO CA **11452500**	Leave alone. Reasonable to expect 0 cfs flows in this area.
USGS	YUBA R BL ENGLEBRIGHT DAM NR SMARTSVILLE CA **11418000**	N/A
USGS	YUBA R NR MARYSVILLE CA **11421000**	N/A
USGS	YOLO BYPASS NR WOODLAND CA **11453000**	N/A
USGS	SACRAMENTO WEIR SPILL TO YOLO BYPASS NR SAC CA **11426000**	Leave alone. Reasonable to expect 0 cfs flows in this area.
USGS	SPRING C PH A KESWICK CA **11371600**	Leave alone. Reasonable to expect 0 cfs flows in this area.

For the selected CDEC stations, Kelly Ridge Power Plant releases had the most zero value data (more than 16% in the period of record). This might be because Kelly Ridge does not operate every day to release for hydropower. For this station, zero values will not be changed. The reservoir evaporation set had the next most zero value data after Kelly Ridge. This is assumed reasonable for evaporation data especially in the winter months. As a result, no additional processing will be done for the Shasta, Oroville, and Folsom evaporation. For the rest of the selected CDEC stations (Shasta release, Oroville release, Black Butte release), the zero values will be left alone since there might have been repairs or outages. As for Fremont weir spills, zero values may indicate no spills so this station’s zero values will not be modified.

After post processing, Shasta and Oroville reservoir inflow, Colusa and Vina flow, and Fremont weir spills now show up in the heatmap. These data were negative initially but were converted to zeroes for post processing.

For the selected USGS NWIS stations, zero value data exists in the Spring Creek Powerhouse at Keswick (11371600), Cache Creek at Yolo (11452500), and Sacramento Weir Spill at Yolo Bypass (11426000). It may have been possible that zero value data occurred at Spring Creek Powerhouse due to outages or maintenance. As for Yolo area stations, zeroes may be due to the lack of spills from the Sacramento River to Yolo Bypass. In summary, no post processing was conducted for the selected USGS NWIS stations.

CDEC

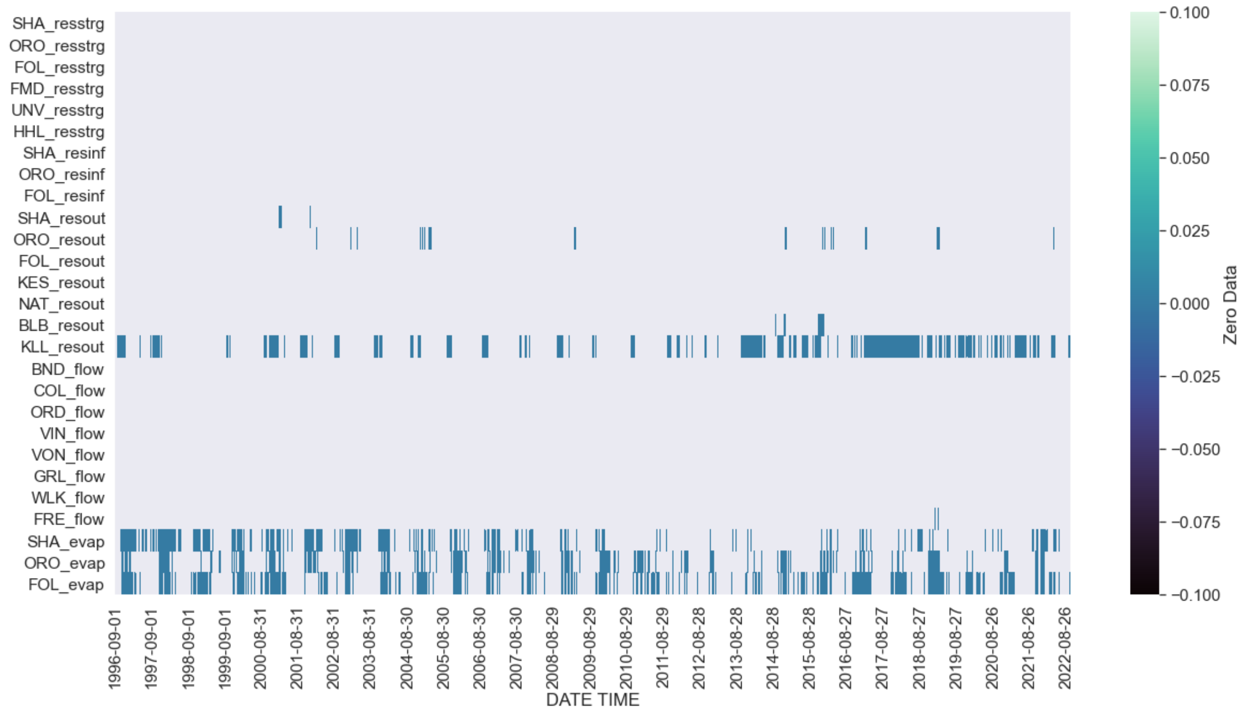

Figure 102. Heatmap showing the occurrences of zero cfs or TAF data from selected CDEC stations from Sep 1996 to Sep 2022

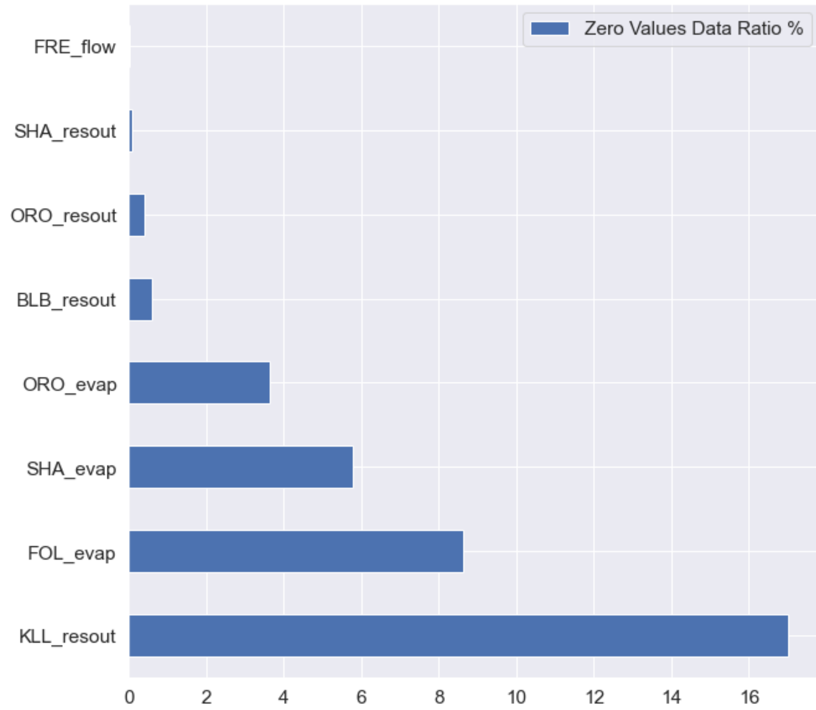

Figure 103. Selected CDEC stations with high lowest (top) and highest (bottom) zeroes data ratio from Sep 1996 to Sep 2022.

