Sacramento Valley Integrated Reservoir Optimization Model: Flood Control Linear Program

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ABSTRACT

The Sacramento Valley Integrated Reservoir Optimization Model is a spreadsheet based optimization model that determines the releases from five reservoirs in Northern California based on input hydrographs and penalty functions for excessive downstream flows, reservoir storage and ramping. The formulation and constraints of the hydrodynamic model are outlined. The Sacramento Valley Integrated Reservoir Optimization Model is applied using inflow hydrograph data from the 1986, 1995 and 1997 floods to produce optimal releases from Shasta, Black Butte, Oroville, New Bullards Bar and Folsom reservoirs. The Shasta, Black Butte, Oroville and New Bullards Bar Reservoirs synchronize and alternate releases to minimize the combined peak flow downstream at the Fremont Weir. Folsom reservoir acts more independently and makes releases before and after peak upstream flows to use the downstream channel capacity efficiently. Releases depend on the travel time to river convergences and the flows accumulated from local runoff in addition to the penalty functions. The Sacramento Valley Integrated Reservoir Optimization Model results are compared with those of two previously constructed models, the Flood Control Optimization model and Hydrologic Engineering Center's ResSIM. Later when weir diversions are optimized, the flood control linear program improves performance by routing flood waves through the bypass systems more efficiently, which allows for greater releases and shifts the locations where flow penalties are accumulated. The analysis suggests that increased channel and diversion capacities at the Fremont Weir would most effectively improve the system.

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INTRODUCTION

This report presents the formulation of the Sacramento Valley Integrated Reservoir Optimization Model (SVIROM), which optimizes five reservoir's releases using historical data to minimize flood damage in the Sacramento Basin. The deterministic model calculates a time series of reservoir releases and downstream flows based on inflow hydrographs and penalty functions for reservoir storage volume, ramping rates and exceeding channel capacities downstream.

The SVIROM model was developed subsequent to two other optimization models analyzing flood operations in the Sacramento Basin. Dustin Jones established the Flood Control Mixed Integer Program (FCMIP) based on the constraints formulated by Dr. David Ford's PhD 1978 dissertation (Jones 1997). Christy Jones modified this model to create the Hydrologic Engineering Center's Reservoir Flood Control Optimization Program model for the system (FCLP)(Jones 2013). Both models are mixed integer linear programs that produce a time series of optimal reservoir releases, storage and downstream flows. In addition to these optimization models, the Hydrologic Engineering Center has established a flood wave simulation model for the region that implements established reservoir operating rules (HEC-ResSIM).

The SVIROM was created on an Excel spreadsheet with the intention of establishing a more user friendly, accessible and self contained version of the previous models. The SVIROM is similarly structured as a mixed integer linear program and is solved using an optimization add-in solver (Lindo's What's Best), which uses binary variables and branch and bound iterations. USGS hydrograph data tables provided the model's inflow values. The previous studies and HEC-ResSIM provided reservoir and channel parameters (Jones 2013).

BACKGROUND

This study focuses on the Sacramento Basin in northern California. The SVIROM includes five major reservoirs in this region: Shasta, Black Butte, Oroville, New Bullards Bar and Folsom. The reservoir releases enter a river network of the Sacramento, Feather, Yuba and American Rivers, which eventually drains into the Delta. The watershed has two bypasses (Yolo and Sutter) which divert water from the Sacramento River at five weirs along its course. The combined flows of all reservoirs eventually combine in Rio Linda and enter the Delta (and exit the SVIROM). Figure 1 shows the schematic of the SVIROM.

Flood flows in California are often caused by atmospheric rivers, also known as pineapple express storms, from the Pacific Ocean. These storms form a jet stream about a mile above the ground, often hundreds of miles wide and thousands of miles long, that travel across the state of California. When the atmospheric river travels over the Coastal and Sierra Nevada mountain ranges, the elevation increase causes a drop in pressure and temperature, which releases vast amounts of precipitation in a relatively small region and timeframe (Dettinger, et al 2013). Additionally, these storms originate in tropical climates and are relatively warm, which can melt existing snowpack and add to the observed flood flows. The three floods analyzed in this paper (1986, 1995, 1997) were likely caused by atmospheric rivers.

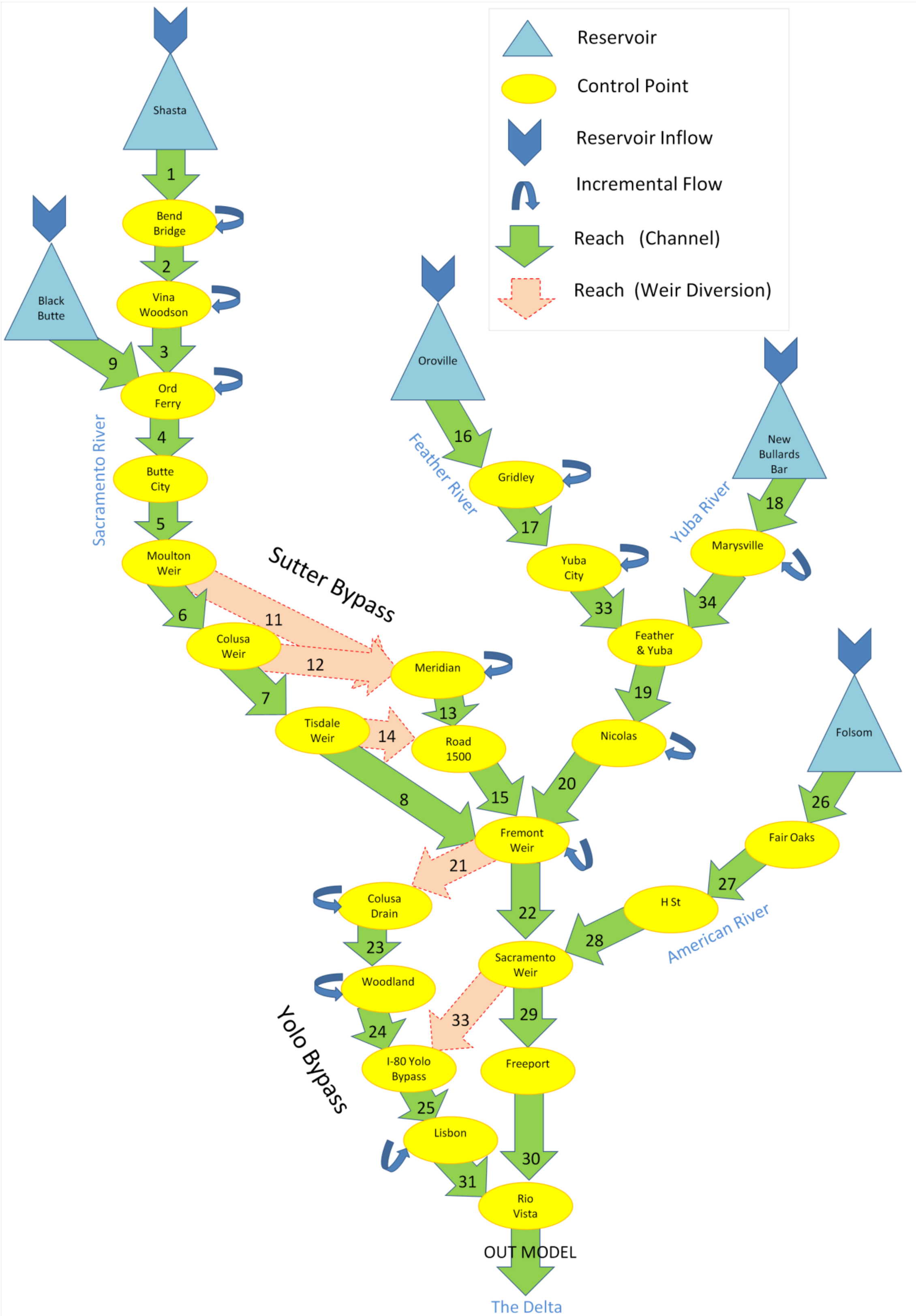

Figure 1. SVIROM Schematic of the Sacramento Basin

This report begins with an explanation and presentation of the structure and formulation of the SVIROM. The objective function, penalty functions, constraints and simplifications to the model are outlined and explained. Results of the analysis for three floods are then presented. Analysis includes the distribution of inflows over the basin, inflow and outflow hydrographs of the five reservoirs, Fremont and Sacramento Weirs as well as statistics that measure the SVIROM's success in reducing flood flows compared to no reservoir operation. Inferences and observations of the SVIROM's operation are presented along with plots and tables of the data. Next, the optimized reservoir releases and downstream weir diversions at the Fremont and Sacramento Weirs for the 1997 flood are compared to those determined from the FCLP and HEC-ResSIM models. The report then presents the SVIROM's optimal weir diversion parameters which suggest where in the system diversions are most important during floods. The report closes with conclusions and generalities of the analysis.

SVIROM STRUCTURE

The flood control system is modeled with five reservoirs and a series of control point nodes connected by reaches. Reservoirs contain an initial volume of water and inflows are added each 6 hour time step from inflow hydrographs, while releases calculated from the SVIROM are deducted. The reservoirs are depicted as triangles in Figure 1. Control points represent urban areas adjacent to the river course (represented by ovals in Figure 1). The control points account for incoming and outgoing flows at river junctions and weir diversions. Similar to the reservoirs, incremental flows from local runoff (shown as rotating arrows in Figure 1) are added each time step when data exists. A reach represents either a channel or bypass that connects two control points (shown as straight arrows in Figure 1). Reaches are used to route the flood waves downstream to account for the travel time between control points.

CONSERVATION OF MASS

The SVIROM performs a mass balance at each control point and reservoir during each time step to assure that water does not disappear and is only generated from input hydrographs. The formulation assumes reaches do not store water. The control points account for all incoming and outgoing flows at a specific location in the river. Since a control point cannot store water, the sum of the flow is equal to the sum of the outflow, as shown by the following equation for control point c at time t.

$$\sum Inflow_{c,t} = \sum Outflow_{c,t}$$

Reservoirs can store water and so the mass balance is constructed differently. The SVIROM uses an end of period storage variable. The storage at the end of time t for reservoir r is expressed by the following equation:

$$\boldsymbol{Storage_{r,t} = Storage_{r,t-1} + Inflow_{r,t} - Release_{r,t}}$$

The SVIROM calculates reservoir storage in acre feet and releases in cubic feet per second. To uphold the mass balance, unit conversions are implemented when appropriate. The change in storage over a six hour time period at a constant rate of X cfs is calculated with the following conversion:

$$\left(\frac{X\ cubic\ feet}{second}\right)\left(\frac{1\ AcreFt}{43560\ cubic\ feet}\right)\left(\frac{3600\ seconds}{1\ hour}\right)\left(\frac{6\ hours}{period}\right) = 0.496(\mathrm{X})\frac{AcreFt}{Period}$$

FLOOD ROUTING

Changing the rate of release from a reservoir changes the stage in the channel and creates a wave, which travels downstream. To model this behavior for floods, the SVIROM uses the Muskingum routing method. This approach considers the flow exiting a reach (or entering a control point downstream) is a function of the flow entering the reach during the given time and the flow entering and exiting the same reach in the previous time step. The flow through control point c at time t is calculated with the following expression (HEC, 2000):

$$Flow_{c,t} = \left(\frac{\Delta t - 2KX}{2K(1-X)+\Delta t}\right)Flow_{c-1,t} + \left(\frac{\Delta t + 2KX}{2K(1-X)+\Delta t}\right)Flow_{c-1,t-1} + \left(\frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}\right)Flow_{c,t-1}$$

When a control point is adjacent to a reservoir, the $Flow_{c-1}$ term is taken from the release of the reservoir. Additionally, the above equation is only used for control points that are connected (shown in Figure 1). Δt is equal to the time step interval (6 hours in this study). Values of X and K are found empirically for each river reach. The values used in the SVIROM were taken from "Application of Mixed Integer Programming for Flood Control in the Sacramento Valley: Insights and Limitations", (Jones 1997). When values were not defined for a reach, no routing was implemented for that river section.

INITIAL CONDITIONS

The flood routing and reservoir storage calculations require that flows in the channels and volumes in the reservoirs are initially defined. Initial reservoir storage volumes were provided from a previous study (Jones 1997). The initial flows in the channels were approximated using inflows to the reservoirs during the first two time steps. First, a reservoir's inflow during time step 0 was interpolated from the inflows from steps 1 and 2 using a conditional statement so that the initial flow is always the minimum of the three. This initial release in time step zero provides the initial flow to the adjacent control point where the incremental flow is calculated using the same interpolation technique. The next control point in turn receives the reservoir release and accumulates estimated incremental flow from upstream so that the initial flow in the channel increases along the river course.

OUTLET CURVES

The head at a reservoir and the size of its outlet structures determine the maximum release capacity for each time step. Since the stage of the reservoir determines the head, the maximum rate of reservoir release is a function of the water volume in storage. The SVIROM uses outlet curves to set maximum release rates for each reservoir. The size and number of outlets and spillways differ for each dam, so each reservoir has a unique outlet curve. Additionally, as storage and reservoir stage increases, additional spillways begin to crest, which increases the range of possible releases to a new maximum rate. Although in reality the outlet curves are non-linear functions of storage, the SVIROM approximates these functions as either one or two linear segments. The maximum release of each reservoir as a function of storage is plotted in Figure 2. The slope intercept of each line segment present on the graphs are used by the SVIROM to constrain release rates for given states of storage during model runs.

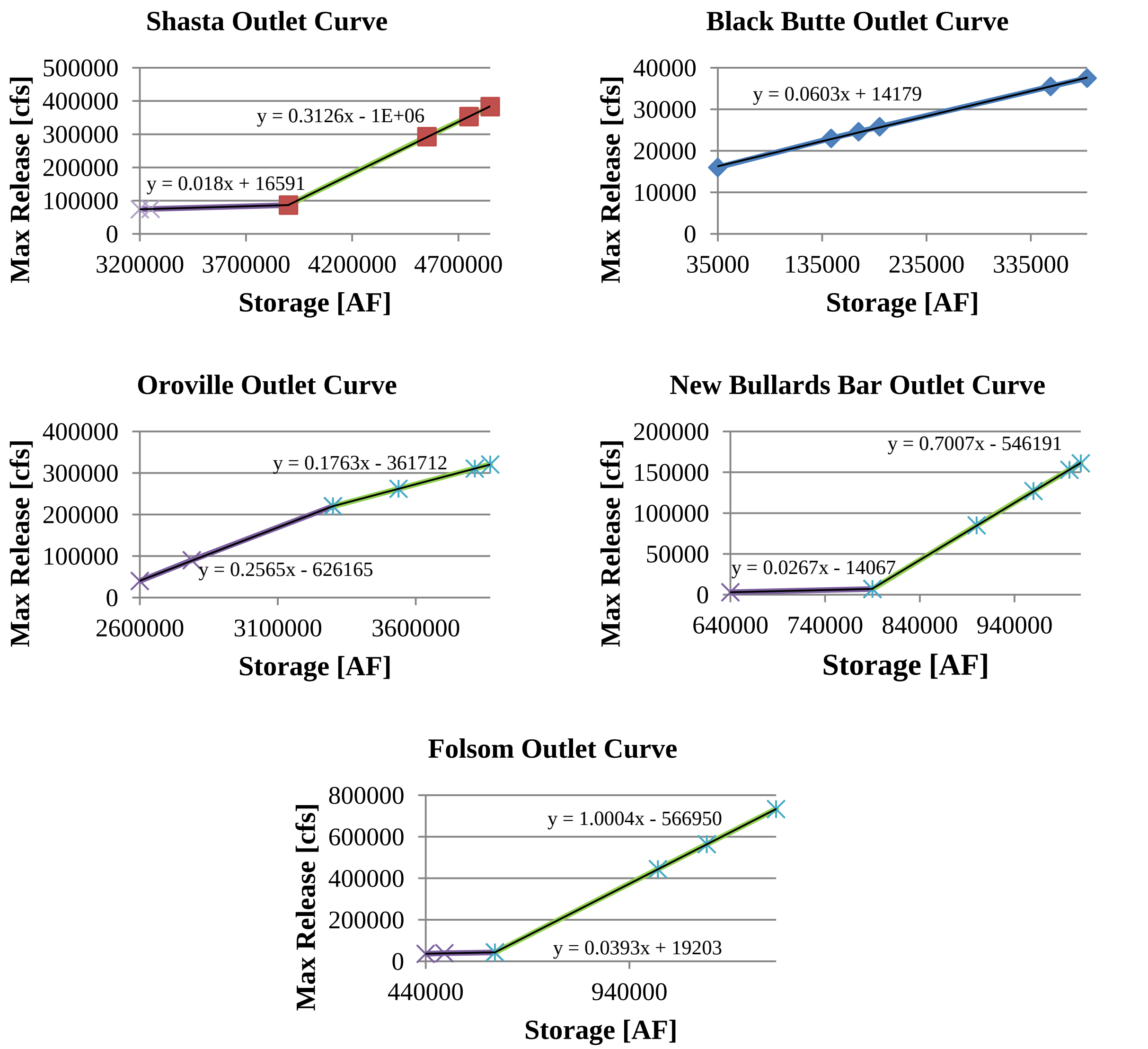

Figure 2. Linear Reservoir Outlet Rating Curves

PENALTIES

Penalties drive the SVIROM optimization and ultimately form the basis for the time series of reservoir releases. Penalties are preferred over hard constraints because greater freedom expands the solution space and may lead to a better solution. The SVIROM implements three types of penalties: reservoir storage, storage ramping and flow exiting a control point. Penalties are assessed for each reservoir and each control point during every time step.

