Simulation of Cooperative Water Supply and Flood Operations for Two Parallel Reservoirs on the Feather and Yuba Rivers, California

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Abstract: Cooperative operation of a parallel, two-reservoir system may produce more benefits than independent operation. Storage reallocation and re-operation project alternatives are evaluated for New Bullard's Bar and Oroville Reservoirs in the Feather-Yuba River basin of California. Ideas for re-operation project alternatives were generated using participatory input from ?????. Reallocation and re-operation project alternatives were simulated on a monthly computation interval over the historical period of record using HEC-5 and on an hourly timestep over 34-day probabilistic-based synthetic flood events in HEC-ResSim. Simulation results were evaluated using indicators for water supply reliability, resiliency, and vulnerability, expected annual flood damage, and ability to meet flow objectives at 6 Feather-Yuba basin locations. Results show tradeoffs between EAD and water supply reliability in the Feather and Yuba River basins for each project alternative. The study complements ongoing flood protection improvement investigations within the basins and demonstrates a further use of HEC-ResSim and HEC-FIA software for reservoir system simulation, flood impact analysis, and planning studies within the Corps Water Management System (CWMS) software suite. Recommendations highlight both (i) topics requiring further study for flood protection improvements in the Feather and Yuba basins and (ii) capabilities that should be added to HEC-ResSim, HEC-FIA, and CWMS to make the programs better suited for planning analysis.

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Chapter 1. Introduction

1.1 Background

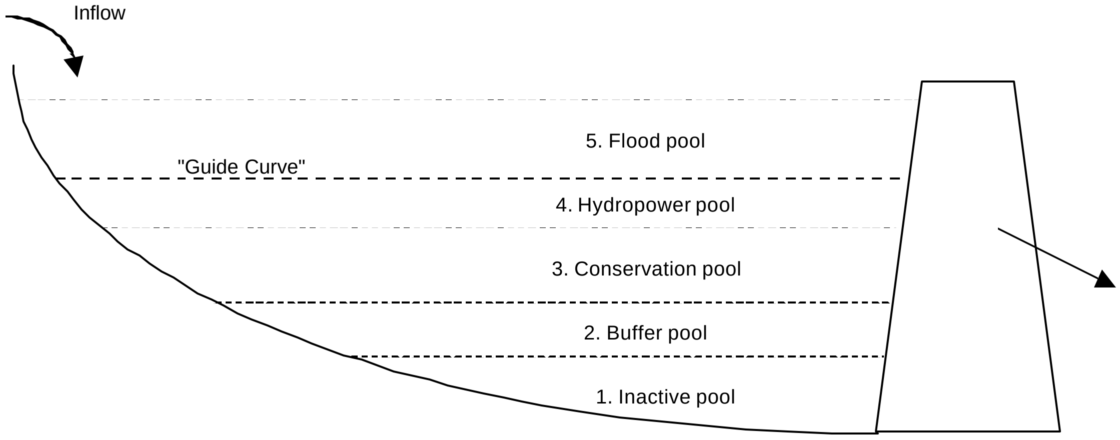
Water resources planners, engineers, and hydrologists have long recognized that the benefits from cooperative operation of a multi-reservoir system may exceed the sum of benefits attained for independently operated reservoirs. Reservoirs are built and operated to achieve multiple objectives such as water supply, flood control, hydropower, recreation, and environmental flow requirements. Their operation requires deciding how to apportion water storage and release. Decisions must consider apportionment among reservoirs, objectives, time periods, and method of release (Bower et al. 1966). Independent operations base these decisions on the state and objectives of the single reservoir and ignore the states of other reservoirs in the watershed. Cooperative operations consider the states of all reservoirs.

Figure 1-1A shows an example reservoir storage partitioned between inactive, buffer, conservation, power, and flood pools. In Figure 1-1B, seasonal flood storage is reserved (empty) to capture winter flood events. Water stored in the power pool can be released to generate hydropower. Conservation pool water is released to satisfy downstream water demands. When the reservoir storage level is critically low, buffer pool water is used exclusively to satisfy downstream flows for environmental, habitat, fish spawning, or other required purposes. The inactive pool is reserved for sediment or debris collection, or is the level below which reservoir operators cannot control reservoir releases.