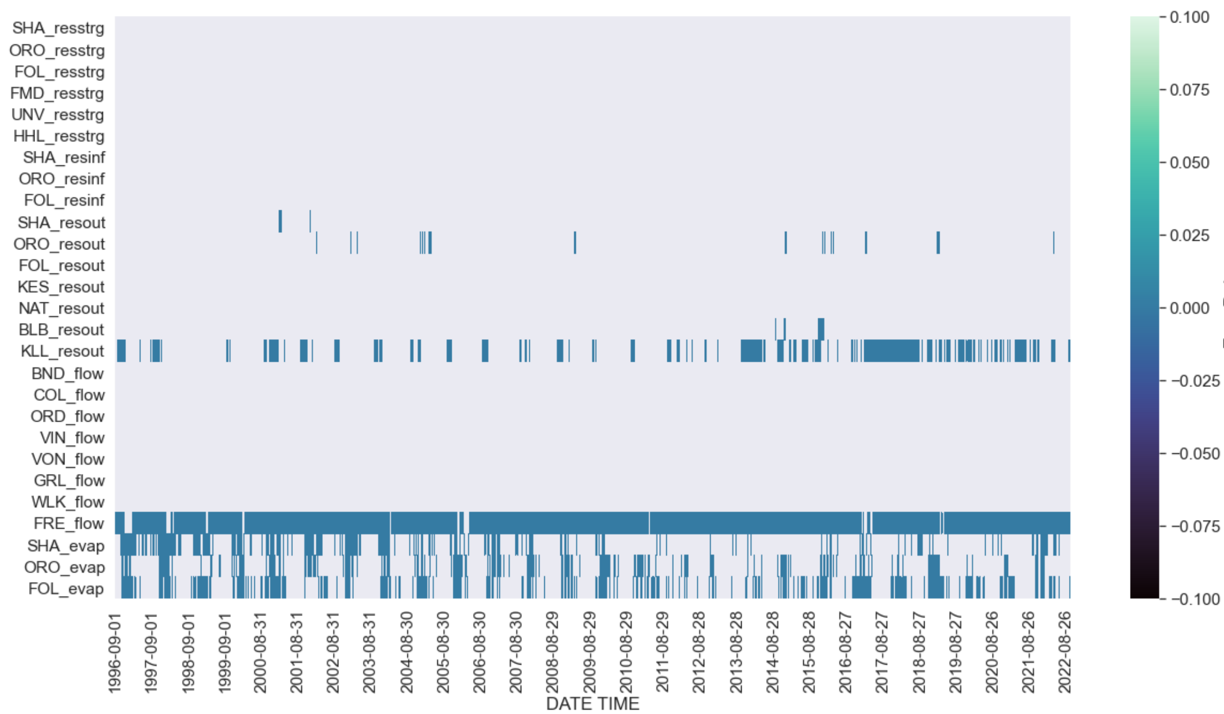

Figure 104. Heatmap showing the occurrences of zero cfs or TAF data from selected CDEC stations from Sep 1996 to Sep 2022 after post processing

USGS NWIS

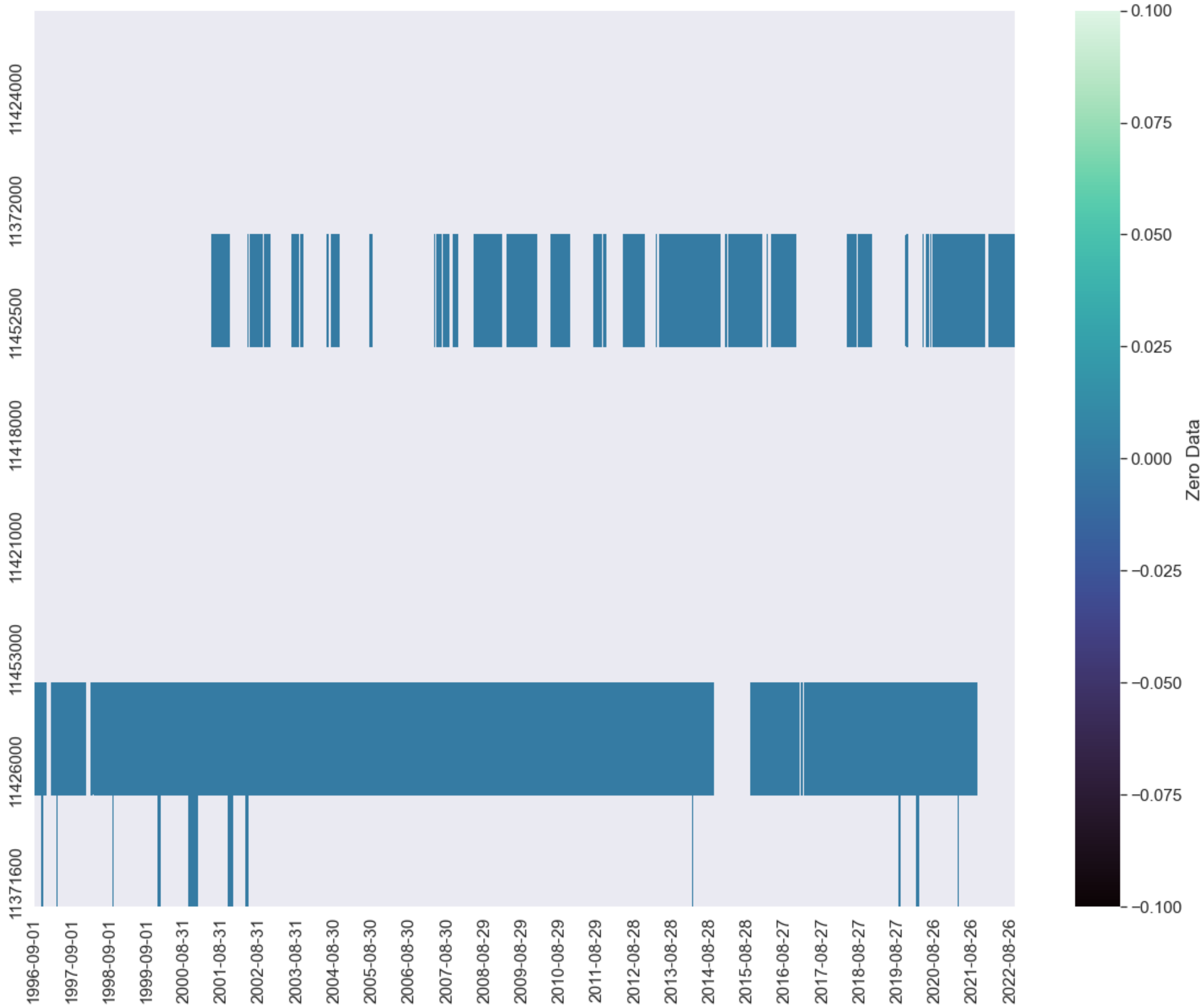

Figure 105. Heatmap showing the occurrences of zeroes from selected USGS NWIS stations from Sep 1996 to Sep 2022