Set parameters determine the severity of the penalty accumulated. No penalty is accumulated if the set parameters are not violated. Storage and flow penalties increase non-linearly as the degree of parameter violation increases. However, since a linear program cannot handle exponentials, penalty functions are approximated with piece-wise-linear functions, which discretize a non-linear convex function's input value and assume a constant linear derivative for each discrete segment. The combined linear functions form a single continuous function with an integral approximately equal to that of the non-linear convex function. Figure 3 shows an example of a convex cost function and its piece wise linear approximation.

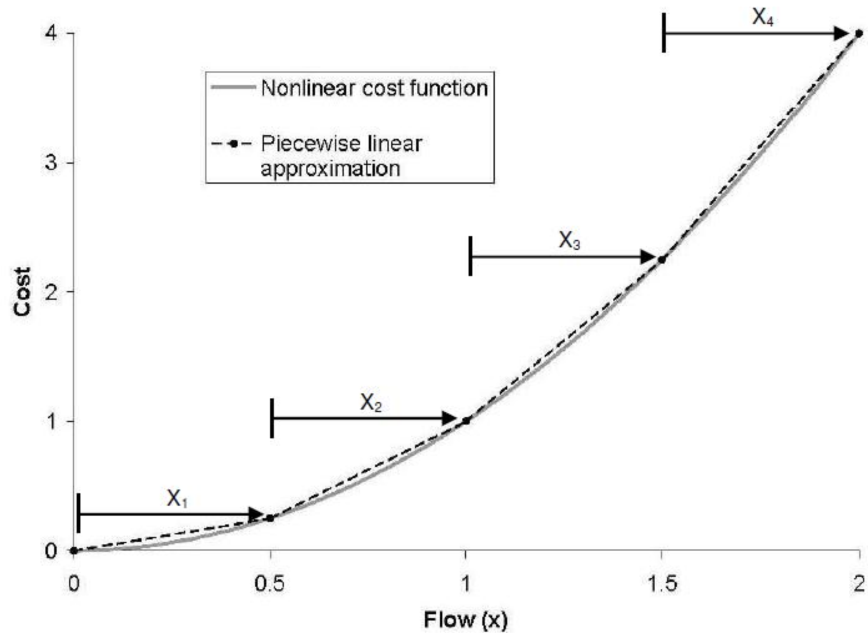

Figure 3. Piece-Wise Linear Approximation of a Convex Cost Function (USACE Hydrologic Engineering Center, 2000)

Storage Penalties

Reservoir operators try and maintain the volume in the reservoir within a specified range to avoid water shortages and to prevent reservoir overtopping from a sudden flood wave. To reflect these operating principles, a penalty is accrued when the storage volume of a reservoir increases or decreases from a single ideal value. The storage penalty curve is convex and parabolic with a minimum value of zero corresponding to the ideal storage volume.

Storage Ramping Penalties

The SVIROM assigns penalties for excessive ramping of reservoir storage. In practice, operators try to limit the ramping up and down of reservoir elevations and releases to prevent sloughing of the reservoir and downstream channel banks. The SVIROM sets an acceptable range by which the storage may increase or decrease during a time period. A penalty accumulates linearly for exceeding either of these limits.

Flow Penalties

Each control volume receives a flow penalty based on the estimated damage curve for the region adjacent to the river section. Each control point is assigned a channel capacity based on estimated values (Jones, 1997). Flows leaving a control point that exceed channel capacity accumulate a penalty, while flows less than channel capacity do not. Additionally, control points adjacent to the reservoir receive low flow penalties if the flow decreases below a lower limit. Each control point receives a final penalty based on the maximum flow of the entire time series. In all cases, flow penalty curves are convex with a non-linear increase from zero at the channel capacity.

CONSTRAINTS

The SVIROM requires constraints to uphold mass balances and allow weir diversions from control points. These hard constraints only limit the system from performing physical impossibilities. The SVIROM also used constraints to discretize variables for assigning penalties using a piece-wise-linear approximation. The following section outlines and explains the constraints used in the SVIROM:

Reservoir Constraints

The following hard constraints establish the direction of flow and prevent the reservoirs from releasing more than the outlet capacity.

$Release_{r,t} \geq 0$ *for all reservoirs r and all times t*

(Releases cannot be negative)

$Release_{r,t} \leq Outlet_{r,t} = f(Storage_r)$ *for all reservoirs r and all times t*

(A reservoir cannot release more water than the outlet capacity)

Weir Diversion Constraints

Weir diversion functions are concave and therefore require binary variables to be solved. Without binary variables the SVIROM will divert water from the main channel over the weir regardless of the flow rate because this operation reduces flow penalties downstream in most cases. Using binary variables, the weirs divert zero flow from the channel until a specified flow rate is exceeded, at which time the water level in the channel would crest the weir.

The total flow leaving a control point with a weir is discretized into bins ($W_{r,t,i}$) so that a percentage of each bin ($\alpha_{c,i}$) can be allotted to the diversion and the rest to the channel. The first bin ranges from zero to the rate required to crest the weir, so that 0% of the water in this discretization will be diverted. The flow exceeding that necessary to crest the weir can then be divided between the channel and weir at a set proportion referred to here as the diversion percentage ($\alpha_{c,2}$).

$Flow_{c,t} = \sum_{j=1}^{n=2} W_{c,t,i}$ *for all control points c and all times t*

(Sum of the values in the bins equals the total flow leaving a control point)

$W_{c,t,i} \geq 0$ *for all control points c, times t and bins i*

(The value in a bin cannot be negative)

$W_{c,t,i} \leq C_{w,i}$ *for all control points c, times t and bins i*

(The value in a bin cannot exceed the capacity of the bin)

$\psi_{c,t,n} = Binary\ (\epsilon\ 0,1)$ $n=1$ *for all control points c and times t*

(For each time step, each control point with a weir is assigned n binary variables for n+1 bins)

$W_{c,t,i} \geq (\psi_{c,t,i})(C_{w,i})$ *for all control points , times t and bins i*

(A bin must fill to capacity before the sequential bin begins to fill)

$W_{c,t,i+1} \leq (\psi_{c,t,i})(C_{w,i+1})$ *for all control points c, times t and bins i*

(A sequential bin will remain zero until the previous bin fills)

Once the bins are filled properly, the following expressions are used to allocate water to the downstream channel and weir diversion. For control point c at time t using the variables $W_{r,t,I}$ and $\alpha_{c,i}$. the allocations are:

$$\textit{\textbf{Weir Diversion}}_{c,t} = \sum_{i=1}^{n=2} (W_{c,t,i})(\alpha_{c,i})$$

$$\textit{\textbf{Downstream Channel flow}}_{c,t} = \textit{\textbf{Total Inflow}}_{c,t} - \textit{\textbf{Weir Diversion}}_{c,t}$$

where : $\alpha_{c,1} = 0$

$0 < \alpha_{c,2} < 1$

Storage Penalty Constraints

A piece-wise-linear function discretizes each reservoir's storage volume into six bins ($S_{r,t,j}$). The bins' intervals are determined from the penalty curve of the reservoir. Each bin has a capacity equal to the range of the interval ($C_{r,i}$). The storage penalty constraints are as follow:

$\text{Storage}_{r,t} = \sum_{j=1}^{n=6} S_{r,t,j}$ *for all reservoir r and times t*

(Sum of the values in all the bins equals the total storage volume)

$S_{r,t,j} \geq 0$ *for all reservoirs r, times t and bins j*

(The value in a bin cannot be negative)

$S_{r,t,j} \leq C_{r,j}$ *for all reservoirs r, times t and bins j*

(The value in a bin cannot exceed the capacity of the bin)

Storage Ramping Penalty Constraints

Ramping penalties used a piecewise linear function and discretize the change in storage from one time step to the next into four bins. Two bins are allotted to negative ramping ($R_{r,t,k}^-$) and two allotted to positive ramping ($R_{r,t,k}^+$). The capacity of the first positive bin equals the acceptable range of positive ramping rates ($C_{r,1}^+$), and any additional positive ramping is allotted to $R_{r,t,2}^+$. The negative ramping bins are structured similarly. The ramping constraints are as follow:

$\text{Storage}_{r,t} - \text{Storage}_{r,t-1} = \sum_{j=1}^{n=2} R_{r,t,k}^+ + \sum_{j=1}^{n=2} R_{r,t,k}^-$ *for all reservoirs r and times t*

(Storage Ramping must equal the sum of the positive and negative bins)

$R_{r,t,k}^{+} \geq 0$ *for all reservoirs r, times t and bins k*

(Positive bins cannot contain negative values)

$R_{r,t,k}^{-} \leq 0$ *for all reservoirs r, times t and bins k*

(Negative bins cannot contain positive values)

$R_{r,t,1}^{+} \leq C_{r,1}^{+}$ *for all reservoirs r and times t*

(Positive ramping values within the acceptable range are allotted to the first positive bin)

$R_{r,t,1}^{-} \geq C_{r,1}^{-}$ *for all reservoirs r and times t*

(Negative ramping values within the acceptable range are allotted to the first negative bin)

Flow Penalty Constraints

The flow constraints are formulated similarly to the storage constraints. The flow leaving a control point in the main channel is discretized into four bins based on the penalty curve for that location. The constraints for the flow penalties at each control point are as follow:

$Flow_{c,t} = \sum_{m=1}^{n=4} F_{c,t,m}$ *for all control points c and times t*

(Sum of the values in all the bins equals the total flow in the channel)

$F_{c,t,m} \geq 0$ *for all control points c, times t and bins m*

(The value in a bin cannot be negative)

$F_{c,t,m} \leq C_{c,m}$ *for all control points c, times t and bins m*

(The value in a bin cannot exceed the capacity of the bin)

Maximum Flow Penalty Constraints

The maximum flow penalty uses the same formulation but different penalty curve to give an extra penalty to the greatest flow through the control point during the time series. The maximum flow penalty constraints are as follow:

$Max\ Flow_{c} \geq Flow_{c,t}$ *for all control points c and times t*

(The max flow of a control point must be greater than or equal to the flow at every time step)

$Max\ Flow_{c} = \sum_{q=1}^{n=4} M_{c,q}$ *for all control points c*

(Sum of the values in all the bins equals the max flow)

$M_{c,q} \geq 0$ *for all control points c*

(The value in a bin cannot be negative)

$M_{c,q} \leq C_{c,m}$ *for all control points c and bins q*

(The value in a bin cannot exceed the capacity of the bin)

OBJECTIVE FUNCTION

Once the SVIROM uses the constraints to define feasible reservoir storage volumes, ramping rates and control point flows into the appropriate bins, the spreadsheet calculates an overall objective function value, which is the sum of penalties on each aspect of system operation. Since the flow and storage bins fill in order, the sum of the bin's penalties nearly equals the value of the non-linear function. This process repeats, accumulating penalties each time step. The SVIROM minimizes the sum of all of the penalties for all time steps and since releases combine and flood routing affects flows downstream during sequential time steps, the SVIROM optimizes the reservoirs releases according to the penalty curves and inflow hydrographs. The SVIROM objective function is formulated as:

$$\text{Min } Z = \sum_{t=1}^{n=60}[\sum_{r=1}^{n=5}\sum_{j=1}^{n=6}(S_{r,t,j})(P_{r,j}) + \sum_{r=1}^{n=5}(\sum_{k=1}^{n=2}(R^{+}_{r,t,k})(P^{+}_{r,k}) + \sum_{k=1}^{n=2}(R^{-}_{r,t,k})(P^{-}_{r,k})) +$$
$$c=1n=24m=1n=4(Fc,t,m)(Pc,m)]+c=1n=24q=1n=4(Mc,q)(Pc,q)$$

Where: $S_{r,t,j}$ = Reservoir storage bin j of reservoir r at time t
$R_{r,tk}^{+}$ = Reservoir positive ramping bin k of reservoir r at time t
$R_{r,t,k}^{-}$ = Ramping negative ramping bin k of reservoir r at time t
$F_{c,t,m}$ = Flow bin m of control point c at time t
$M_{c,q}$=Max flow bin q of control point c
$P_{r,j}$ = Penalty for storage bin j of reservoir r
$P_{r,k}^{+}$= Penalty for positive ramping bin k of reservoir r
$P_{r,k}^{-}$= Penalty for negative ramping bin k of reservoir r
$P_{c,m}$=Penalty for flow bin m of control point c
$P_{c,q}$=Penalty for max flow bin q of control point c

WEIR SIMPLIFICATIONS

Larger numbers of binary variables used in the weir constraints greatly increase the computation time for SVIROM. Decreasing the number of binary variables drastically speeds up the SVIROM. The SVIROM must minimize the objective function for every combination of binary variables. A binary variable has two allowable values (0 or 1), so for n binary variables the SVIROM must optimize the system up to 2^n times. With 5 weirs and one binary variable for each of the 60 time steps the SVIROM must assess up to 2^{300} possible outcomes (2×10^{90}). Although a solution is feasible, the computation time is uncertain.

Initially, SVIROM was constructed with six diversions. When tested, SVIROM would not converge on a solution. A variety of solutions were implemented. First, the Ord Ferry Weir diversion was eliminated entirely. This diversion only occurs at extreme flow rates in the upper Sacramento River and so has little effect to the model's overall results, eliminating binary variables.

The weirs are simplified so that the percentage of water split between the channel and diversion remains constant regardless of the flow rate. This simplification reduces the required number of binary variables needed for a more complicated construction where the diversion percentage changes with the flow rate. Figure 4 demonstrates how a diversion of the SVIROM. During initial trials, once a weir begins to spill additional water is diverted to the bypass at the percentage $\alpha_{c,2}$, which is specific to the weir. Later, the SVIROM will optimize the $\alpha_{c,2}$ variables for each weir and each storm.