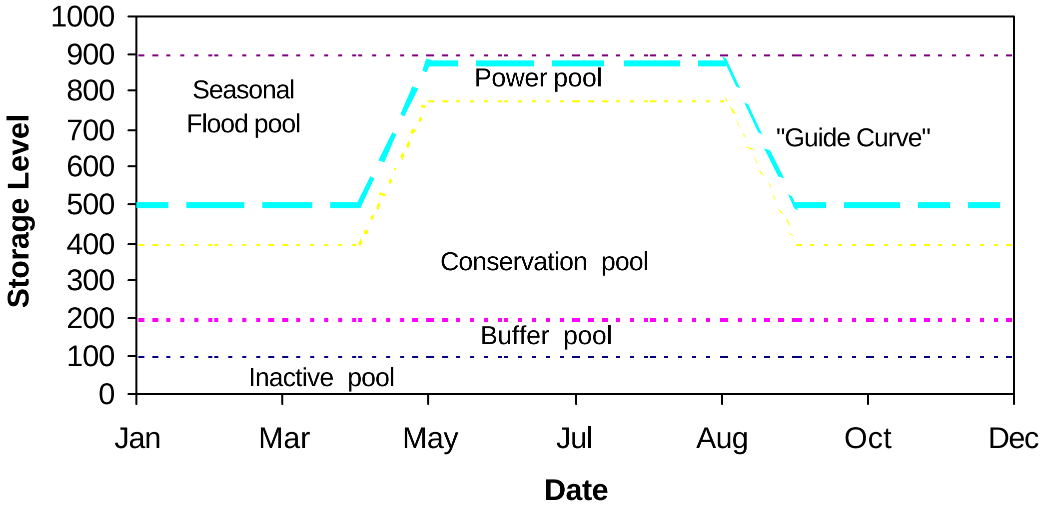
Over the past 4 decades, computational advances in mass-balance accounting, simulation modeling, linear, and dynamic programming have facilitated detailed study of reservoirs

Figure 1-1. Reservoir Storage Partitioned into Zones

A. Constant Zones



B. Seasonal Zones



(Simonovic 1992; Yeh 1985) and reservoir systems (Labadie 1997; Wurbs 1993). Many efforts have located, designed, and sized reservoirs, or formulated rules to jointly operate and maximize benefit over the entire watershed. Additional effort should be focused on identifying potential gains from joint over individual operations—for example, existing systems where reservoirs are operated individually. Needham et al. (2000) give an example where independent operation is as good as cooperative operation, however.

For a basin with several existing, individually operated reservoirs, cooperation will be pursued when each reservoir realizes a benefit from cooperation that exceeds the current individual benefits and marginal cost of cooperation. This constraint must encompass the full economic, social, political, and institutional costs and benefits of altering operations. In this discussion, water supply and flood protection benefits of joint operations are considered; reservoir operators must evaluate whether these benefits meet or exceed their other costs and are sufficient motivation to pursue cooperation.

This thesis explores joint operation for water supply and flood protection objectives using an example from California. New Bullard's Bar reservoir, located on the Yuba River and operated by the Yuba County Water Agency (YCWA), and Oroville reservoir, located on the Feather River and operated by the State Water Project (SWP), are considered. Study objectives are outlined in the next section. Chapter 2 reviews literature regarding operations for reservoirs in parallel, simulation software, and storage reallocation. Background information on the Feather and Yuba basins is presented in Chapter 3. Chapters 4 and 5 describe simulation and study methods used to simulate reservoir operations, develop storage reallocation and reservoir re-operation project alternatives, simulate, and evaluate them. Study limitations, simulation results, conclusions, and recommendations follow in Chapters 6 through 9.

1.2 Study Goals

The goals of this investigation were threefold to:

- Identify promising storage-reallocation alternatives in the Feather-Yuba watershed that improve flood protection and water supply,
- Further test the Hydrologic Engineering Center's (HEC) Reservoir Evaluation System-Simulation software (HEC-ResSim) for (i) new operating rules related to water supply conservation and hydropower production that are different than flood protection, and (ii) a wide range of computational time intervals ranging from hourly to monthly, period of record, and
- Further test and guide the integration of HEC-ResSim with other Corps Water Management System (CWMS) software tools such as Flood Impact Analysis (HEC-FIA) and the Watershed Analysis Tool (HEC-WAT).