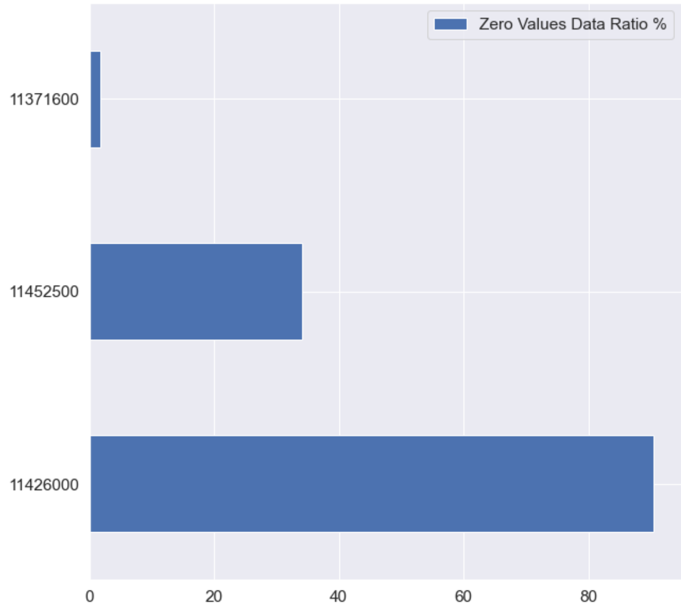

Figure 106. Selected USGS NWIS stations with high lowest (top) and highest (bottom) zeroes data ratio from Sep 1996 to Sep 2022.

Precipitation Data

Precipitation data (in inches) was needed to calculate the Oroville flood control rule curve from USACE. The stations required as shown below in Table 27.

Table 27. Feather River precipitation stations from CDEC

CDEC Station Name and Acronym
Canyon Dam (CNY)
Strawberry Valley (SBY)
Oroville Dam (ORO)
Brush Creek (BRS)
Sierraville (SVL)
Quincy (QCY)
Camptonville (CAM)
De Sabla (DWR)

Missing Data

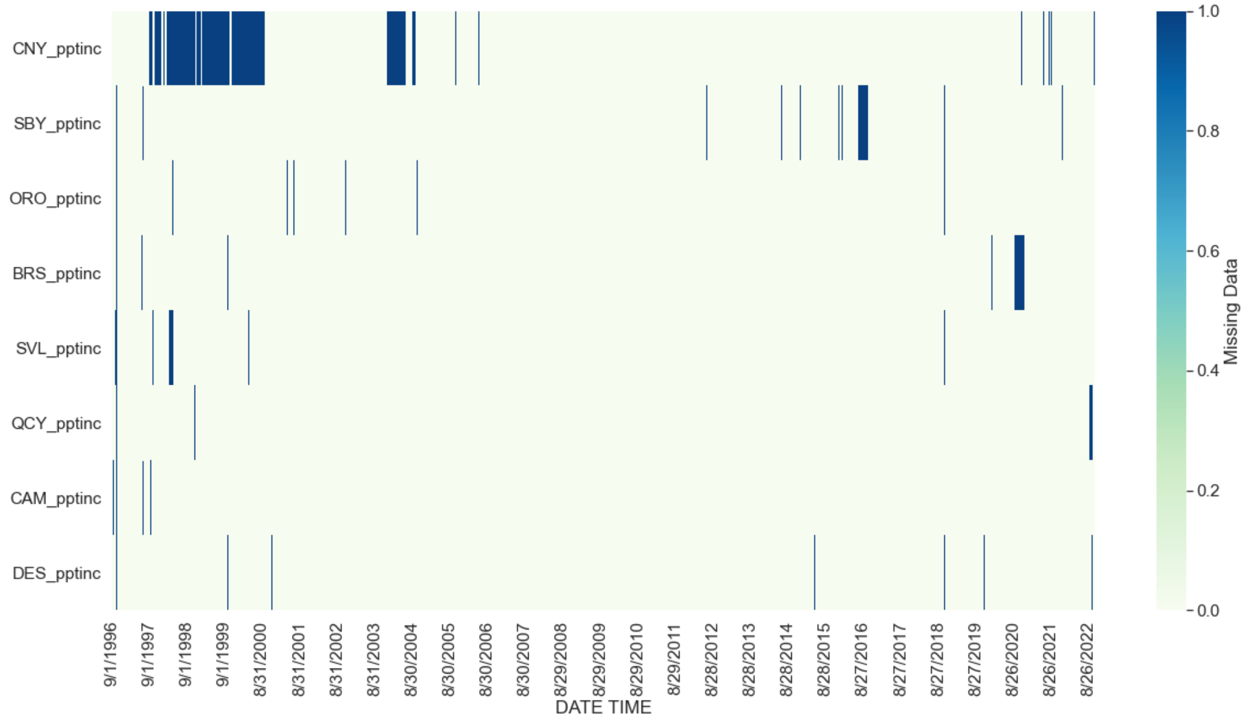

Figure 107. Heatmap showing the occurrences of missing data from selected precipitation stations from Sep 1996 to Sep 2022