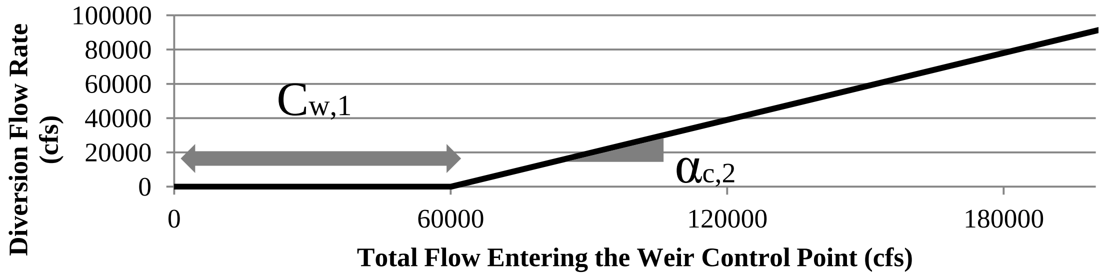

Figure 4. Example Weir Diversion Function and Parameters

To further eliminate binary variables, some of the weir equations were programmed into the spreadsheet rather than controlled by constraints. Binary variables are usually needed near the beginning of a flood at all weirs because initial flows are insufficient to crest any weir. However, the Colusa, Tisdale and Fremont weirs spill relatively easily and so an assumption was made that once crested these weirs will remain active for the remaining storm duration. This allows the diversion equation to be rigidly defined with formulas rather than decision variables and constraints for the remainder of the time series. Using the total inflow to the weir control point, the flow required to crest the weir ($C_{w,1}$) and the diversion percentage ($\alpha_{c,2}$), the weir diversion and downstream channel flow of control point c at time t are calculated with the following expressions:

$$\textbf{Weir Diversion}_{c,t} = (\textbf{Total Inflow}_{c,t} - C_{w,1})(\alpha_{c,2})$$
$$\textbf{Downstream Channel flow}_{c,t} = \textbf{Total Inflow}_{c,t} - \textbf{Weir Diversion}_{c,t}$$

This simplification can produce a globally optimal decision but requires iteration to assure that the weirs are functioning properly. Once a solution is found, the allotments of each weir must be inspected to assure that diversions are only made when the flow in the downstream channel exceeds $C_{w,1}$. If improper diversions are found, the weir constraints and binary variables must be changed to the appropriate time steps.

OUTLET CURVE SIMPLIFICATIONS

Similar to the weir diversions, outlet curve constraints require binary variables for a general formulation in a linear program. To avoid using binary variables, the SVIROM directly defines the segment of the outlet curve than constrains releases based on storage. First the SVIROM optimized the releases with no upper bound constraining outflow rates. Each reservoir begins with releases constrained by the first linear segment of the outlet curve. As storage increases the release constraints follow the first line to the junction with the second linear segment of the outlet curve. Through visual inspection of the releases and storage volumes, the point in the time series where this junction occurs is identified, and the release constraint is modified so that the second segment constrains releases for the remainder of the time series. This method requires iteration and inspection for accurate results but produces a globally optimal solution that obeys the physical constraints of the system.

COMPUTATIONAL PERFORMANCE

Model runs were performed using a 32-bit version of Lindo's "Whats Best" for Microsoft Excel 2007. "Whats Best" operates independently from the solver feature of Excel and creates an additional tab in the top ribbon of the screen, which allows the user to establish decision variables, constraints and the cell "Z" that is minimized. Decision variable cells cannot contain a formula, must contain an initial value and are specified and highlighted for the program to alter during optimization. Constraints are established as inequality functions in the worksheet's cells that refer to adjacent cells on the left and right. The cell "Z" contains a formulation of the objective function and is specified using the minimize button located in the "Whats Best" tab.

The SVROM's run times range from a few minutes to over an hour for different floods because the number of binary variables needed to assure the weirs function properly depends on the distribution and magnitude of the upstream flood. For floods in which the weirs initially and continuously divert water, binary variables are not needed and the run time is much less than for floods where the weirs take time to crest. The number of constraints and decision variables do not significantly affect the SVIROM's run time. Table 1 presents the number of decision variables, constraints, formulas, binary variables and run times required to model the three floods analyzed.

Table 1. Computation Statistics of the Linear Program for Each Flood Year

Flood Year	1986	1995	1997
Computation Time	1 hour 13 min 14 sec	9 min 6 sec	I hour 5 min 8 sec
Binary Variables	64	75	89
Decision Variables	9,177	9,210	9,252
Constraints	19,696	19,893	19,571
Formulas	34,459	34,722	33,884

RESULTS & ANALYSIS

The SVIROM was used to analyze the historical data from three of the most recent large floods in Northern California (1986, 1995 and 1997). The SVIROM shows when and where penalties were accumulated, which suggests weaknesses in the system and shows where improvements and upgrades would be most effective. Here, the floods are presented in the order of most severe (1997) to least severe (1995). The inflow volume to each reservoir and control point was tabulated to establish the flood's distribution over the watershed for each storm (Figures 5, 9 & 13 and Tables 2, 5 & 8). Plots of each reservoir's inflow, outflow and storage over time were constructed for interpretation along with a plot of the optimal releases superimposed upon each other and presented as Figures 6, 10 & 14. Peak flows and storage statistics from the reservoirs are presented for each year in Tables 3, 6 and 9. The flood waves routed downstream to the Fremont and Sacramento Weirs are plotted as Figures 7,11 & 15. Plots of the optimal downstream flood wave compared to unregulated flows are presented as Figures 8, 12 & 16 and Tables 4, 7 & 10. The unregulated flows were calculated with a simplified model which made reservoir releases equal to the inflow for each time step and implemented the same flood routing and weir diversions as the SVIROM model.

1997 FLOOD

The 1997 data spans from December 26th 1996 through January 10th 1997. The FCLP determined the **minimum penalty of 26,661,141** for this flood, ranking this the most damaging of the three. The region received a total inflow volume of 10,539 TAF over 15 days, of which 65% entered the five reservoirs.

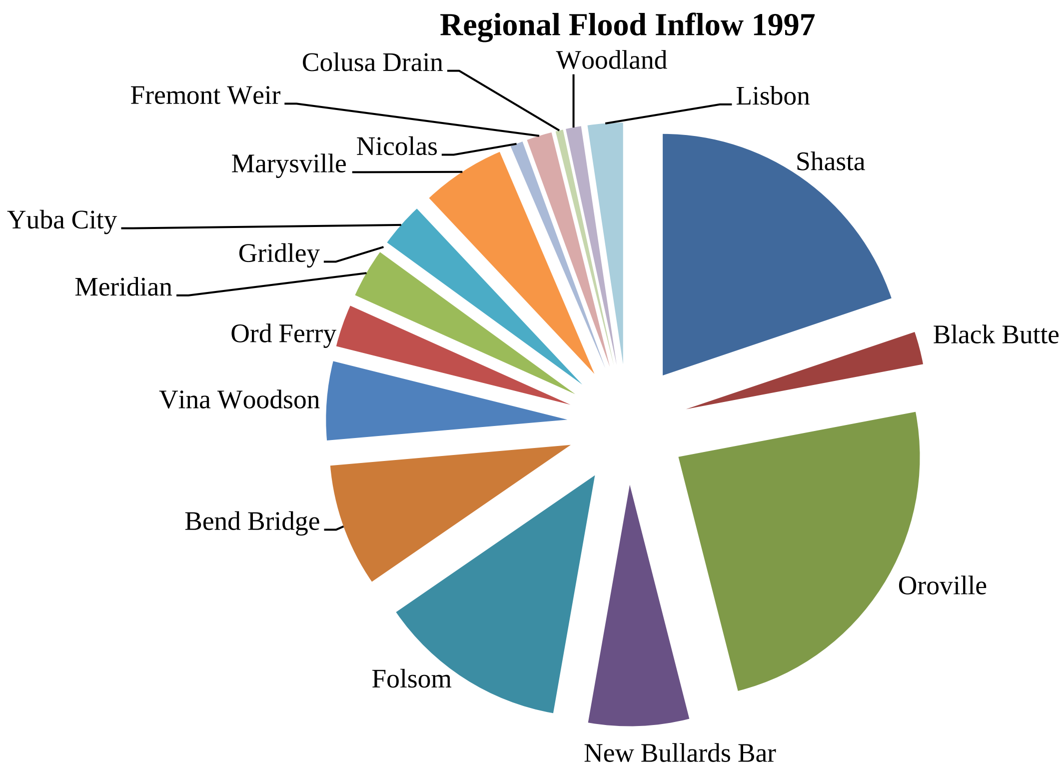

Figure 5. 1997 Regional Flood Distribution

Table 2. 1997 Regional Flood Distribution

	Region	Inflow Volume (TAF)	Percent of Total Volume
Reservoir Inflows	Shasta Reservoir	2,089	20%
	Black Butte Reservoir	231	2%
	Oroville Reservoir	2,531	24%
	New Bullard's Bar Reservoir	710	7%
	Folsom Reservoir	1,333	13%
Incremental Flows	Bend Bridge	866	8%
	Vina Woodson	555	5%
	Ord Ferry	298	3%
	Meridian	346	3%
	Gridley	0	0%
	Yuba City	314	3%
	Marysville	589	6%
	Nicolas	89	1%
	Fremont Weir	178	2%
	Colusa Drain	53	1%
	Woodland	108	1%
	Lisbon	248	2%
	Subtotal Unregulated Inflow	3,645	35%
	Total Inflow Volume	10,539	100%

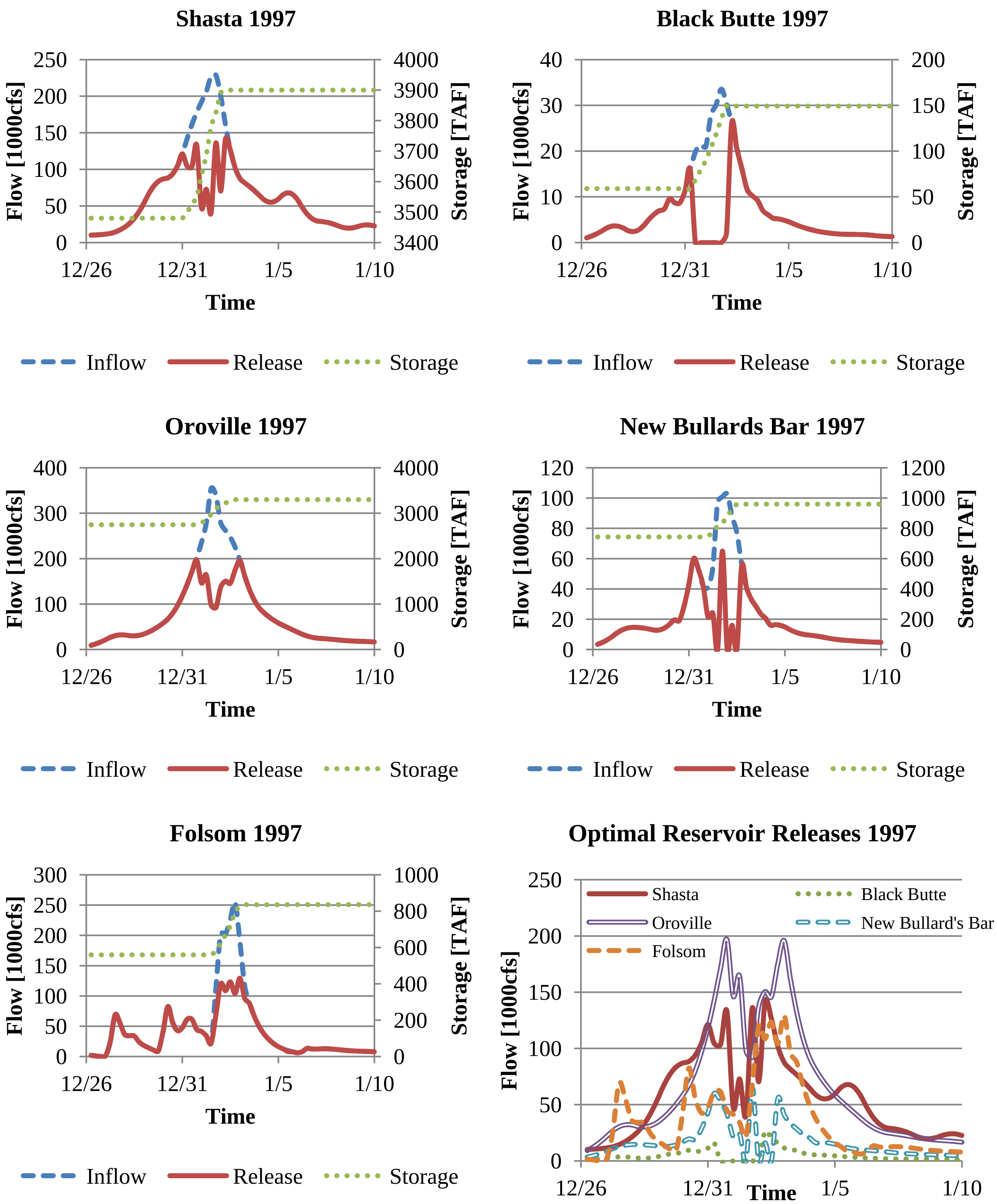

Figure 6. Optimal Reservoir Releases for the 1997 Flood

Table 3. 1997 Reservoir Operation Statistics

Reservoir	Shasta	Black Butte	Oroville	New Bullards Bar	Folsom
Peak Inflow (cfs)	228,649	33,531	354,122	102,639	254,129
Max Release (cfs)	141,561	26,056	196,913	65,013	129,325
Flow Reduction (cfs)	87,088	7,475	157,209	37,626	124,804
Flow Reduction / Peak Inflow	38%	22%	44%	37%	49%
Max Storage (AF)	3,900,000	149,224	3,300,000	960,000	835,965
Initial Storage (AF)	3,480,000	59,000	2,746,100	743,592	559,600
Storage Used (AF)	420,000	90,224	553,900	216,408	276,365
Storage Used/Initial Storage	12%	153%	20%	29%	49%

Reservoirs

The optimized reservoir releases reduce the peak flows in the downstream channels, while cooperating as part of an integrated system to reduce the combined peak flows where the channels converge at the Fremont and Sacramento Weirs. Flow Penalties at these locations cause SVIROM to synchronize reservoir releases to maintain a constant lower peak flow through these control points. Releases are alternated between reservoirs in waves following the determined release hydrographs for several reasons. The releases consider the accumulation of incremental flow along the river course, the travel time to the Fremont and Sacramento Weirs and the change in wave shape due to dissipation as flows are routed downstream.

The optimal releases are sometimes unintuitive but justified. During the intense period of a storm, both the reservoirs and local inflows reach their greatest magnitudes. Since the reservoirs cannot reduce incremental flows, and because incremental inflow account for 35% of the total flood volume, the reservoirs compensate by slowing and in the case of Black Butte, stopping releases entirely to maintain the flow at the Fremont Weir at the optimal rate.

Bypasses & Weirs

Flows from the Shasta, Black Butte, Oroville and New Bullard's Bar Reservoirs eventually converge along with incremental flow from the Sutter Bypass at the Fremont Weir. Optimal releases from these reservoirs combine at this convergence to create a steady flow rate that caps the flood peak for the duration of intense flooding. The controlled superposition of these upstream flows is apparent from Figure 7(a). The water not diverted to the Yolo Bypass at the Fremont Weir converges with the releases from Folsom Reservoir at the Sacramento Weir. After the model minimizes the peak flow to the Fremont Weir, releases from Folsom Reservoir are scheduled so that peak outflows arrive at the Sacramento Weir just before and just after the flood peak approaching from upstream. This operation caps the flood peak at the Sacramento Weir and decreases the peak flow by increasing the flood duration. Figure 7(b) shows the superposition of inflows to the Sacramento Weir control point.