Chapter 2. Theoretical Development and Literature Review

A variety of analysis techniques including simulation and optimization algorithms have been developed over the last four decades to study water resources systems (Labadie 1997; Loucks et al. 1981; Simonovic 1992; Wurbs 1993). Simulations track the movement of water through a system while optimization programs search for an optimal operating policy to achieve a specific objective. Yeh (1985) reviews state of the art examples of both kinds of models. In discussing large, multi-reservoir systems, Labadie (1997) notes that the difference between simulation and optimization modeling is often obscured because optimization models almost always embed simulation models to verify and test proposed operating policies.

Simulation modeling provides a useful framework for explicitly testing specific possibilities for cooperatively operating reservoirs in parallel and is the focus of further discussion. Simulation analysis, potential alternatives including operating rules, storage reallocation, and other possible management such as conjunctive use of surface water and groundwater are reviewed. Selected simulation software and example studies of joint operations for reservoirs in parallel are also discussed.

2.1 Simulation analysis

Simulation models use inflows (hydrology), operations (decision rules), and mass-balance basin accounting (connectivity) to represent the hydrologic behavior of a reservoir system. System performance is quantified by selecting indicators of benefit based on system flow and/or storage that the modeler feels best characterize the important aspects and objectives of the system. Indicators can include reservoir storage levels; in-stream flows; hydropower generation; water supply deliveries or shortages;

hydropower revenues; flood damage; or summaries of these quantities such as firm supply, supply reliability (based on frequency analysis), expected annual flood damage, or explicit economic performance, to name a few. To perform simulation analysis, the modeler first computes performance using selected indicators for a base case representing the system's existing hydrologic behavior. Next, the modeler develops a series of alternative system behaviors (by changing reservoir storage allocations, operating rules, demand levels, and/or hydrology, etc.) and computes performance for these hypothesized alternatives. Lastly, the modeler compares base case performance to performance under tested alternatives. The bulk of simulation work consists of formulating alternatives to test and explicitly modeling them.

2.2 Operating rules

Operating rules describe the logic used to make decisions on storing or releasing water. "Guide Curve" and "Space" rules are discussed.

2.2.1 Guide Curve Operation

The "Guide Curve" (see Figure 1-1) specifies the reservoir level between the flood and hydropower pools. Guide curve operation oversees releases to maintain that storage level. The general release operation is to (i) release water as quickly as possible when high inflows encroach into the flood pool and raise storage above the guide curve, or (ii) curtail releases to the minimum required amounts necessary to satisfy buffer, conservation, or hydropower requirements when inflows are low and storage level is drawn-down below the guide curve. As inflows decrease (after flood pool encroachment) or inflows rise (after draw-down into the hydropower or conservation pools), guide curve operations tends to guide storage level back towards the "Guide Curve."

2.2.2 Space Rule

Bower et al (1966) describe a “space rule” to operate multiple reservoirs in parallel for a common purpose. The rule equalizes the probability that the active storage space within each of the parallel reservoirs will spill by the end of the drawdown-refill cycle to maximize the expected total storage in the system. Releases (during the drawdown period) are computed using current storage levels and inflows forecasted for the next refill period. Towards the end of the drawdown period, release calculations become increasingly sensitive to the quality of the inflow forecasts. Furthermore, monthly flow variation and the correlation between flows on the adjacent streams influence the effectiveness of the rule.

Sand (1984), Lund and Guzman (1996) and Lund and Guzman (1999) present modifications and extensions of the space rule to apportion releases among reservoirs for flood protection, hydropower production, or differing values of water in conservation or flood control storage. In general, the modified rules still equalize the probabilities of (i) spill among the several reservoirs in the refill season, and (ii) emptying in the drawdown season.

2.3 Storage reallocation

Reallocation is defined as change among purposes in reservoir storage volume, priority, timing, or method of delivery (Johnson et al. 1990). For example, a reallocation can raise the guide curve (i.e., increase storage for water supply and decrease storage available to manage flood waters) or vice versa. Johnson et al (1990) identify 8 general cases of reallocation based on observations in Texas (Wurbs and Carriere 1988) and the U.S. Army Corps of Engineers (USACE) experience elsewhere throughout the country (IWR 1988).