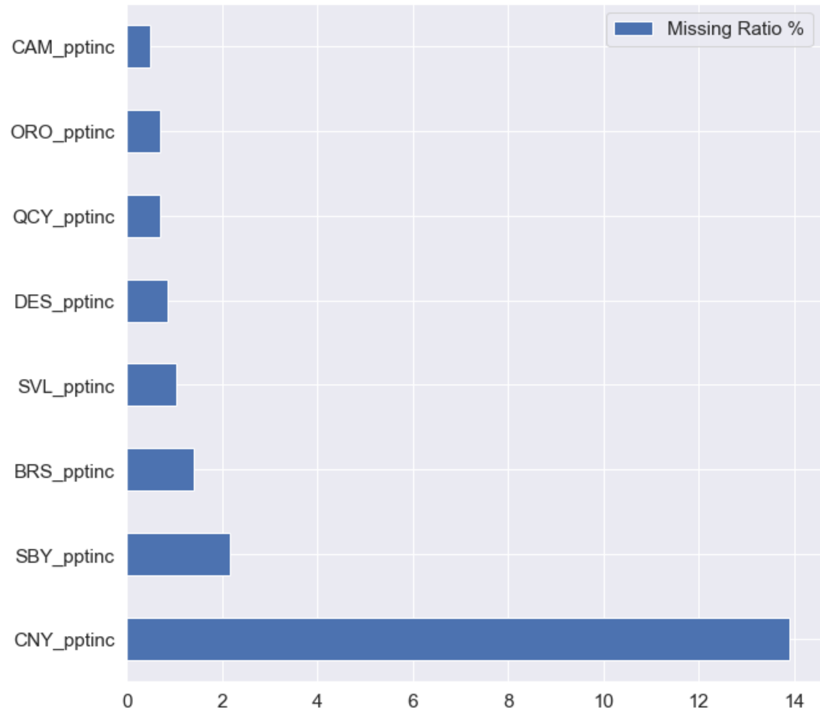

Figure 108. Selected precipitation stations with high lowest (top) and highest (bottom) missing data ratio from Sep 1996 to Sep 2022.

Outliers

There was one notable outlier for Canyon Dam (CNY) shown in Figure 109. This is assumed to be a replaceable outlier because the rest of the precipitation stations in the Feather River basin never incurred precipitation of greater than 20 inches during the period of record. The outlier was replaced by taking the median of CNY precipitation data over the period of record (1996-2022). The updated box plot is shown in Figure 110.

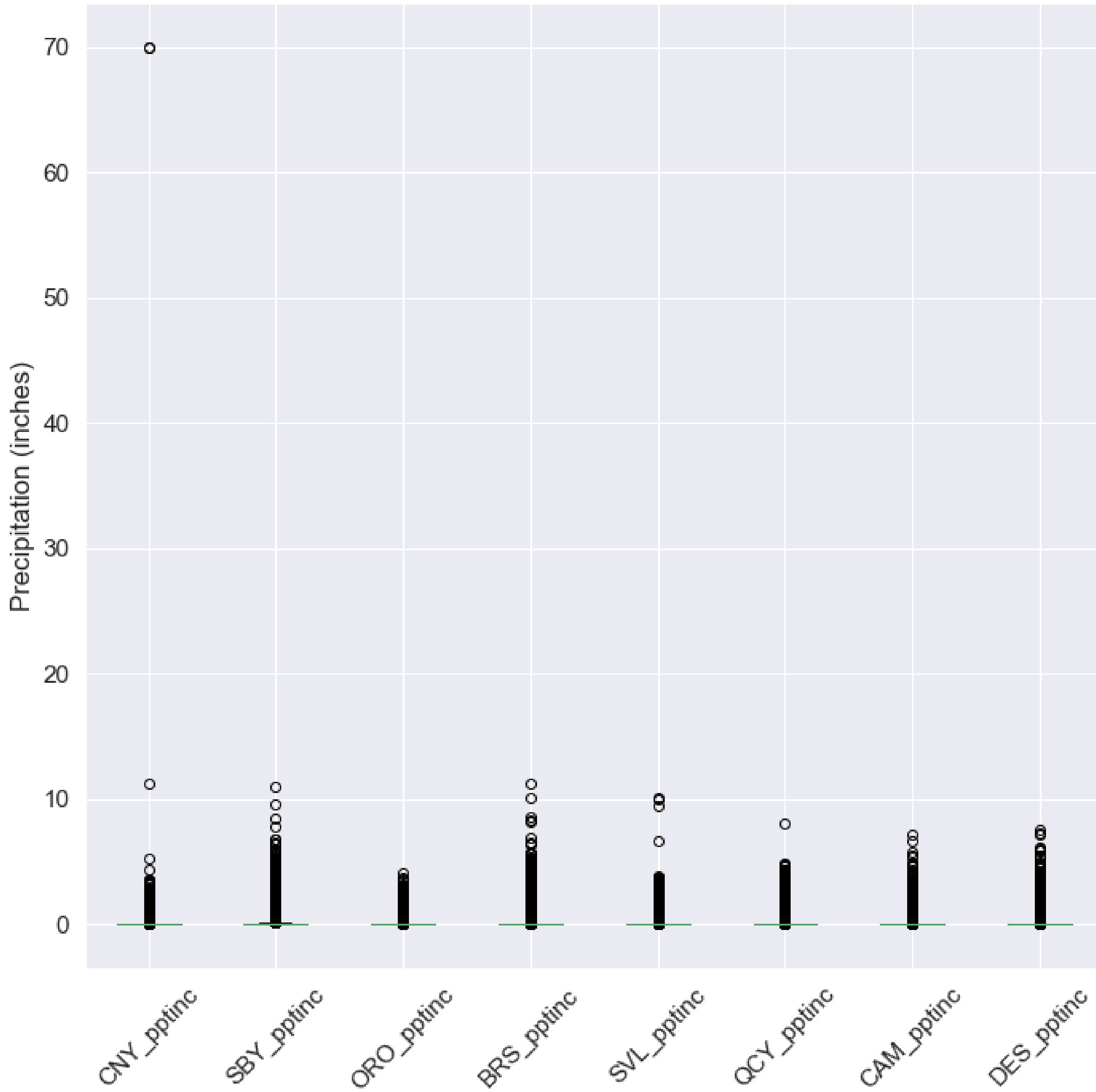

Figure 109. Boxplot of daily incremental precipitation for selected Feather River stations from Sep 1996- Sep 2022 before post-processing.