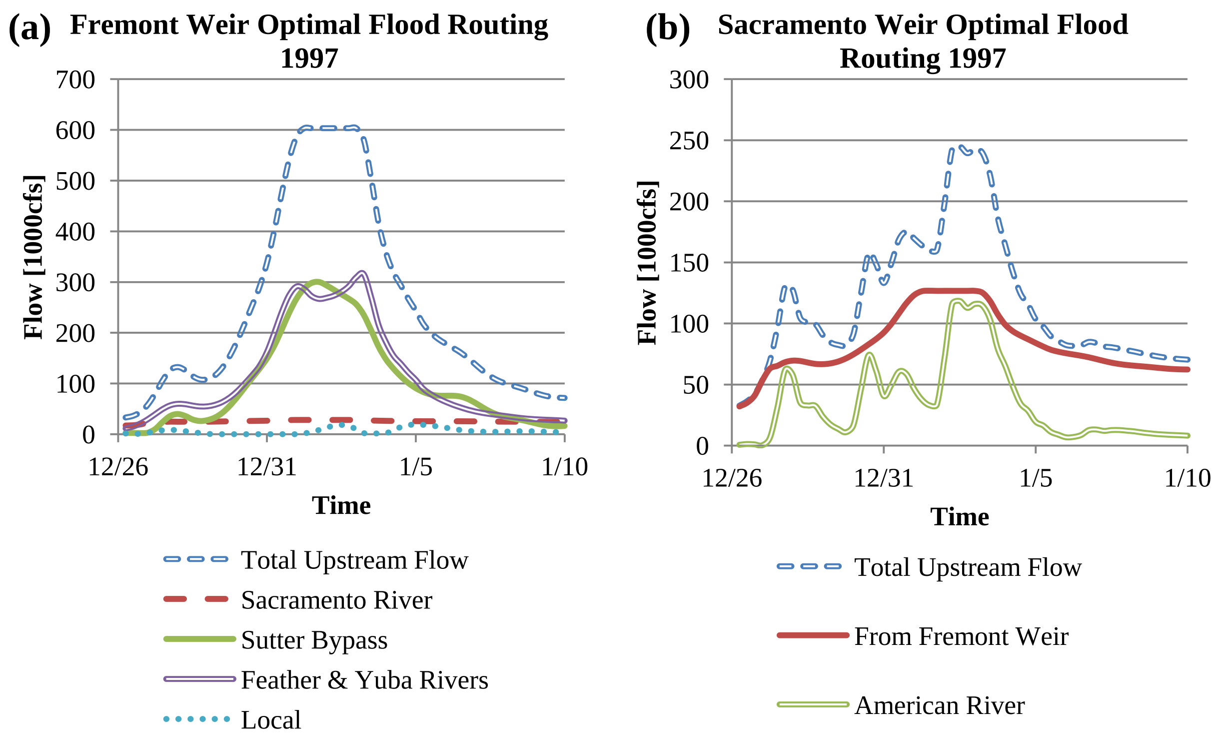

Figure 7. Optimal Flood Routing at the Fremont (a) and Sacramento (b) Weirs for the 1997 Flood

Flood reduction at the Fremont and Sacramento Weirs is apparent when compared to the flood wave produced with no simulated reservoir storage. Figure 8 presents the comparison of inflows simulated through the Fremont and Sacramento Weir control points respectively with optimal reservoir releases and an absence of reservoirs upstream. The no reservoir simulation was performed by setting the release equal to the inflow for each reservoir. Table 4 presents the statistics of the plots. Optimal reservoir operation during this flood reduced the flow through the river confluence control points considerably compared to that expected with no reservoir operation.

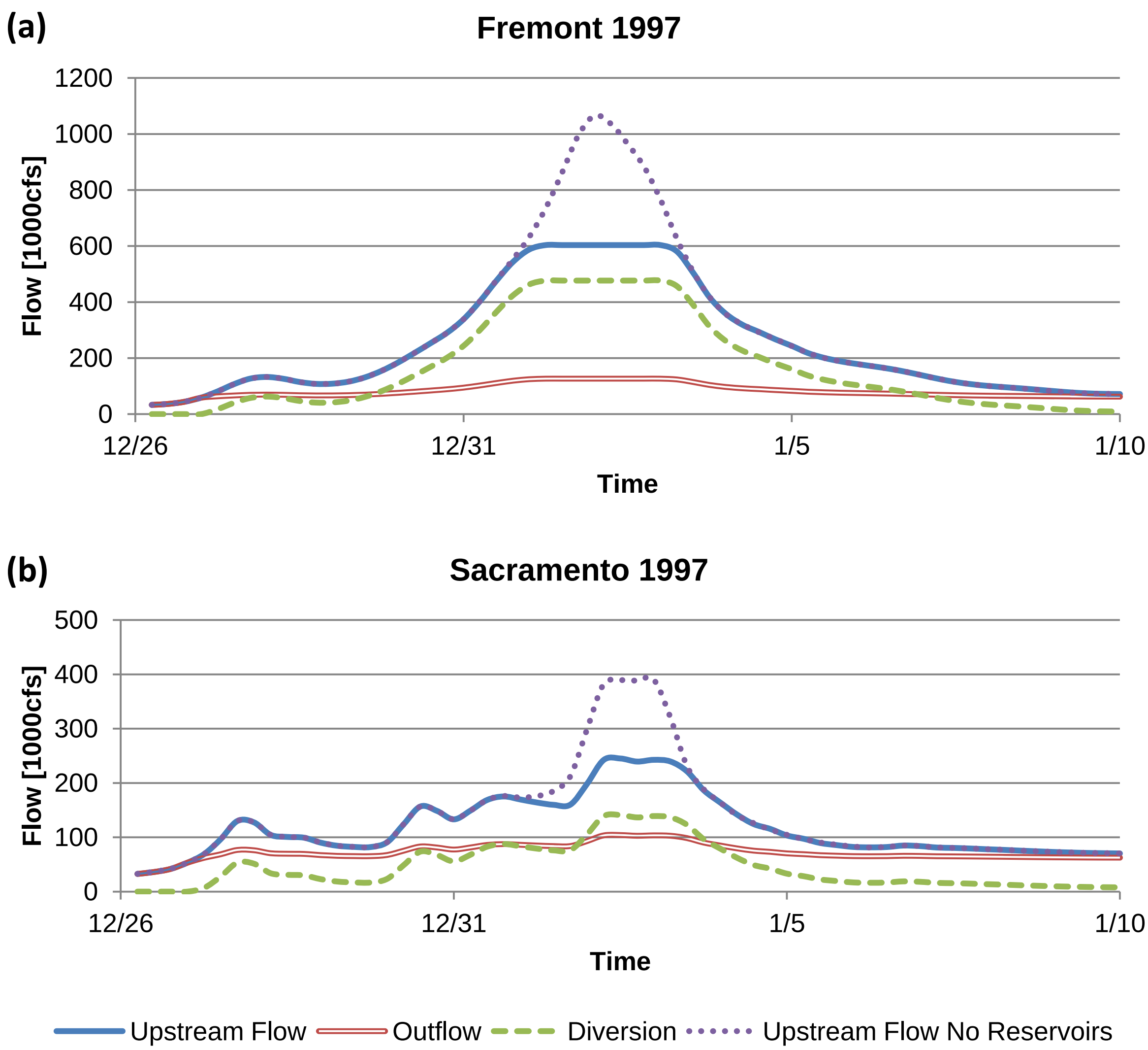

Figure 8. Comparison of No Reservoirs and Optimized Reservoir Releases Routed through the Fremont (a)and Sacramento (b) Weirs for the 1997 Flood

Table 4. 1997 Flood Reduction Statistics

Weir		Fremont	Sacramento
Max Flow With No Reservoirs	(cfs)	1,605,351	390,547
Max Inflow With Reservoirs	(cfs)	603,380	245,106
Flow Reduction From Reservoir Operation	(cfs)	461,971	145,441
Percent of Flow Reduced		43%	37%

1986 FLOOD

The 1986 data spans from February 10th to the 25th. The FCLP determined that the **minimum penalty of 23,690,433** for this flood. The flood had a total inflow of 10,322 TAF over 15 days, with 63% of the water arriving to the five reservoirs.

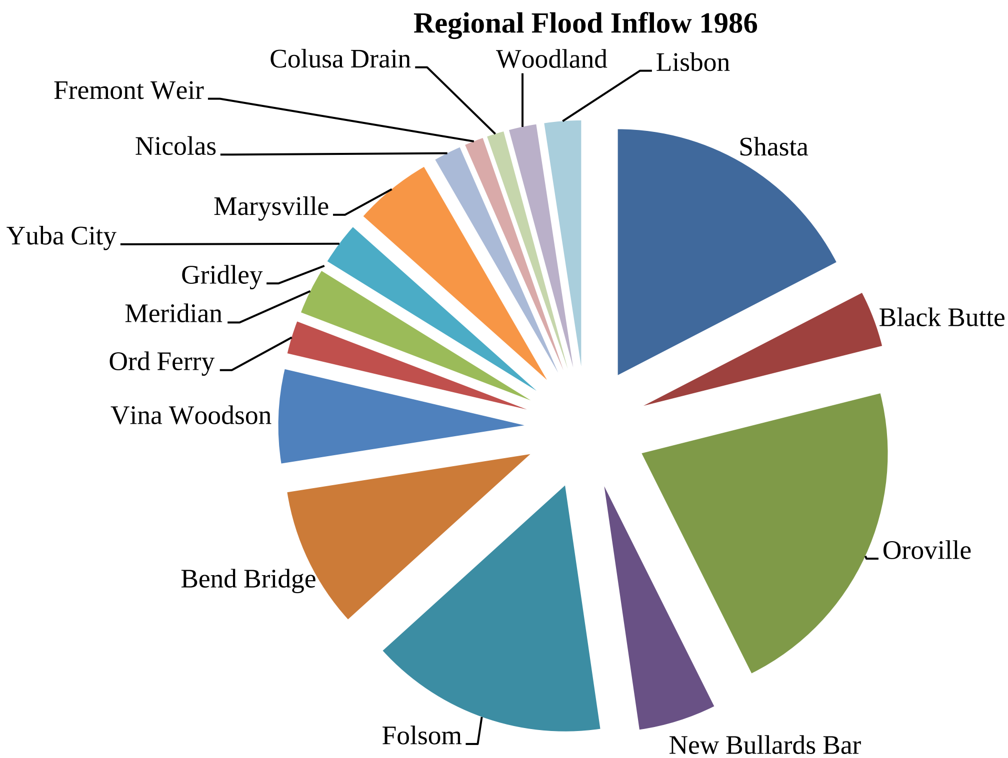

Figure 9. 1986 Regional Flood Distribution

Table 5. 1986 Regional flood Distribution

	Region	Inflow Volume (TAF)	Percent of Total Volume
Reservoir Inflows	Shasta Reservoir	1,796	17%
	Black Butte Reservoir	380	4%
	Oroville Reservoir	2,224	22%
	New Bullard's Bar Reservoir	525	5%
	Folsom Reservoir	1,606	16%
Incremental Flows	Bend Bridge	954	9%
	Vina Woodson	635	6%
	Ord Ferry	223	2%
	Meridian	310	3%
	Gridley	0	0%
	Yuba City	286	3%
	Marysville	524	5%
	Nicolas	184	2%
	Fremont Weir	127	1%
	Colusa Drain	115	1%
	Woodland	185	2%
	Lisbon	248	2%
	Subtotal Unregulated Inflow	3,791	37%
	Total Inflow Volume	10,322	100%

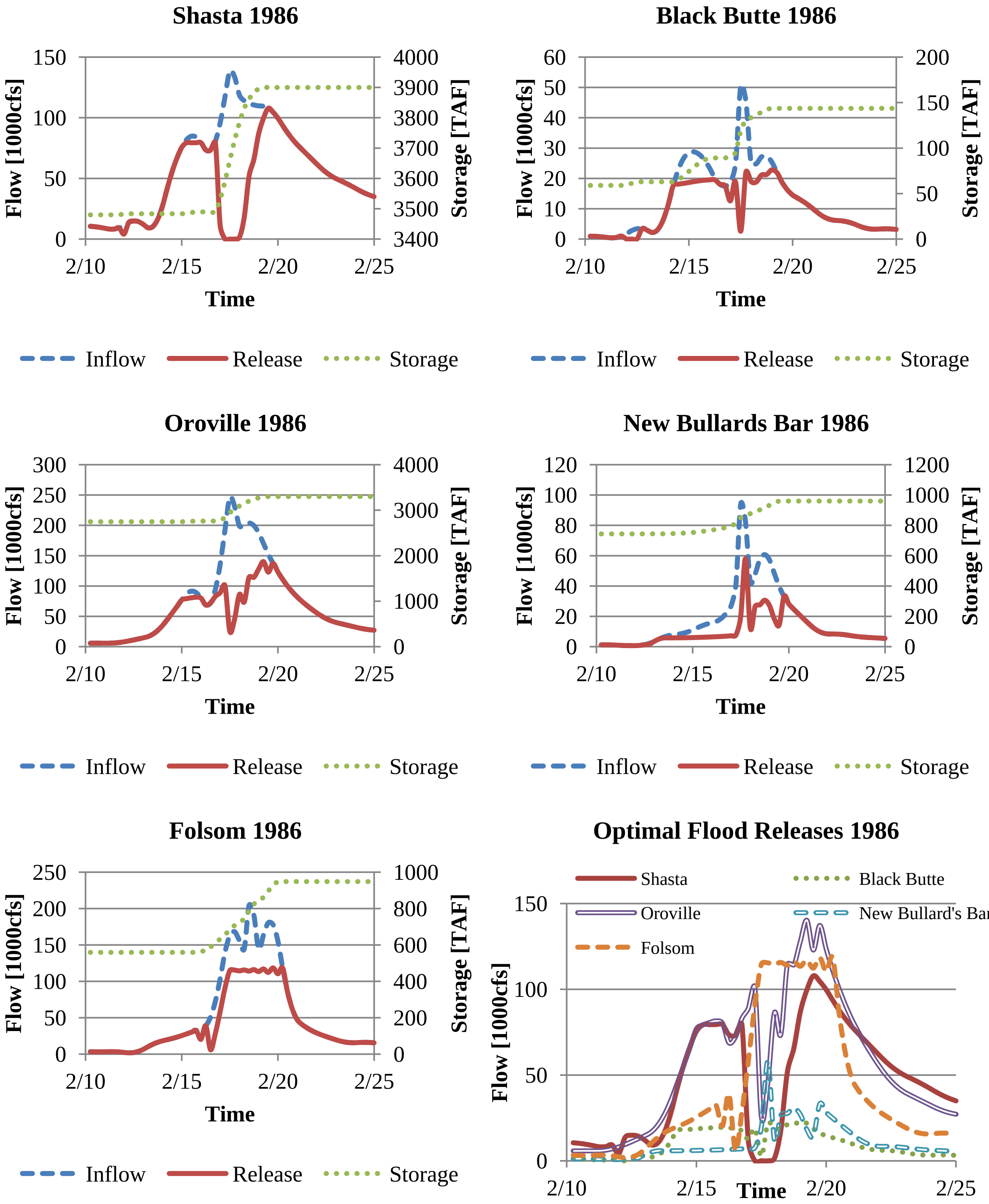

Figure 10. Optimal Reservoir Releases for the 1986 Flood

Table 6. 1986 Reservoir Operation Statistics

Reservoir	Shasta	Black Butte	Oroville	New Bullards Bar	Folsom
Peak Inflow (cfs)	138,463	50,534	245,869	93,924	204,045
Max Release (cfs)	107,799	22,843	140,249	58,064	118,491
Flow Reduction (cfs)	30,665	27,691	105,621	35,860	85,554
Flow Reduction/Peak Inflow	22%	55%	43%	38%	42%
Max Storage (AF)	3,900,000	143,676	3,300,000	960,000	948,026
Initial Storage (AF)	3,480,000	59,000	2,746,100	743,592	559,600
Storage Used (AF)	420,000	8,4676	553,900	216,408	388,426
Storage Used /Initial Storage	12%	144%	20%	29%	69%

Similar to the 1997 flood operation, the 1986 optimal reservoir operation stores water during the peak inflows to the reservoirs. The counterintuitive result of releasing the least amount of water during times of peak inflow occurs to make space in the downstream channels to accommodate incremental flows. Flows through the Fremont and Sacramento Weirs again drive the optimal reservoir releases. The flood peak is capped at a maximum through the Fremont Weir and Sacramento Weirs as shown in Figure 11. Folsom Reservoir caps the releases to a relatively constant value so as to not exceed channel capacity when the flow combines with the flood wave arriving from Fremont Weir.