Reallocation strategies that show promise in the Feather-Yuba basins include temporary use of storage allocated for future conservation purposes and sediment (Johnson et al's (1990) case ii), reducing flood-control space (case v), and system-wide regulation of reservoirs (case viii). Seasonal use of flood-control space during the dry season (case iv) is already in place at both reservoirs. More generally, flood-control space can be reallocated when: (1) the reallocations in flood-control volumes are small and have little or no effect on flood protection; or (2) additional reservoirs are constructed in the basin. Wurbs and Carriere (1988) observe that most storage-reallocation implemented in Texas and elsewhere in the nation involves converting flood pool storage to municipal and industrial water supply.

To simulate the performance of storage-reallocation schemes, Ford (1990) introduces PC software that calculates water-supply, energy-system, and flood damage reduction reliability, resiliency, and vulnerability (Hashimoto et al. 1982). Wurbs and Cabezas (1987) claim that complex technical and institutional considerations make measuring performance more difficult; they develop an aggregated economic criterion that estimates annual losses, in dollars, due to flooding, water shortage, and implementing storage-reallocation measures. They calculate economic loses due to flooding as expected annual flood damage using discharge-damage and regulated discharge-frequency relationships. They determine water shortage costs by first, studying water demand (present use, long-term demand management, and future water needs), second, developing reliability versus storage capacity and demand relationships through hydrologic simulation, and lastly, computing average annual losses based on the shortage-loss relationship. They estimate implementation costs as modifications to boat ramps, marinas, roads, bridges, and water-supply intake structures required to accommodate raising or lowering the top of the conservation pool. Wurbs and Cabezas (1987) apply their criteria and method to 4 reallocation alternatives proposed for Waco Reservoir in Central Texas.

2.4 Other types of coordinated, reservoir-based cooperation

Cooperative operations can extend beyond joint operation rules or storage-reallocation. For example, flood protection objectives can also be achieved with floodplain management and/or constructing other flood management structures such as levees (Williams 1994). This management can reduce flood storage space required in one or more reservoirs in a system.

Additional management strategies such as conjunctive use of surface water and groundwater storage may mobilize additional system capacity for water supply storage (Hinks and Eichinger 1986; Maknoon and Burges 1978), flood protection (Coe 1989), or both, simultaneously (USACE 2001). With these alternatives, operations also require decisions concerning water transfer rates between reservoir(s) and the aquifer(s). Rates are constrained by aquifer storage, recharge, and extraction rates, as well as reservoir-to-aquifer and aquifer-to-end-user conveyance capacities (USACE 2001).

2.5 System simulation software

To date, software used for simulating operating rules and storage reallocations has included spreadsheet programs, HEC-5, HEC-3, Stella®, and other study-specific programs identified in reviews by Wurbs (1993) and Yeh (1985). Stella® is commercially-available and provides an object- and graphically-oriented environment in which to simulate a reservoir or multi-reservoir system. The HEC-numbered codes were developed at HEC, a division of the USACE, in Davis, California. Of publicly available programs, they are the most well documented and capable for performing network systems simulation analysis, including flood management, water supply, and hydropower operations (Feldman 1981; HEC 1998).

At present, HEC is replacing the HEC-5 code with HEC-Reservoir Evaluation System (HEC-ResSim), a next generation reservoir systems analysis software that will also be object-, graphically-, and database- oriented for real-time or planning analysis studies. HEC-ResSim will also link to other modules for flood impact estimation, unsteady river flow, flood plain inundation, and ecosystems functioning within the Corps Water Management System (CWMS) software suite. It is also planned to extend these capabilities for planning studies. For the present study, HEC-ResSim was chosen to model flood operations; output hydrographs were linked to the HEC-Flood Impact Analysis (HEC-FIA) module in CWMS to estimate flood damages. Simulation and study methods are further detailed in Chapters 4 and 5.

2.6 Some examples of cooperative operations for reservoirs in parallel

Hirsch et al (1977) apply an operating rule that maintains proportional amounts of empty space in each reservoir to capture synergistic water supply gains from joint operation of three reservoirs on three streams in the Baltimore, Maryland area. The synergistic gains arise as a result of a diversity of flows in the several streams. This diversity comes from a deterministic portion (due to differences in climate) and a stochastic portion (due to differences in weather). The deterministic portion of synergistic gains are captured by employing an operating policy that drafts more from a reservoir in a season when its inflow is relatively high compared to that of other reservoirs; conversely, drafting less from a reservoir when its inflow is lowered compared to the other reservoirs. Stochastic gains are captured by releasing water from full reservoirs.