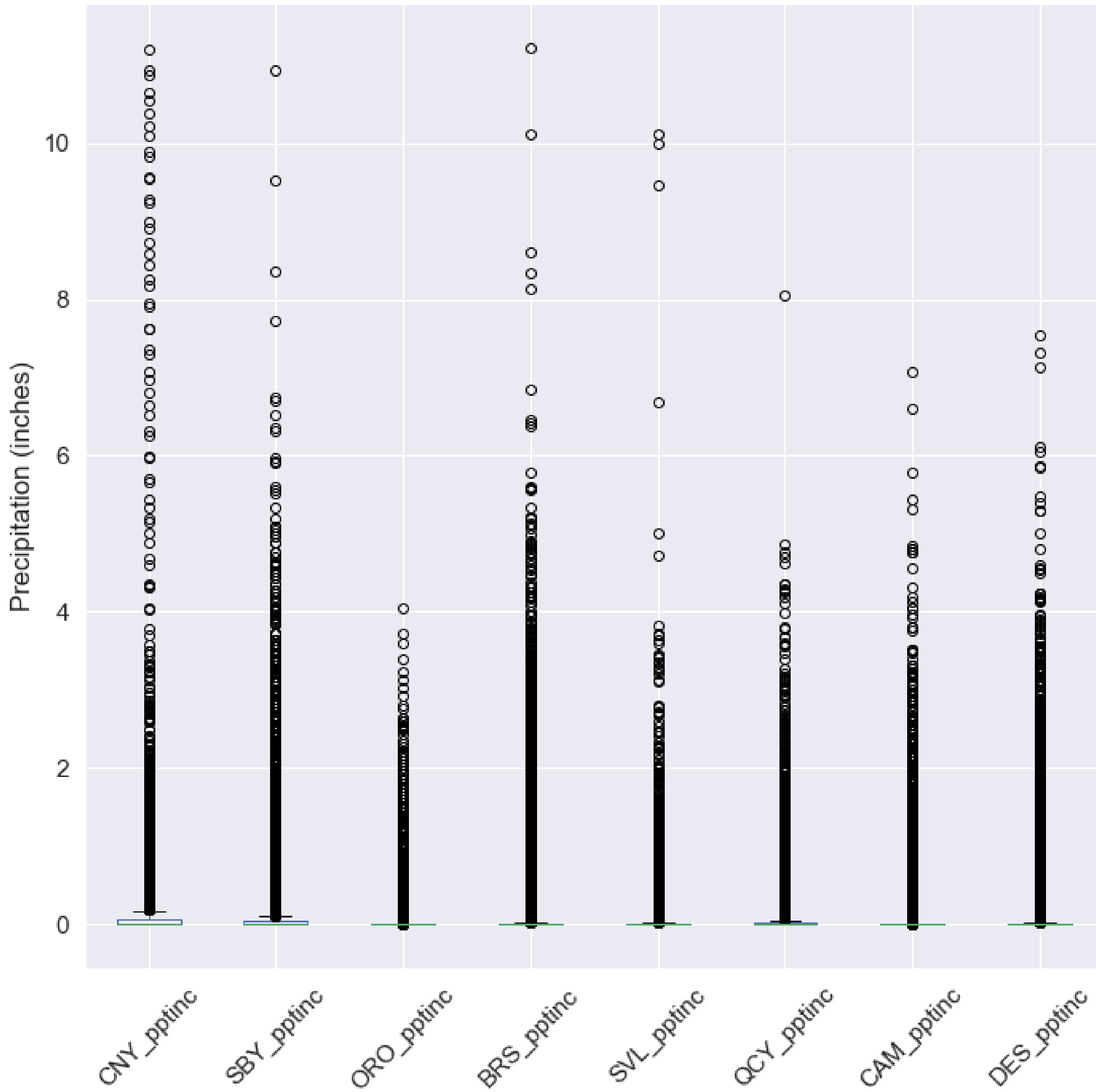

Figure 110. Boxplot of daily incremental precipitation for selected Feather River stations from Sep 1996- Sep 2022 after outlier post-processing.

Negative Data

There were no negative values in the precipitation dataset.

Zeroes Data

There were many days of zero precipitation days as shown in Figure 111 and Figure 112. This is expected so no additional processing will be made to “replace” zero data days.

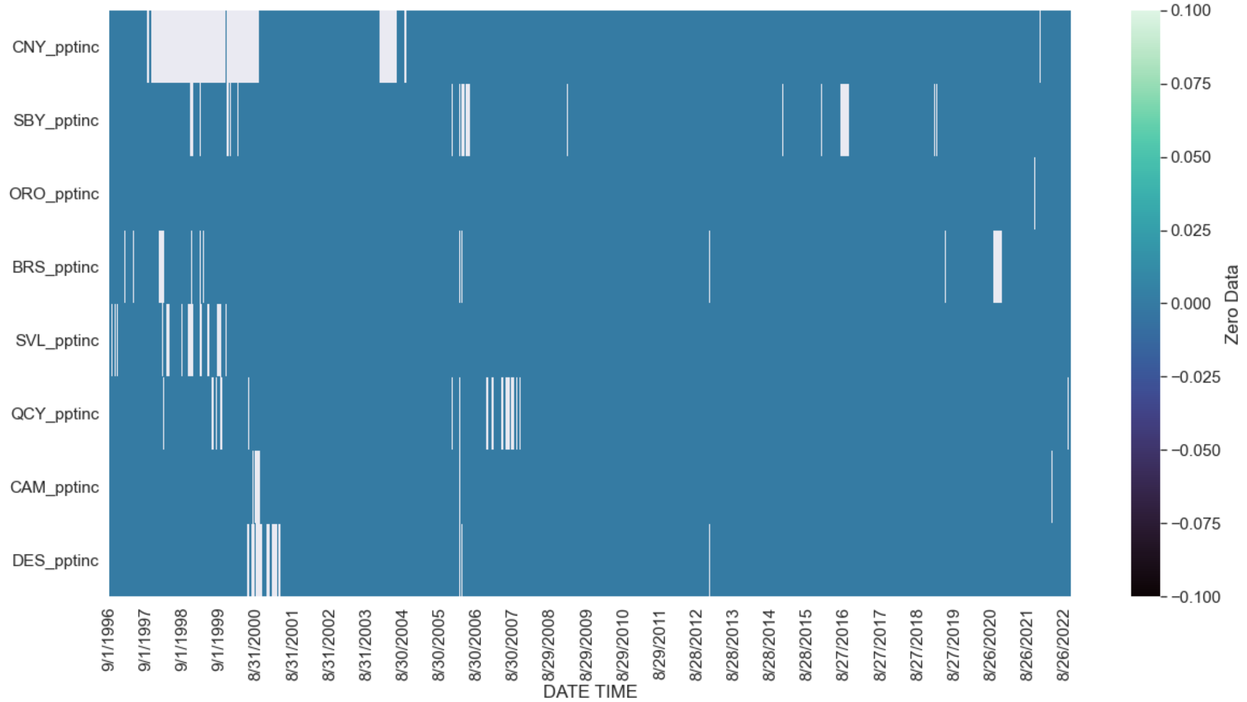

Figure 111. Heatmap showing the occurrences of zero precipitation data from selected precipitation stations from Sep 1996 to Sep 2022