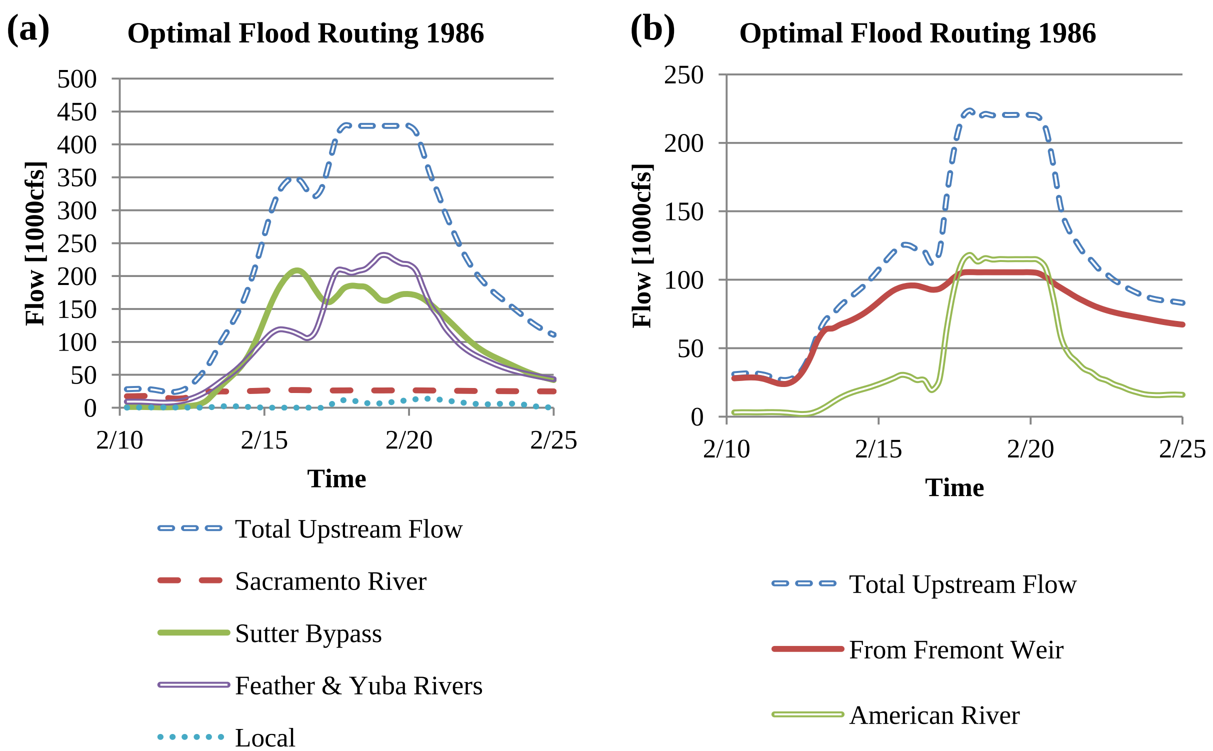

Figure 11. Optimal Flood Routing at the Fremont (a) and Sacramento (b) Weirs for the 1986 Flood

Optimal reservoir releases during the 1986 flood could not reduce peak flows as effectively as the 1997 flood. Figure 12 presents the flows through the Fremont and Sacramento control points with optimal reservoir releases and during the no reservoir simulation. Table 7 presents the maximum flow and flow reduction statistics for the 1986 flood. Peak flows could not be reduced as effectively because the duration of the 1986 flood was longer, and more distributed over time than the 1997 flood. The resulting no reservoir hydrograph is broader, which reduces the reservoirs' effectiveness in reducing the peak flows to the channel.

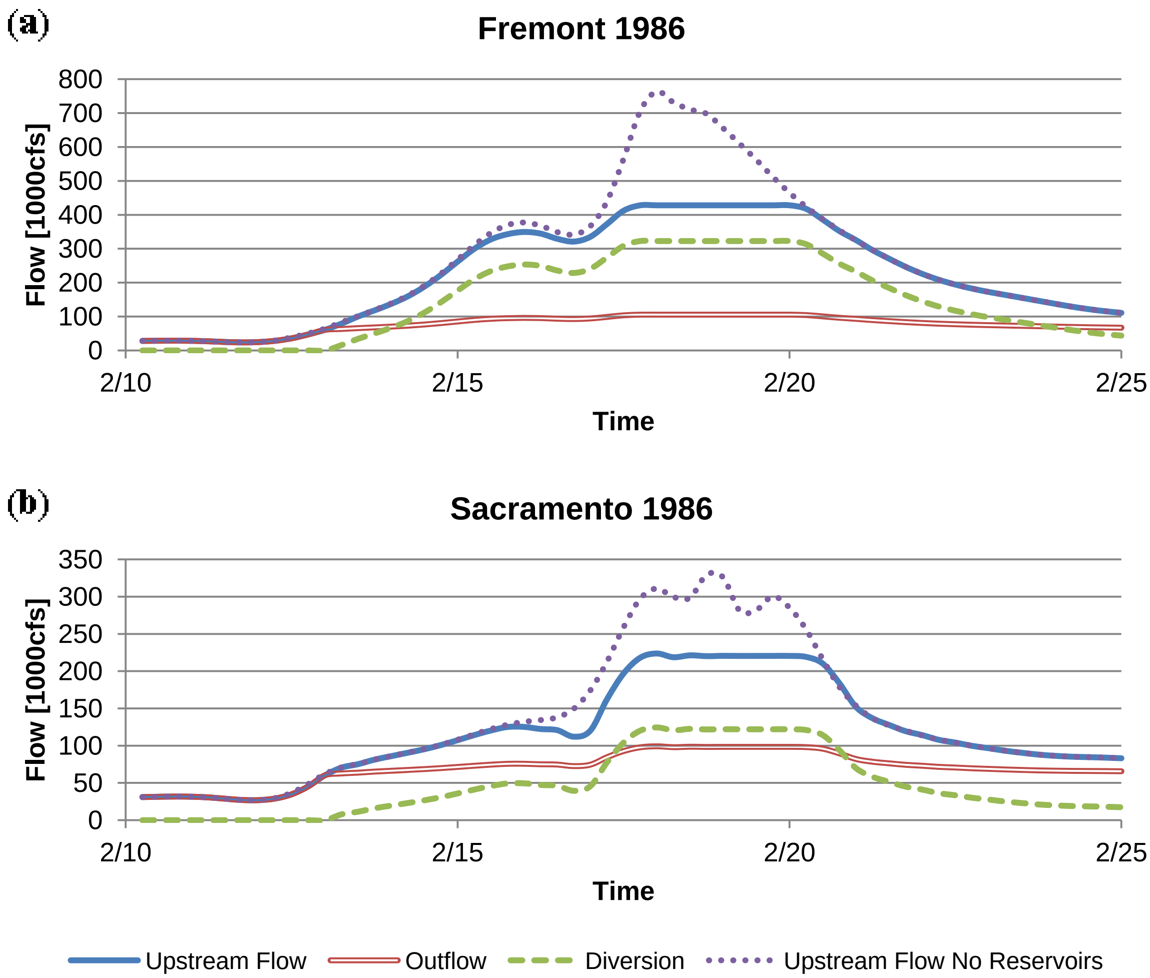

Figure 12. Comparison of No Reservoirs and Optimized Reservoir Releases Routed through the Fremont (a)and Sacramento (b) Weirs for the 1986 Flood

Table 7. 1986 Flood Reduction Statistics

Weir	Fremont	Sacramento
Max Flow With No Reservoirs (cfs)	763,661	329,241
Max Flow With Reservoirs (cfs)	428,252	223,660
Flow Reduction From Reservoir Operation (cfs)	335,409	105,580
Percent of Flow Reduced	44%	32%

1995 FLOOD

The 1995 data spans from March 8th through the 23rd. The FCLP determined that the **minimum penalty of 5,381,768** for this flood, ranking this the least damaging of the three floods analyzed. The region received a total of 8,942 TAF of inflow over 15 days, of which 51% was captured by reservoirs.

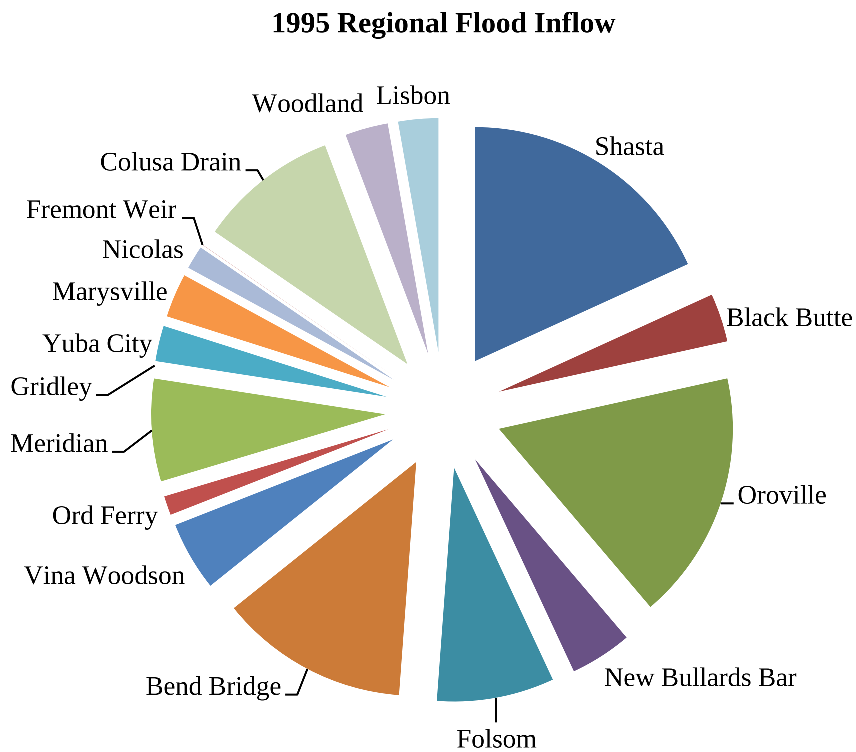

Figure 13. 1995 Regional Flood Distribution

Table 8. 1995 Regional Flood Distribution

	Region	Inflow Volume (TAF)	Percent of Total Volume
Reservoir Inflows	Shasta Reservoir	1,627	18%
	Black Butte Reservoir	299	3%
	Oroville Reservoir	1,542	17%
	New Bullard's Bar Reservoir	382	4%
	Folsom Reservoir	726	8%
Incremental Flows	Bend Bridge	1,169	13%
	Vina Woodson	429	5%
	Ord Ferry	118	1%
	Meridian	633	7%
	Gridley	0	0%
	Yuba City	220	2%
	Marysville	272	3%
	Nicolas	145	2%
	Fremont Weir	2	0%
	Colusa Drain	866	10%
	Woodland	266	3%
	Lisbon	247	3%
	Subtotal Unregulated Inflow	4,366	49%
	Total Inflow Volume	8,942	100%

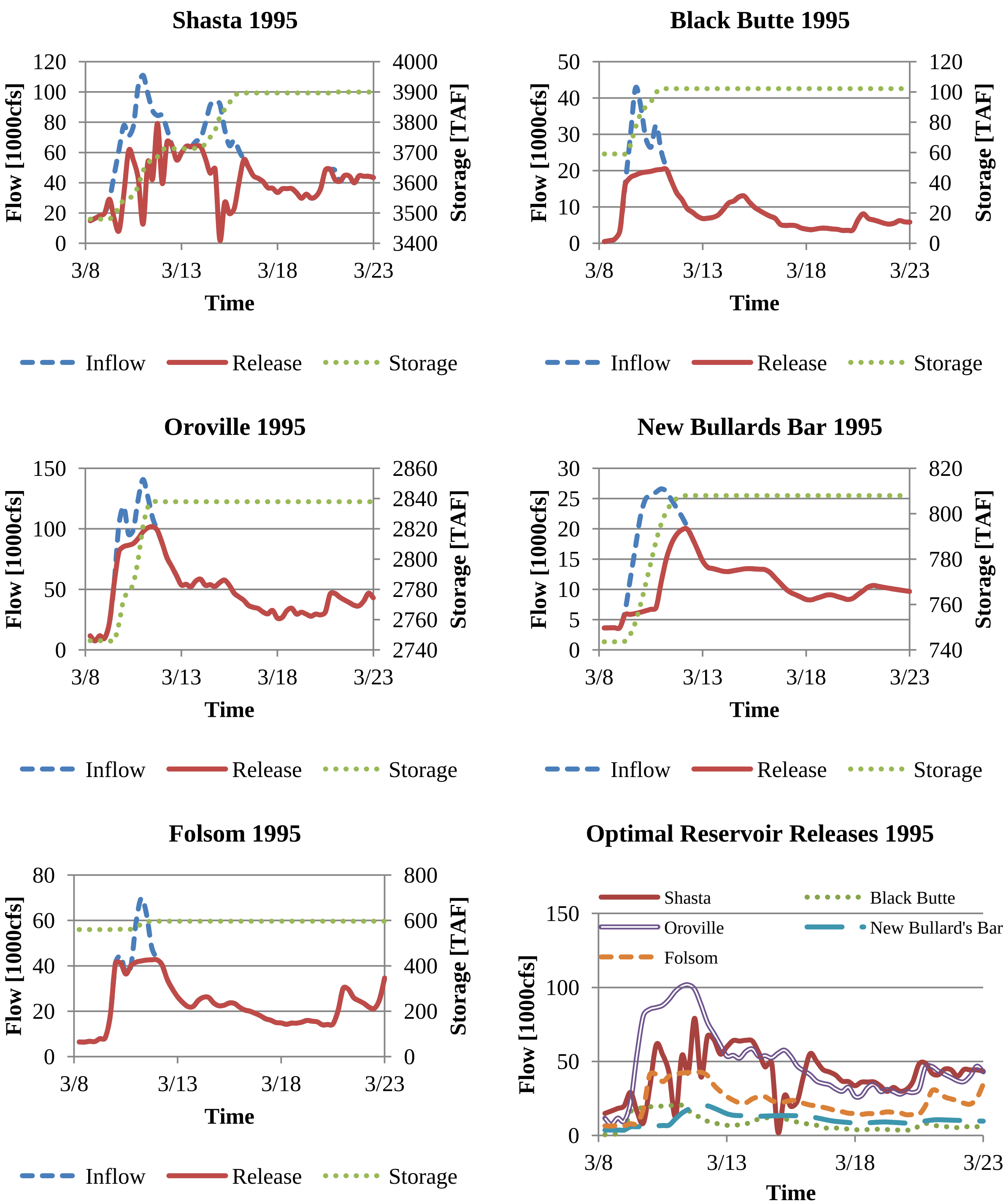

Figure 14. Optimal Reservoir Releases for the 1995 Flood

Table 9. 1995 Reservoir Operation Statistics

Reservoir	Shasta	Black Butte	Oroville	New Bullards Bar	Folsom
Peak Inflow (cfs)	110,982	42,650	140,748	26,600	69,783
Max Release (cfs)	79,171	20,340	101,773	19,973	42,659
Flow Reduction (cfs)	31,811	22,310	38,976	6,627	27,125
Flow Reduction/Peak Inflow	29%	52%	28%	25%	39%
Max Storage (AF)	3,900,000	102,172	2,837,964	807,998	596,833
Initial Storage (AF)	3,480,000	59,000	2,746,100	743,592	559,600
Storage Used (AF)	420,000	43,172	91,864	64,406	37,233
Storage Used /Initial Storage	12%	73%	3%	9%	7%

Once again, the SVIROM optimizes reservoir releases to cap the peak flow through the Fremont weir control point as shown in Figure 15. However during this relatively small flood the releases from Folsom are unregulated (outflow=inflow) for most of the flood duration. The maximum release from Folsom is constrained by the outlet curve and not penalties for flooding downstream. The inflows to the Sacramento Weir shown in Figure 15(b) are uncapped. This behavior further demonstrates the inference that the Fremont Weir has more impact on the SVIROM optimization than the Sacramento Weir. Reducing peak flows to the Fremont weir reduces flows to all other control points downstream, which form the initial basis for the optimization. Once flows through the Fremont weir are established, the releases from Folsom are determined. Folsom release calculations are therefore more independent in the optimization than the other reservoirs since they do not affect damages upstream.