Hirsch et al (1977) apply their rule as a means to appropriately size a reservoir to be added to a system. They also put forward the “Hypothetical Reservoir” method as an analysis technique to calculate the maximum bound on the safe yield of a system of jointly operated reservoirs. All potential cooperation alternatives can be compared against this theoretical, maximum bound.

Iþen and Kadioðlu (2000) present an algorithm to minimize evaporative loses from the 6-reservoir Istanbul municipal water supply system. The simple, adaptive, joint operation rule is a variant of the NYC rule. The Bosphorus Straight separates the system’s reservoirs between the continents of Europe and Asia. Although water can be transferred from Asian-side reservoirs to meet city demand on the European side, the city generally faces seasonal shortages starting in March for three reservoirs, July or August for two reservoirs, and October for the remaining reservoirs. By the end of the dry season, shortage can reach from 22 – 93% of demand and creates a “rationale” for “public tolerance and patience” to accept reduced deliveries. Application of the joint operation rule rolls back both the starting date and magnitudes of rationales.

Palmer et al (1982) outline joint management of five reservoirs in the Potomac and Patuxent River basins which serve the Washington, D.C. metropolitan area. They first use simulation modeling and the Hypothetical Reservoir method formulated by Hirsch et al (1977) to identify the maximum “synergistic gain” from cooperative operation. Second, they use linear programming to identify water-use objectives (upstream deliveries, reservoir storage and release capacities, withdraw capacities from the Potomac and Patuxant rivers, and environmental flow-by requirements) that constrain achieving the maximum synergistic gain for scenarios of altered water demand, upstream flow requirements, environmental flow-by, and reservoir treatment capacity. These scenarios highlight two significant tradeoffs between system yield and (i) upstream release and (ii) environmental flow-by requirements.

Needham et al (2000) offer a counter-example and show that cooperative operation of 1 reservoir on the Iowa River with 2 reservoirs on the Des Moines Rivers provides little additional flood protection benefit for a downstream location on the Mississippi River. Key reasons for this result are: first, that the reservoirs are located on tributaries and only control a small portion of the total flood damaging flow at the downstream location. And second, that flood operations for locations immediately downstream of the reservoirs are very restrictive and do not offer flexibility to operate for locations further downstream on the Mississippi river. However, Needham et al (2000) also conclude that flood damages could be reduced if operations could be implemented with several months of flood forecasting.

Chapter 3. Background Information on the Feather and Yuba River basins

The Feather and Yuba River basins are located in the northern part of California within the Eastern portion of the Sacramento River basin north of the City of Sacramento (Figure 3-1). Prominent features of the Feather-Yuba system are sketched in Figure 3-2 and include Oroville and New Bullard's Bar reservoirs, Thermalito afterbay, the city of Marysville (on the Yuba River), Yuba City (on the Feather River), the confluence of the Yuba and Feather Rivers, the confluence of the Bear and Feather Rivers, and Nicolaus operation point on the Feather River.

Marysville reservoir was authorized, but never constructed. Ten miles downstream of Nicolaus, the Feather River meets the Sacramento River. The Sacramento River flows south past the city of Sacramento and into the Sacramento-San Joaquin Delta. Although the Fremont Weir is located upstream of the Feather-Sacramento Rivers confluence, it directs most Sacramento and Feather River water into the Yolo Bypass. The Bypass flows east of the main Sacramento River channel and the city of Sacramento. Oroville and New Bullard's Bar supply water for local municipal and agricultural needs in the Feather and Yuba basins respectively (Feather River Service Area [FRSA] diverted from Thermolito; and Yuba diversions at Marysville). Both reservoirs also release water for export out of the Sacramento basin through the Delta.