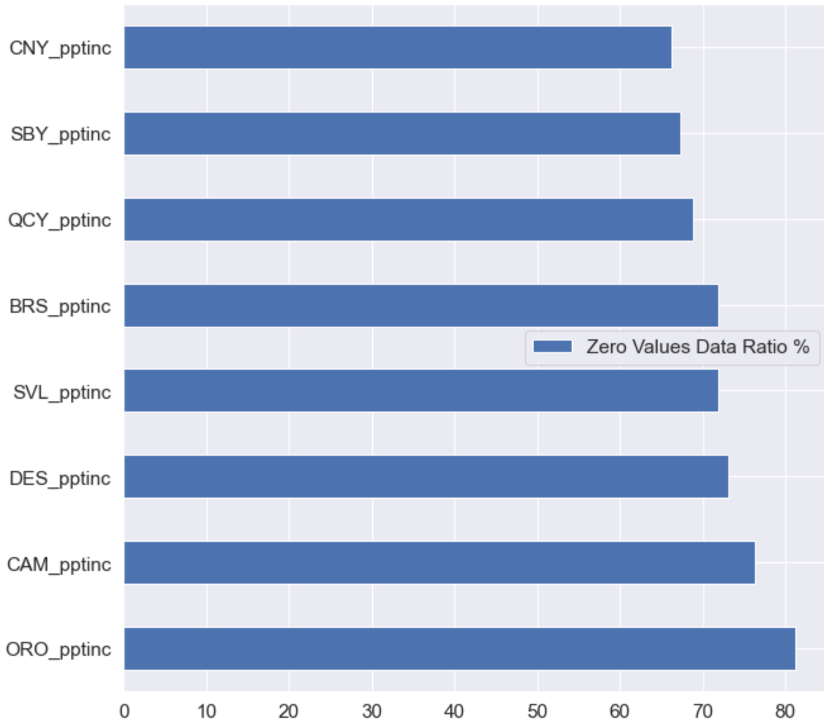

Figure 112. Selected precipitation stations with high lowest (top) and highest (bottom) zero precipitation data ratio from Sep 1996 to Sep 2022.

Appendix E – Pre-Adjusted Routing MTO Scenario

Timeseries Plots

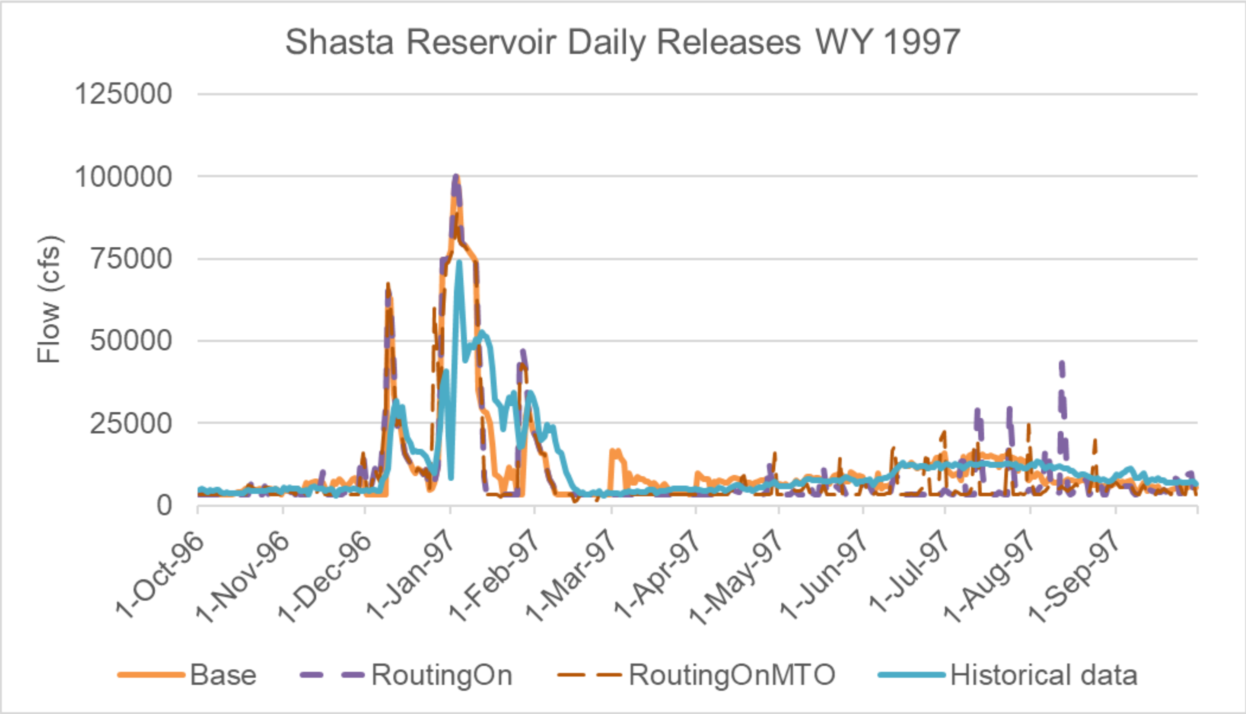

Figure 113. Pre-adjusted RMTO daily Shasta reservoir releases for simulations and historical data in WY 1997