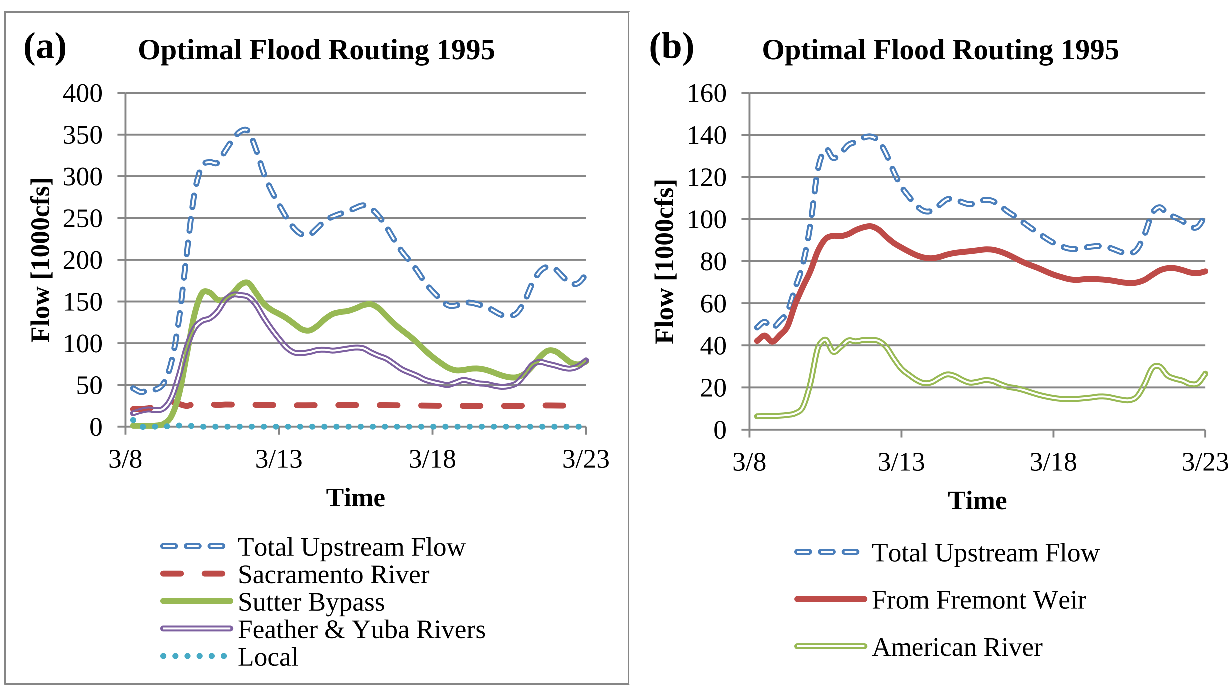

Figure 15. Optimal Flood Routing at the Fremont (a) and Sacramento (b) Weirs for the 1995 Flood

Figure 16 presents the optimized flows through the Fremont and Sacramento Weirs respectively compared to the no reservoir case. Table 10 presents the peak flow and peak flow reduction statistics of the plots. In this case, minimizing the flood peak through the Sacramento Weir was sub-optimal because of the penalty accumulated in Folsom reservoir for excessive storage.

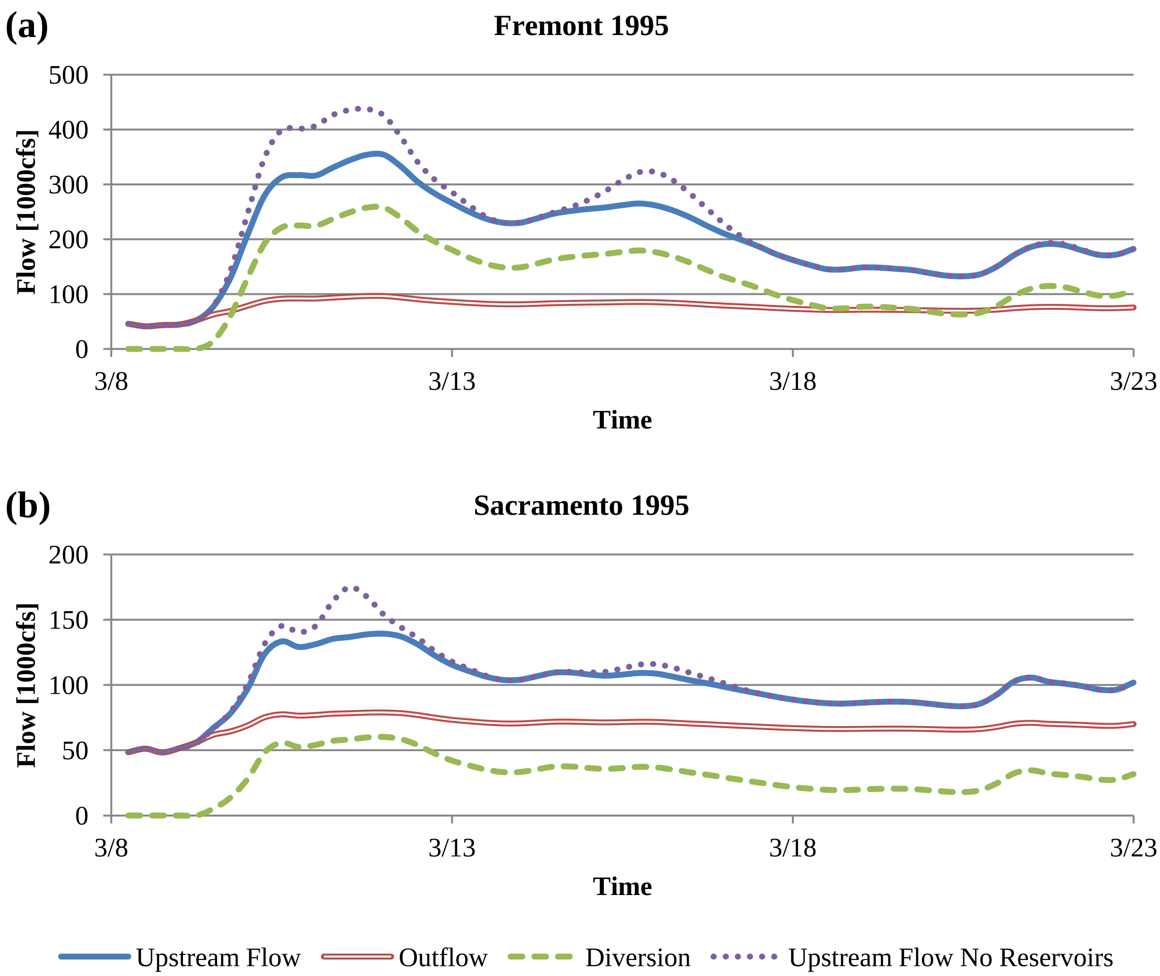

Figure 16. Comparison of No Reservoirs and Optimized Reservoir Releases Routed through the Fremont (a)and Sacramento (b) Weirs for the 1995 Flood

Table 10. 1995 Flood Reduction Statistics

Weir	Fremont	Sacramento
Max Flow With No Reservoir (cfs)	437,463	174,843
Max Flow With Reservoirs (cfs)	354,132	139,226
Flow Reduction From Reservoir Operations (cfs)	83,331	35,617
Percent of Flow Reduced	19%	20%

MODEL COMPARISON

The SVIROM's optimization operates the reservoirs differently from the HEC ResSIM simulation model and the previous FCLP optimization model. Although the three models use the same routing parameters, differences in the release rules, weir formulas and channel parameters cause variations in the resulting downstream flood waves. HEC ResSIM implements reservoir releases according to the actual operating rules of the individual reservoirs. The optimized releases of the SVIROM and FCLP models ignore these operating rules. The HEC ResSIM model diverts water at the weirs in accordance to non-linear diversion functions. The FCLP model uses piece wise linear functions to regulate the weir diversions; however errors in the programming cause inconsistent and sometimes faulty diversions to occur. The FCLP model also changed the weir parameters that implement the diversions from the HEC ResSIM model. The SVIROM model uses the same weir diversion parameters as the HEC ResSIM model, but uses simple linear diversion functions that were interpolated from the HEC ResSIM weir diversion functions. Figure 17 shows the diversion functions of the three models for the Sacramento Weir. Although the FCLP was programmed to implement the shown function, actual diversions did not follow the path shown.

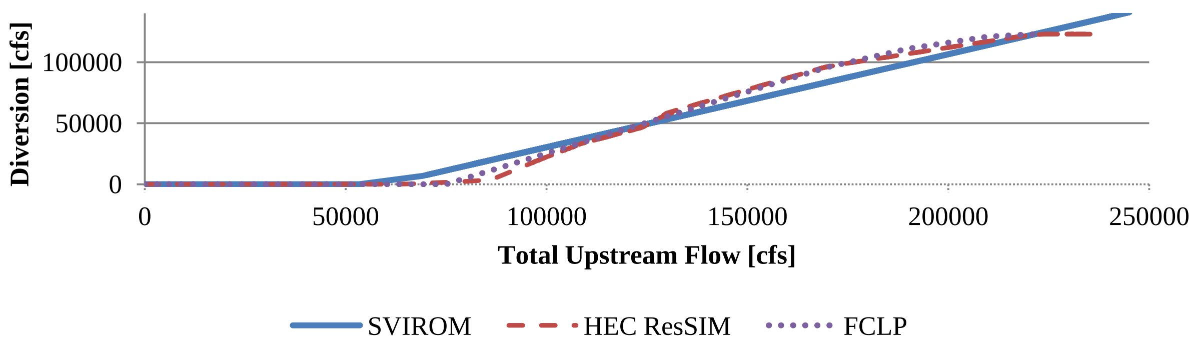

Figure 17. Sacramento Weir Diversion Functions for the SVIROM, HEC ResSIM and FCLP models.

The reservoir release results of the HEC ResSIM, SVIROM and FCLP models and observed flood flows for the 1997 flood are plotted for comparison. Table 11 summarizes of the comparison of the three models and observed results. Criteria were based on visual inspection of Figures 18 through 24.

Table 11. Summary of the Comparison of Results for the SVIROM, HEC-ResSIM, FCLP and Observed Flows for the 1997 Flood Based on Figures 18 through 24

		Model								
		HEC-ResSIM			FCLP			Observed		
	Location	Peak Flow	Time of Peak	Shape	Peak Flow	Time of Peak	Shape	Peak Flow	Time of Peak	Shape
Reservoir	Shasta	Differs	Similar	Differs	Differs	Similar	Differs	Differs	Similar	Differs
	Black Butte	Differs	Similar	Differs	Differs	Same	Similar	Differs	Same	Differs
	Oroville	Differs	Similar	Similar	Similar	Similar	Differs	Differs	Differs	Differs
	New Bullards Bar	Differs	Similar	Differs	Differs	Differs	Differs	Similar	Similar	Differs
	Folsom	Similar	Same	Similar	Similar	Same	Similar	Similar	Same	Similar
Weir	Fremont	Differs	Same	Similar	Differs	Same	Similar	Differs	Same	Similar
	Sacramento	Similar	Same	Similar	Similar	Differs	Differs	Differs	Same	Differs

The model results do not align in most cases, however some trends are observed. The SVIROM does not make pre releases and instead makes unregulated releases prior to and after the flood peak has arrived. The HEC ResSIM model does not make pre-releases, but does evacuate water from reservoir storage after the flood peak has subsided. Another difference between the HEC ResSIM model and SVIROM is that the SVIROM model anticipates and compensates releases for local inflows downstream, resulting in minimum releases during the flood peak. The FCLP model makes prereleases to increase flood storage volume and evacuates flood storage after the flood peak has subsided.

Differences in the results are likely caused from multiple factors. Variations in the model routing and diversion formulations and parameters likely caused discrepancies in the results. Errors in the FCLP weir diversions caused the model to route the water through the system in ways that are physically impossible, creating chaotic behavior in some cases. Even if these errors had not occurred, the FCLP and SVIROM models used different solvers during computation, which could affect the results if multiple optima exist. The ResSIM model releases water based on a set of reservoir operating rules and since the SVIROM model is not constrained by operating rules other that the outlet curves, the releases and resulting flood waves of the two models would only match if the current operating rules are optimal in reducing the penalties of the SVIROM model.

Shasta Releases Comparison

Figure 18 presents the models' Shasta reservoir release hydrographs for the 1997 flood. SVIROM releases are double that of the other models for most of the time series. However, all three models and the observed decrease the release rate during the flood peak. In this case, the ResSIM, FCLP and observed releases match closely to one another, while the SVIROM releases diverge from the other results considerably.

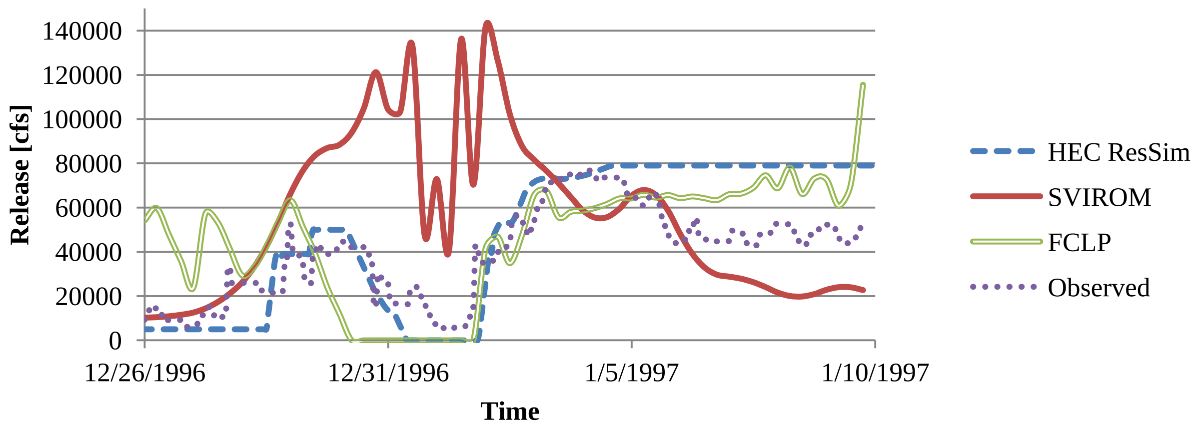

Figure 18. Comparison of Shasta Reservoir Releases of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood.

Black Butte Releases Comparison

Figure 19 presents the models' Black Butte reservoir release hydrographs for the 1997 flood. SVIROM and the FCLP nearly eliminate all flow during the flood peak to compensate for incremental flows downstream while HEC ResSIM only caps the flood peak. The SVIROM releases deviate from the other models and the observed releases because of the spikes before and after the flood peak. The other models do not ramp the release rate as much as the SVIROM and begin to store water earlier.