3.1 Historical project development

Basin data and storage allocations for the two existing and one proposed reservoir are listed in Table 3-1. Oroville Dam and Reservoir were completed in 1967 as part of the

Figure 3-1. Location of Feather and Yuba Rivers in the Sacramento Basin and Sac. Basin within California (inset)

Figure 3-2. Schematic of Feather and Yuba River Basin System

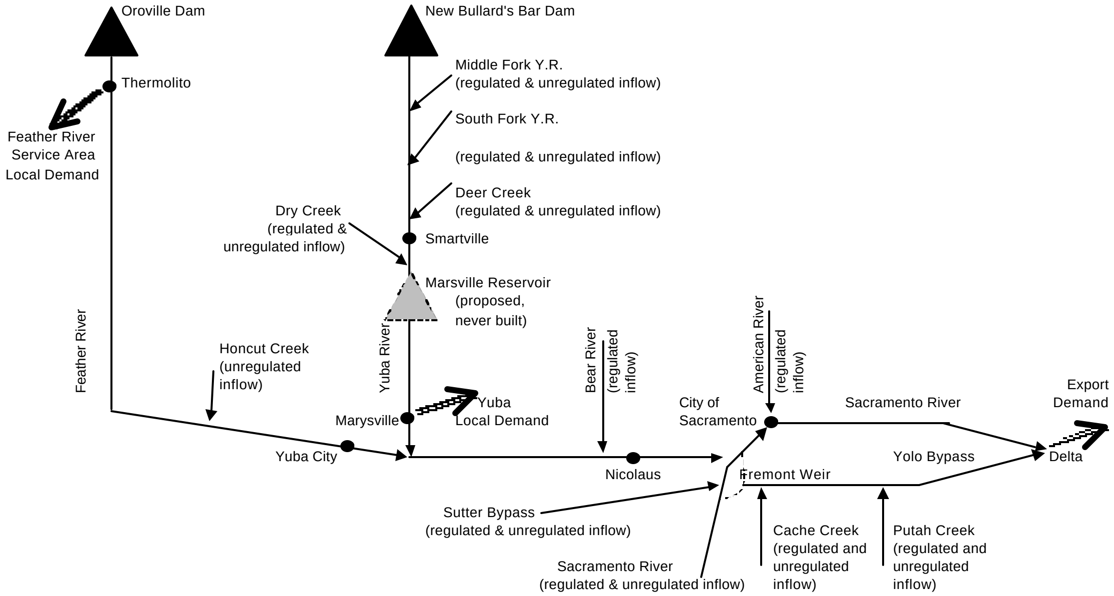


Table 3-1. Basin Data and Reservoir Storage Allocations

Description (1)	**Oroville Reservoir**[a] (on Feather River) (2)	**New Bullard's Bar**[b] **Reservoir** (on North Fork Yuba River) (3)	**Marysville Reservoir**[c] (proposed on Yuba River) (4)
(a) Basin data			
Drainage area (sq mi)	3,611	489	1,324
Mean annual natural flow (ac-ft)	4,138,000	1,100,000	1,850,000
(b) Storage Allocations (ac-ft)			
Inactive	852,200	1,731	100,000
Water Conservation	1,935,800	788,169	608,000
Flood Control	750,000	170,000	260,000
Spillway Surcharge	276,000	38,100	52,000
Active Gross Total	*3,538,000*	*959,900*	*968,000*
Total	*3,814,000*	*998,000*	*1,020,000*

Notes:

a. Source: USACE (1970b)

b. Source: USACE (1972)

c. Proposed, never constructed, source: USACE (1970a)

California State Water Project (SWP) and are now operated by the State of California, Department of Water Resources (DWR). Oroville provides 3,540,000 ac-ft of gross active storage of which 750,000 ac-ft is reserved for flood storage (USACE 1970b). The project was constructed on the main branch of the Feather River immediately East of the city of Oroville and approximately 32 miles upstream of Yuba City. The dam and reservoir operate for multiple purposes including water supply, flood management, and hydropower generation. Thermalito afterbay was constructed immediately downstream of the dam to divert water to FRSA, generate additional hydropower, and provide off-peak, pump-back capacity.

New Bullard's Bar reservoir was completed in August 1970 and financed entirely by the Yuba County Water Agency (YCWA). The reservoir provides 969,600 ac-ft of storage, of which 170,000 ac-ft is reserved for flood management via agreement between the YCWA and USACE. The project was constructed on the North Fork of the Yuba river approximately 35 miles east and upstream of Marysville and replaced an older Bullard's Bar facility with 31,500 ac-ft of storage that YCWA built in 1923 (DWR 1985). New Bullard's Bar dam and reservoir operates as a multipurpose water supply, flood management, and hydropower generation facility (Sarkaria 1968).