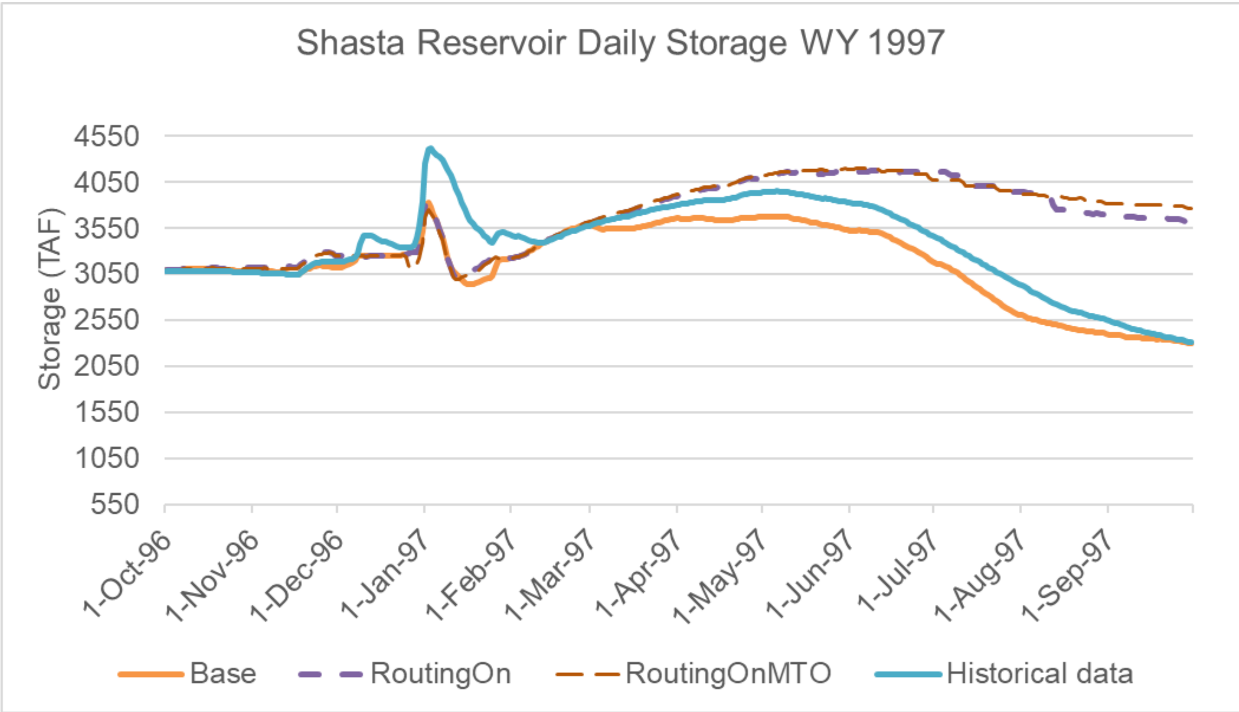

Figure 114. Pre-adjusted RMTO daily Shasta reservoir storage for simulations and historical data in WY 1997

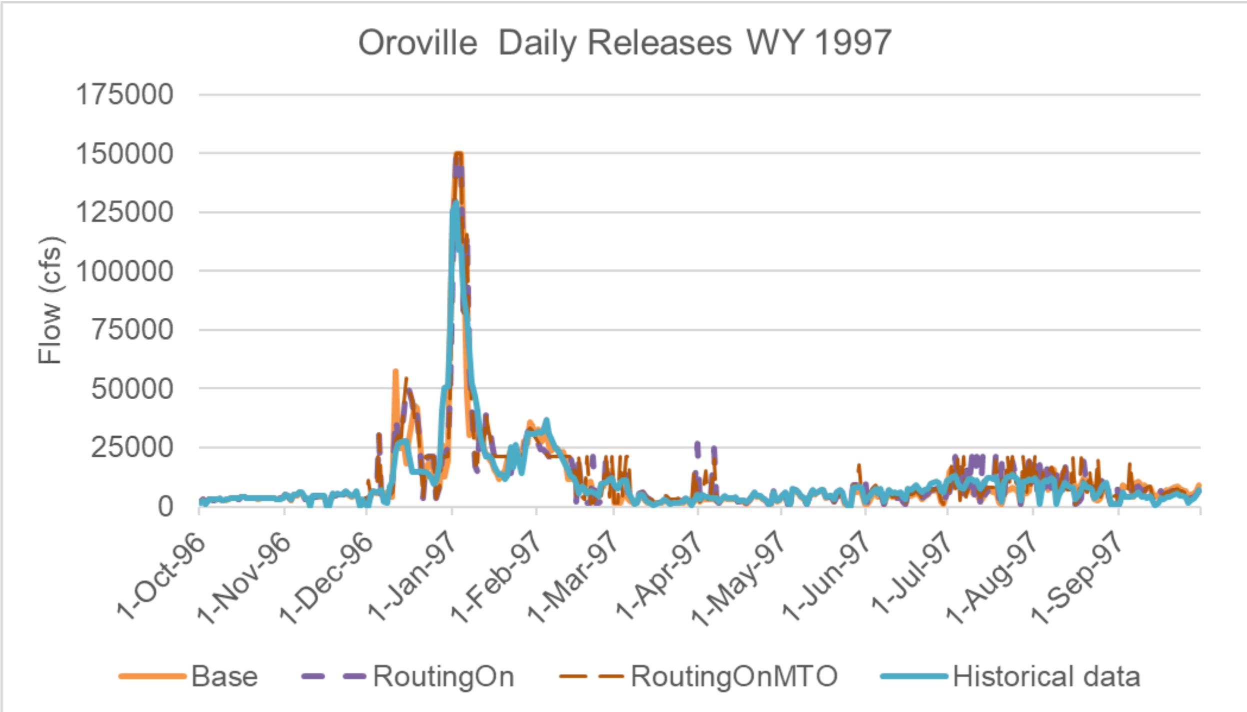

Figure 115. Pre-adjusted RMTO daily Oroville reservoir releases for simulations and historical data in WY 1997

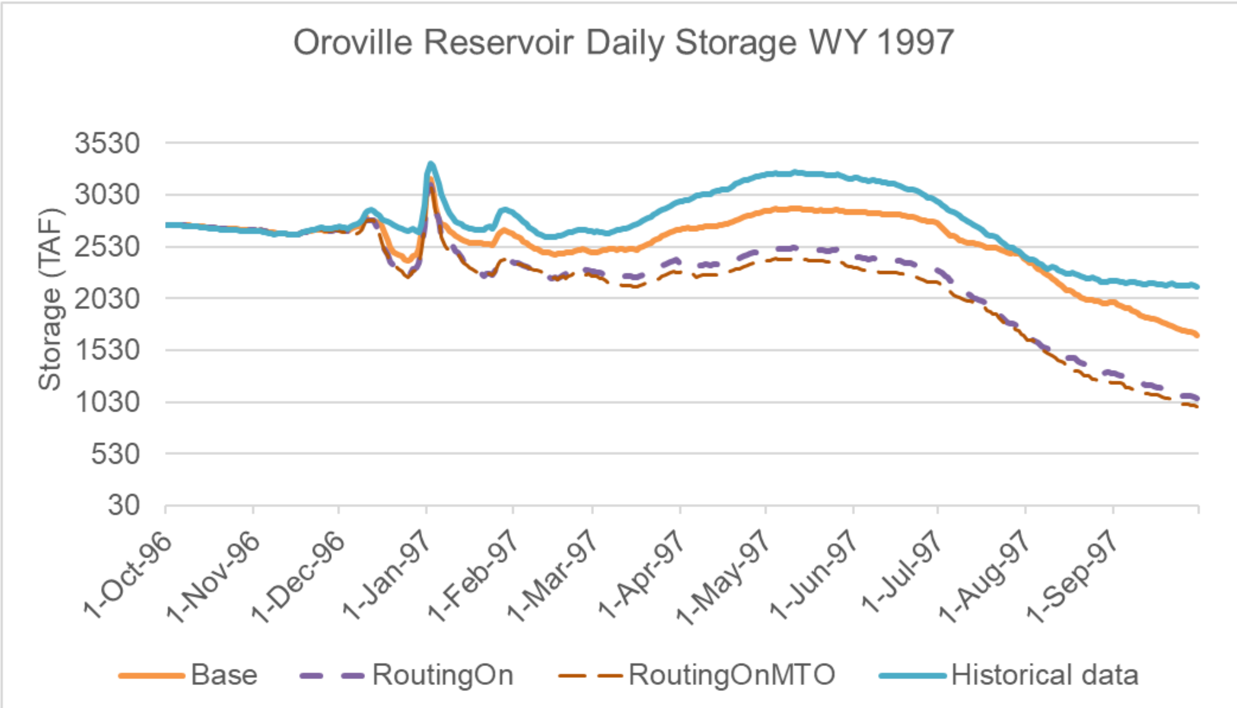

Figure 116. Pre-adjusted RMTO daily Oroville reservoir storage for simulations and historical data in WY 1997