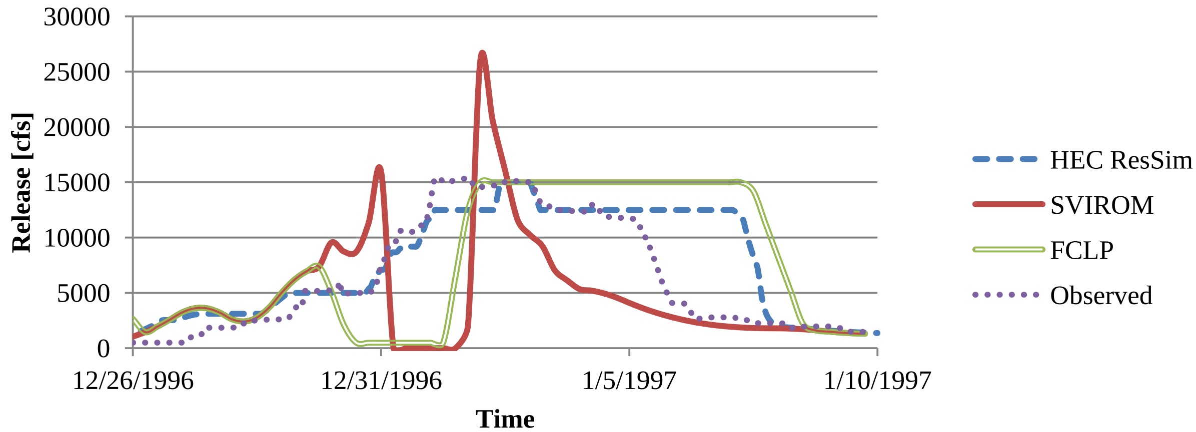

Figure 19. Comparison of Black Butte Reservoir Releases of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood.

Oroville Releases Comparison

Figure 20 presents the models' Oroville reservoir release hydrographs for the 1997 flood. In this case the models results generally follow the same trend. The peak release of the SVIROM model falls between that of the FCLP and HEC ResSIM models peak releases and occurs at roughly the same time. All three models decrease the release rate to approximately the same value near the arrival of the flood peak. However, the FCLP and HEC ResSIM models begin to store water before the SVIROM, and evacuate the flood storage pool after the inflows begin to subside.

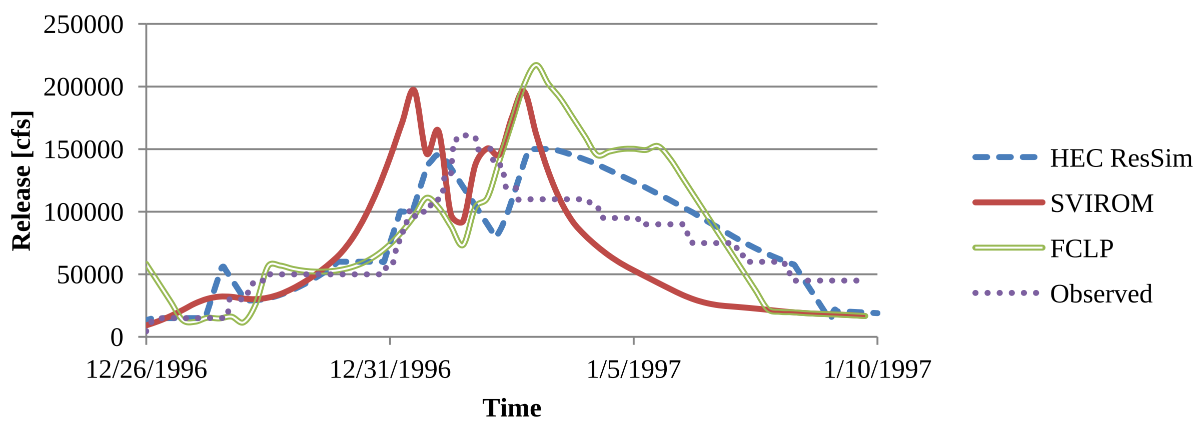

Figure 20. Comparison of Oroville Reservoir Releases of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood.

New Bullards Bar Releases Comparison

Figure 21 shows the models' New Bullards Bar reservoir release hydrographs for the 1997 flood. Again the SVIROM and FCLP decrease releases during the flood peak to compensate for incremental flow downstream. The FCLP and HEC ResSIM release more water from this reservoir at higher maximum flow rates than the SVIROM. Again, the FCLP and HEC ResSIM begin to store water before the SVIROM begins to regulate releases.

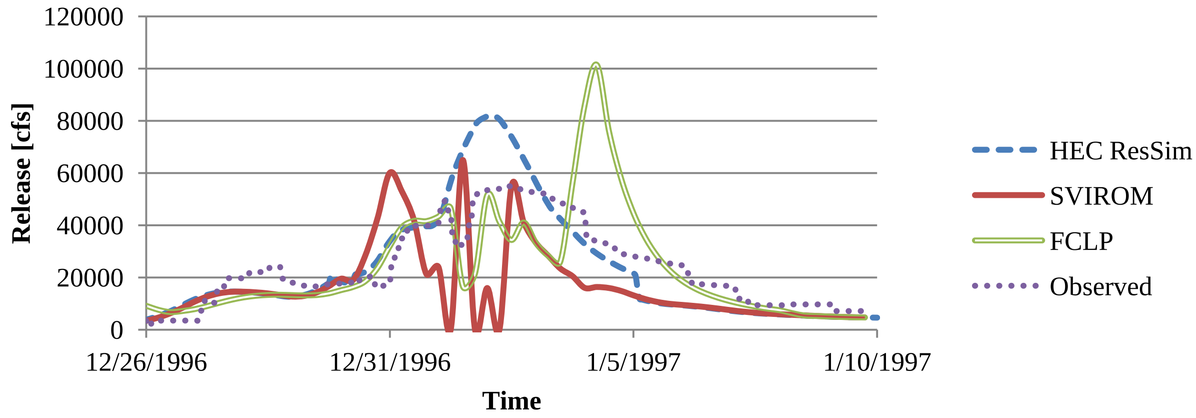

Figure 21. Comparison of New Bullards Bar Reservoir Releases of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood

Folsom Releases Comparison

Figure 22 shows the models' Folsom reservoir release hydrographs for the 1997 flood. Here the models' results align reasonably well. The maximum release rate, which caps the flood peak is approximately the same for all three models and the observed release. However, the duration of the maximum release is less for the SVIROM because after the flood peak the release is matched to the reservoir inflow, while the other models evacuate the flood storage pool. The HEC ResSIM does not ramp the release rate as much as the SVIROM which results in less spikes and smoother transitions when the flow rate is altered.

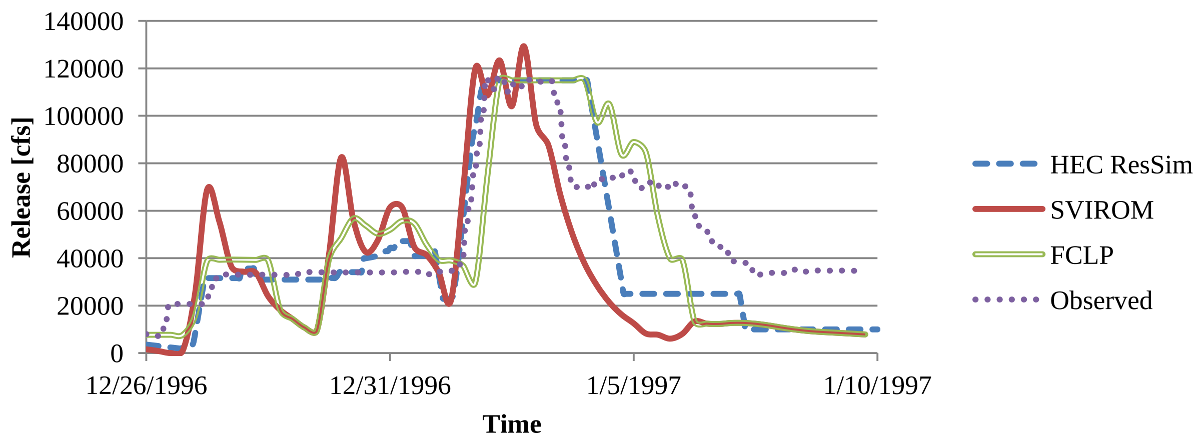

Figure 22. Comparison of Folsom Reservoir Releases of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood

Fremont Weir Diversion Comparison

The reservoir releases directly affect the weir diversion hydrographs downstream. Since the three models release water from the reservoirs differently, the weir diversions downstream do not align. Figure

23 shows the diversion at the Fremont Weir from the HEC ResSIM, SVIROM and FCLP along with the observed diversion. Here the SVIROM begins its diversion before the other models and at a greater maximum rate. This behavior occurs because the SVIROM releases more water from Shasta reservoir and begins to store water in its reservoirs after the other two models have already begun to use reservoir storage. Similarly, the other models drain reservoir storage after the flood peak has subsided, which prolongs the diversion downstream.

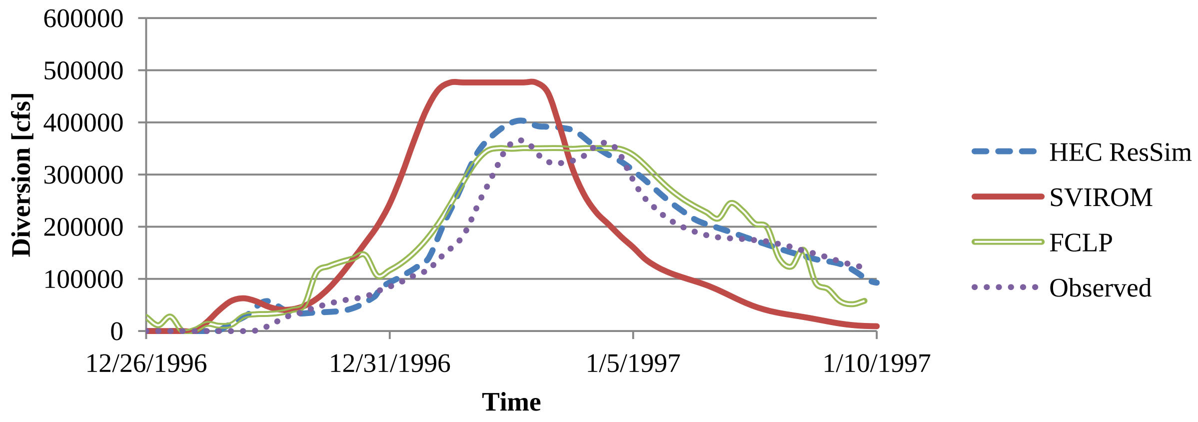

Figure 23. Comparison of Fremont Weir Diversions of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood

Sacramento Weir Diversion Comparison

Figure 24 shows the diversion at the Fremont Weir from the HEC ResSIM, SVIROM and FCLP along with the observed diversion. The results reasonably align with one another in general. At the beginning of the time series the SVIROM diversion exceeds the other models because less water is stored and the flow is largely unregulated. The peak diversion arrives at approximately the same time for the SVIROM and HEC ResSIM and although the magnitude is slightly greater for the SVIROM, the models behave similarly at this control point. As before, the duration of the diversion is greater for the HEC ResSIM and FCLP models because flood storage is evacuated after the flood peak subsides.

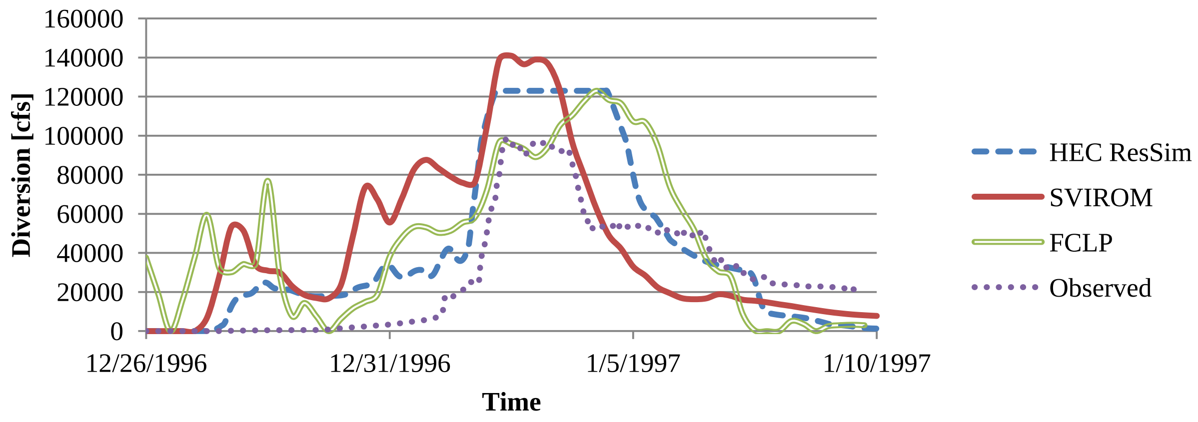

Figure 24. Comparison of Sacramento Weir Diversions of the HEC ResSIM, SVIROM, FCLP Along With the Observed for the 1997 Flood

WEIR OPTIMIZATION

The SVIROM was modified so the diversion percentage between each weir and downstream channel is selected as part of the optimization. Additional constraints allowed the SVIROM to adjust the weir diversion percentages so the optimal value of $\alpha_{c,2}$ could be determined for each weir for each storm. Weir diversion percentages are not a function of time and remain fixed for the duration of an individual flood. The additional constraints to the SVIROM are as follow:

$$\alpha_{c,2} \geq 0$$

$$\alpha_{c,2} \leq 1$$

where $\alpha_{c,1}=0$, for all weirs c

WEIR OPTIMIZATION RESULTS

The optimized weir diversion percentages are tabulated in Table 12 and presented graphically in Figure 25.

Table 12. Optimal Weir Diversion Percentages ($\alpha_{c,2}$) for the 1986, 1995 and 1997 Floods

Flood Year	Moulton	Colusa	Tisdale	Fremont	Sacramento	Average
1986	0.34	0.75	0.70	0.92	0.68	0.68
1995	0.97	0.10	0.71	1.00	0.44	0.64
1997	1.00	0.02	0.71	0.94	0.60	0.65

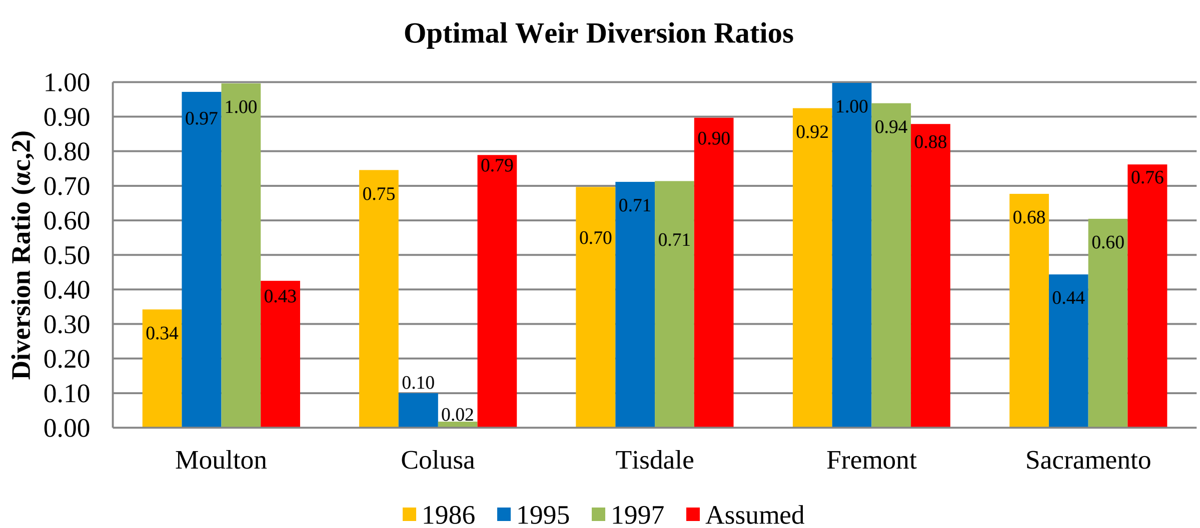

Figure 25. Optimal Weir Diversion Ratios ($\alpha_{c,2}$) for the 1986, 1995 and 1997 Floods

Allowing the SVIROM to adjust the weir diversions reduces the minimum penalty for all floods. More control over the flood wave's path allows reservoirs to make greater releases and steer high flows away from important control points. Channel capacities are used more efficiently and kept fuller and for longer than with non-optimized weir percentages. Although there is scatter in the optimal weir diversion percentages (Table 8, Figure 36), likely due to the variation of regional inflow distribution from storm to storm, the results do suggest a trend. In all cases the diversion percentages from the Fremont Weir are increased from the assumed value to approach the maximum allowable, demonstrating this weir is vital to the system and would benefit from an increased capacity. The diversion at Moulton Weir also nearly approaches the upper limit during two storms; however during the 1986 storm the Colusa Weir was more important. The diversion at the Tisdale Weir converged at approximately 70% for all three storms, suggesting an optimal weir design that diverts water at this proportion would help system performance during future floods in the basin and that the current weir may be over designed. Similarly, weir optimization nearly removes the Colusa Weir entirely for two of the floods analyzed, suggesting that under some hydrologic conditions diverting water into the bypass at this location has no benefit for flood control. Interestingly, the average diversion ratio of all weirs for each storm is approximately 0.65, independent of the hydrology and magnitude of flooding.

CONCLUSIONS

The SVIROM must balance the penalties for storing water and storing water too quickly with penalties for exceeding channel capacity downstream. As storage penalties begin to accumulate, the SVIROM will choose to release water and cause flood damages. The input parameters and penalty functions of the SVIROM determine the results. However, there are generalities that can be observed from the SVIROM analysis.

The optimized release hydrographs from reservoirs in series are waves that form a constant peak flow once combined at a river convergence. Coordination between reservoirs upstream from river junctions can greatly reduce the combined flow. To perform this most effectively, reservoirs should alternate releases and account for the distribution of the flood volume over the watershed. In many cases, the minimum release from a reservoir should be made during peak inflow to compensate for runoff downstream, which also likely reaches a maximum during this time. Knowing flow travel times, downstream effects and anticipating runoff accumulation allows better synchronism between reservoirs and gives reservoir operators more control of the peak flows downstream. Stream gages on tributary streams along the river course and accurate weather forecasts would help reservoir operators better implement a more optimal and coordinated flood control strategy. Current reservoir operating rules may neglect these considerations and instead focus on the stage of the reservoir and upstream flows entirely.

Minimizing the peak flow through the Fremont Weir is a main priority of the SVIROM. Shasta, Oroville and New Bullards Bar Reservoirs should coordinate releases to cap the flood peak at Fremont Weir, by considering forecasting and travel times to assure the peak releases do not coincide with one another. Black Butte should also coordinate its releases, but since it is smaller relative to the other reservoirs, its efforts will have less of an impact. Releases from Folsom reservoir are determined from available storage and Fremont Weir‘s outflow hydrograph. Folsom Reservoir is less important during the initial coordination because its releases converge with those from the other four reservoirs downstream of the main bottleneck at Fremont Weir. Folsom reservoir should store water so its peak releases do not coincide with peak flows arriving upstream from the Sacramento River. However, if the inflows to Folsom are large relative to those of the more northern reservoirs, Shasta, Black Butte, Oroville and New Bullards Bar Reservoirs may need to store as much water as possible so that the Sacramento Weir junction does not become overwhelmed.

In the primary application, the most apparent regulations to flow from optimized reservoir releases occurred at the Fremont Weir during all three floods. During the following weir optimization, the diversion ratio was increased at Fremont weir in all three cases. These findings suggest that increased channel capacity of the Sacramento River at the junction with the Feather and Yuba rivers combined with a greater diversion rate at the Fremont Weir would improve the system's performance.

Functioning as an integrated system, the reservoirs still reduced flood peaks to their individual channels in most cases. Although these reservoirs may have performed better individually, the resulting flows downstream would be less than ideal. Therefore, some compromise to individual reservoir performance to establish an integrated reservoir management approach may provide better flood protection to the Sacramento Basin than independent reservoir operating procedures.

Although the SVIROM model functions reasonably well and can offer some insights about flood control operations in the Sacramento Basin, more data and better computing power would improve the model's results. Verified and complete data parameters would produce a more accurate model. Muskingum routing parameters were unavailable for two river reaches which likely altered the flood waves traveling from the Oroville and New Bullards Bar reservoirs. Incremental flow at many of the control points from local run off and tributary streams were also unavailable and ignored. The weir diversions and outlet curves could be better represented in the model with a more complicated formulation involving more binary variables. Although the current computer processing and software available was unsuccessful in handling the needed number of binary variables for a more complicated formulation, technological advancements may allow these features to be improved in the future. These improvements would allow for an additional diversion at Ord Ferry from the main stem of the Sacramento River to the Sutter Bypass, non-linear diversion functions at all of the weirs and a more automated model that does not require iteration to assure the diversions and outlet curves function correctly.

WORKS CITED

Dettinger, Michael D., & Ingram, B. Lynn. "The Coming Megafloods." *Scientific American* January 2013: 64-71. Print.

Jones, Christy "Optimization Modeling as an Approach to Examine the Benefits of Expanding the Sacramento River Watershed Bypass System" MS Degree Paper, Civil & Environmental Engineering Department, UC Davis, 2003.

Jones, Dustin "Application of Mixed-Integer Programming for Flood Control in the Sacramento Valley: Insights & Limitations" MS Degree Paper, Civil & Environmental Engineering Department, UC Davis, 1997.

"Hydrologic Engineering Center's Reservoir Flood Control Optimization Program HEC- ResFloodOpt " Hydrologic Engineering Center, Corps of Engineers, U.S. Army.Davis: CA 2000.

Needham, Jason T. "Linear Programming for Flood Control in the Iowa and De Moines Rivers" Journal of Water Resources Planning and Management, 2000.

APPENDIX

Muskingum Routing Coefficients					
Reach	X	K (Hours)	C1	C2	C3
[1]	0.10	3.00	0.47	0.58	-0.05
[2]	0.20	2.50	0.50	0.70	-0.20
[3]	0.15	2.00	0.57	0.70	-0.28
[4]	0.20	2.00	0.57	0.74	-0.30
[5]	0.20	2.00	0.57	0.74	-0.30
[6]	0.20	1.00	0.74	0.84	-0.58
[7]	0.25	2.00	0.56	0.78	-0.33
[8]	0.38	1.00	0.72	0.93	-0.66
[9]	0.20	2.00	0.57	0.74	-0.30
[10]	0.10	4.00	0.39	0.52	0.09
[11]	0.10	4.00	0.39	0.52	0.09
[12]	0.10	4.00	0.39	0.52	0.09
[13]	0.20	2.00	0.57	0.74	-0.30
[14]	0.20	2.00	0.57	0.74	-0.30
[15]	0.20	2.00	0.57	0.74	-0.30
[16]	0.20	2.00	0.57	0.74	-0.30
[17]	0.17	2.00	0.57	0.72	-0.29
[18]	0.15	2.00	0.57	0.70	-0.28
[19]	0.35	1.00	0.73	0.92	-0.64
[20]	0.20	2.00	0.57	0.74	-0.30
[21]	0.20	2.00	0.57	0.74	-0.30
[22]	0.20	2.00	0.57	0.74	-0.30
[23]	0.20	2.00	0.57	0.74	-0.30
[24]	0.20	1.00	0.74	0.84	-0.58
[25]	0.20	2.00	0.57	0.74	-0.30
[26]	0.40	1.00	0.72	0.94	-0.67
[27]	0.20	2.00	0.57	0.74	-0.30
[28]	0.20	2.00	0.57	0.74	-0.30
[29]	0.20	2.50	0.50	0.70	-0.20
[30]	0.20	2.00	0.57	0.74	-0.30
[31]	0.20	2.00	0.57	0.74	-0.30
[32]	0.20	6.00	0.23	0.54	0.23
[33]			1	0	0
[34]			1	0	0

Weir Parameters		
Weir	Flow to Activate Diversion (cfs) $C_{w,i}$	Diversion Percentage $\alpha_{c,2}$
Moulton	70,000	0.425
Colusa	30,000	0.789
Trisdale	23,500	0.879
Fremont	61,000	0.879
Sacramento	60,220	0.762

Flow Penalties				
Control Point	Range (cfs)	Capacity (cfs) $C_{c,m}$	Flow Penalty $P_{c,m}$	Max Flow Penalty $P_{c,q}$
Bend Bridge	0-6,090	6,090	-1,000	-1,000
	6,090-80,000	73,910	0	0
	80,000-200,000	120,000	2	5.81
	>200,000	∞	3	13.25
Vina Woodson Bridge	0-90,000	90,000	0	0
	90,000-100,000	10,000	0.1	0.01
	100,000-200,000	100,000	0.2	0.83
	>200,000	∞	0.3	0.84
Ord Ferry	0-130,000	130,000	0	0
	130,000-211,900	81,900	0.1	0.01
	211,900-216,300	4,400	0.2	1.94
	>216,300	∞	0.3	1.95
Butte City	0-160,000	160,000	0	0
	160,000-216,500	56,500	0.01	0.01
	216,500-221,000	4,500	0.02	3.21
	>221,000	∞	0.03	3.22
Moulton Weir	0-160,000	160,000	0	0
	160,000-279,900	119,900	0.01	0.01
	279,900-285,600	5,700	0.02	4.78
	>285,600	∞	0.03	4.79
Colusa Weir	0-60,000	60,000	0	0
	60,000-63,100	3,100	0.01	0.02
	63,100-64,500	1,400	0.02	107.85

	>64,500	∞	0.03	107.9
Trisdale Weir	0-30,000	30,000	0	0
	30,000-48,510	18,510	0.01	0.01
	48,510-49,500	990	0.02	47.35
	>49,500	∞	0.03	47.36
Meridian	0-130,000	130,000	0	0
	130,000-634,800	504,800	0.01	0.01
	634,800-647,800	13,000	0.02	9.24
	>647,800	∞	0.03	9.25
Rd 1500 (Sutter Bypass)	0-150,000	150,000	0	0
	150,000-380,000	230,000	0.01	0.01
	380,000-385,000	5,000	0.02	0.02
	>385,000	∞	0.03	0.03
Marysville	0-3,510	3,510	-100	-100
	3,510-145,000	141,490	0	0
	145,000-176,400	31,400	2	0.02
	>176,400	∞	3	109
Gridley	0-15,150	15,150	-100	-100
	15,150-150,000	134,850	0	0
	150,000-258,900	108,900	0.5	0.1
	>258,900	∞	1	7.21
Yuba City	0-200,000	200,000	0	0
	200,000-205,800	5,800	0.01	0.01
	205,800-210,000	4,200	0.02	282.36
	>210,000	∞	0.03	282.4
Feather & Yuba Junction	0-300,000	300,000	0	
	300,000-310,000	10,000	0.01	
	310,000-320,000	10,000	0.02	
	>320,000	∞	0.03	
Nicolaus	0-320,000	320,000	0	0
	320,000-493,900	173,900	0.5	0.01
	493,900-504,000	10,100	1	2.99
	>504,000	∞	1.5	3
Fremont Weir	0-100,000	100,000	0	0
	100,000-104,500	4,500	0.1	0.01
	104,500-106,700	2,200	0.2	559.77
	>106,700	∞	0.3	560
Fair Oaks	0-7,720	7,720	-100	-100
	7,720-115,000	107,280	0	0

	115,000-194,500	79,500	0.02	89.32
	>194,500	∞	0.04	90
H St	0-75,000	75,000	0	0
	75,000-197,000	122,000	0.02	0.02
	197,000-201,000	4,000	0.03	4,658.68
	>201,000	∞	0.04	4,659
Sacramento Weir	0-75,000	75,000	0	0
	75,000-110,000	185,900	0.01	0.01
	110,000-266,200	5,300	0.03	2,703.92
	>266,200	∞	0.04	2,704
Colusa Drain	0-343,000	343,000	0	
	343,000-480,000	137,000	0.02	
	480,000-485,000	5,000	0.03	
	>485,000	∞	0.04	
Woodland	0-377,000	377,000	0	0
	377,000-573,900	196,900	0.01	0.01
	573,900-585,600	11,700	0.02	0.06
	>585,600	∞	0.03	0.1
I-80 (Yolo Bypass)	0-480,000	480,000	0	
	480,000-573,900	93,900	0.02	
	573,900-585,600	11,700	0.03	
	>585,600	∞	0.04	
Lisbon	0-490,000	490,000	0	0
	490,000-772,800	282,800	0.02	0.02
	772,800-788,600	15,800	0.03	0.92
	>788,600	∞	0.04	0.95
Freeport	0-110,000	110,000	0	0
	110,000-131,200	21,200	0.02	0.02
	131,200-133,800	2,600	0.03	63.78
	>133,800	∞	0.04	64
Rio Vista	0-560,000	560,000	0	0
	560,000-568,400	8,400	0.02	0.02
	568,400-580,000	11,600	0.03	0.44
	>580,000	∞	0.04	0.5

Reservoir Storage Penalties			
Reservoir	Range(AF)	Capacity (AF) $C_{r,j}$	Penalty $P_{r,j}$
Shasta	0-3,200,000	3,200,000	-0.1
	3,200,000-3,250,900	50,900	-0.05
	3,250,900-3,900,000	649,100	0.015
	3,900,000-4,552,000	652,000	0.08
	4,552,000-4,750,000	198,000	2
	>4,750,000	∞	3
Black Butte	0-35,000	35,000	-0.05
	35,000-143,676	108,676	0.01
	143,676-170,000	26,324	0.5
	170,000-190,100	20,100	1
	190,100-354,000	163,900	2
	>354,000	∞	3
Oroville	0-2,600,000	2,600,000	-0.2
	2,600,000-2,788,300	188,300	-0.1
	2,788,300-3,300,000	511,700	0.05
	3,300,000-3,537,600	237,600	0.5
	3,537,600-3,814,000	276,400	2
	>3,814,000	∞	3
New Bullards Bar	0-640,000	640,000	-0.02
	640,000-790,000	150,000	-0.01
	790,000-900,000	110,000	0.1
	900,000-960,000	60,000	0.3
	960,000-998,000	38,000	2
	>998,000	∞	3
Folsom	0-440,000	440,000	-0.15
	440,000-486,000	46,000	-0.1
	486,000-610,000	124,000	0.02
	601,000-1,010,000	400,000	0.04
	1,010,000-1,130,000	120,000	1.5
	1,130,000-1,300,000	∞	2

Reservoir	Reservoir Ramping Penalties					
	Increasing Flow More Than			Decreasing Flow More Than		
	cfs/hr	cfs/time step $C_{r,1}^{+}$	Penalty $P_{r,k}^{+}$	cfs/hr	cfs/time step $C_{r,1}^{-}$	Penalty $P_{r,k}^{-}$
Shasta	7,500	45,000	1	-2,000	-12,000	-1
Black Butte	1,000	6,000	1	-500	-3,000	-1
Oroville	5,000	30,000	1	-2,500	-15,000	-1
New Bullards Bar	5,000	30,000	1	-5,000	-30,000	-1
Folsom	7,500	45,000	1	-5,000	-30,000	-1