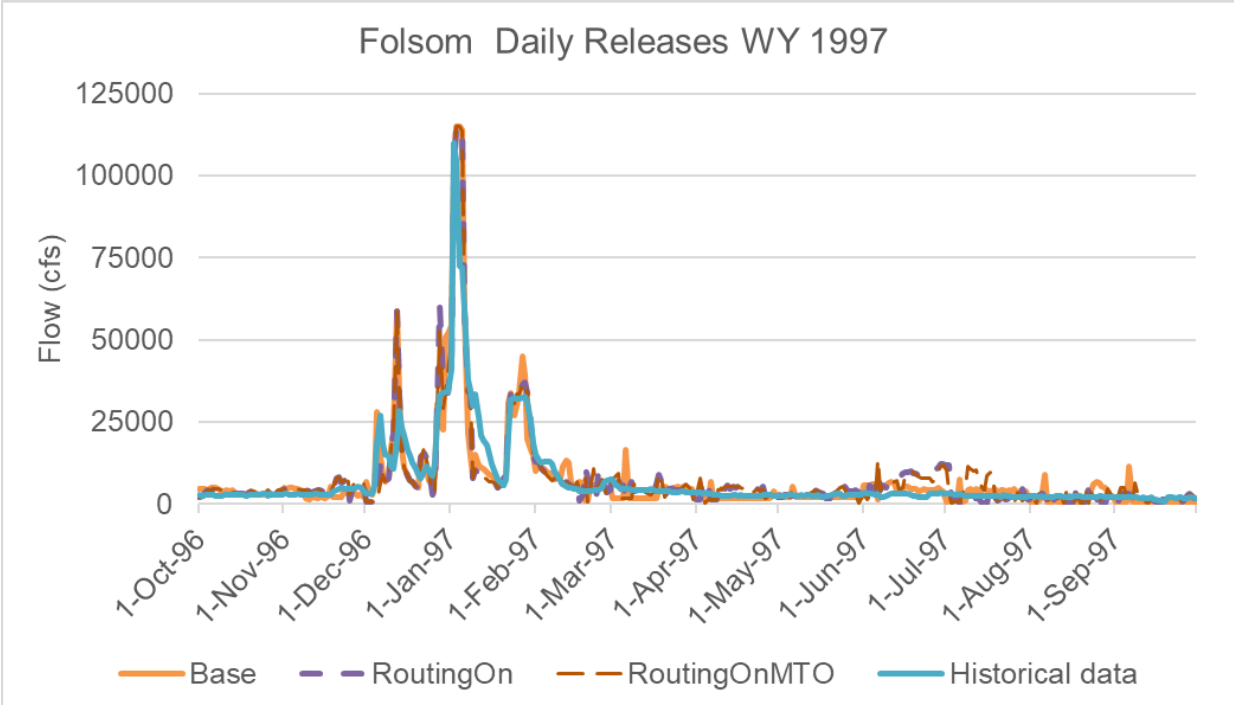

Figure 117. Pre-adjusted RMTO daily Folsom reservoir releases for simulations and historical data in WY 1997

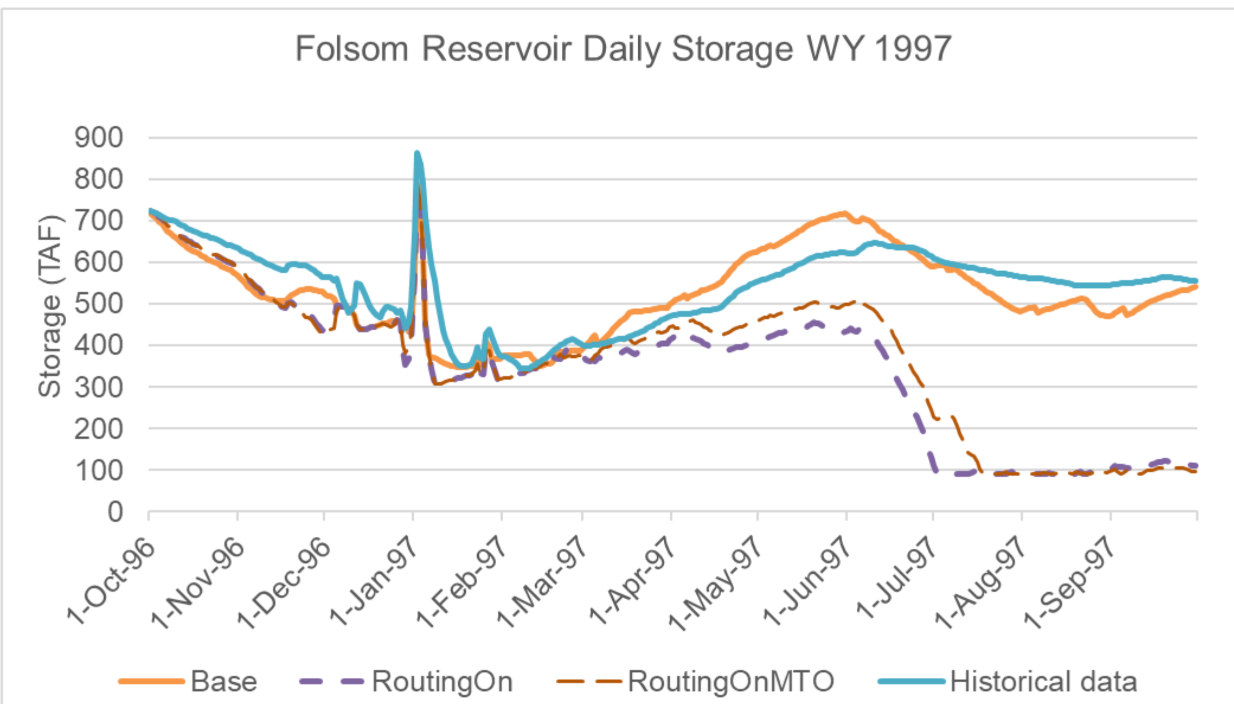

Figure 118. Pre-adjusted RMTO daily Folsom reservoir storage for simulations and historical data in WY 1997