The location of New Bullard's Bar allows the project to regulate less than half the total runoff in the Yuba River basin (USACE 1972, p. 24). Unregulated inflows enter the main stem of the Yuba river from Deer and Dry creeks and the Middle and South forks of the Yuba River. Flood storage space in New Bullard's Bar was sized assuming 260,000 ac-ft of *additional* flood storage space would be available in Marysville reservoir (USACE 1970a; USACE 1972). The proposal intended a total of 400,000 ac-ft of flood protection in the entire Yuba Basin and considered flood storage at New Bullard's Bar as 80% as effective as equivalent storage space at Marysville. Since the Marysville reservoir was never constructed, New Bullard's Bar only provides protection to the Marysville-Yuba City area for floods that have an approximately 1.7% or higher occurrence probability. (USACE 1970a; USACE 1972). Therefore, a substantial interest exists to improve this level of flood protection.

3.2 Ongoing Project Work

In response to both the low level of protection at Yuba City-Marysville and severe flooding that occurred throughout the Central Valley in January 1997, the U.S. Congress authorized the USACE and State of California Reclamation Board (SCRB) to develop a comprehensive plan for flood damage reduction and ecosystem restoration. This effort has since come to be known as the Sacramento and San Joaquin Rivers Comprehensive Study. The Comprehensive Study developed a series of synthetic inflow hydrology (Hickey et al. 2002) and flood operations models (USACE and SCRB 2000). Additional project alternatives are being evaluated for the Yuba-Feather Supplemental Flood Control Project (Countryman 2002; Whitin 2002). These works are explained and reviewed as they relate to the Feather and Yuba watersheds.

3.2.1 Synthetic flood hydrology

Hickey et al (2002) outline the methods used to calculate synthetic hydrographs representing 50, 10, 4, 2, 1, 0.5, and 0.2% exceedance flood events (i.e. floods likely to re-occur at 2-, 10-, 25-, 50-, 100-, 200-, and 500-year intervals) for most locations within the Sacramento and San Joaquin Basins. Separate hydrographs were specified for storms centered over the entire basin and in individual tributaries. Flow records from more than 50 observed storm events were classified into 25 storm patterns. For each pattern, frequency distributions were computed for the total unregulated flow arriving at each location of interest. Flows were then summed over successive 5-day intervals to obtain a frequency-indexed volume. Using a tributary-specific flow record, volumes were patterned back into flood waves for each 5-day interval. Thus, the composite, synthetic hydrographs span a 32-day period, start with three successively-increasing local-maximum waves, are followed by the global maximum event, and end with two local maximum waves. Example synthetic hydrographs for Oroville Inflow, Honcut Creek local flows, and New Bullard's Bar Inflow are presented as Figures B-1 through B-3 in Appendix B.

3.2.2 Flood operation simulation models

Hickey et al's (2002) synthetic hydrology was used as input for a comprehensive flood operation simulation model developed in HEC-5 for the Sacramento Basin (USACE and SCRB 2000). The HEC-5 model data and operations were used to develop a HEC-ResSim watershed of flood operations for the Sacramento Basin. Details of this adaptation specific to the Feather and Yuba basins are presented in Chapter 4 section 1.

The HEC-5 model and HEC-ResSim watershed both use physical reservoir data, standard definitions of the buffer and surcharge pools; seasonal definitions of the "guide curve" partitioning the top of the conservation pool and the bottom of the flood pool; and Muskingum routing parameters to specify attenuation along each network reach. Flood management operations include rate-of-change of release, channel capacity at downstream control points, emergency spillway release (surcharge) operations, and variable channel capacity downstream of the dam as a function of either pool elevation (storage) or rate of inflow.

In HEC-5, the Sacramento Basin is split into two sub-models that separate the basin into "Headwaters" and "Lower Basin" locations (along each tributary). In the Feather and Yuba Basins, the "lower basin" model covers locations depicted in Figure 3-2. Locations upstream of Oroville dam along the Feather River (for example, Sly Creek, Little Grass Valley, Frenchman, Lake Davis, Antelope, Mountain Meadows, Almanor, Butt Valley, and Bucks Lake reservoirs) are defined in the "headwaters" model (and not shown in Figure 3-2). These headwaters locations feed a single, combined inflow to Oroville dam that is the transition point between the "headwaters" and "lower basin" models in the Feather River basin.

In the Yuba River basin, transition points between the two sub-models are defined at the confluences of the Yuba River with Deer Creek, Dry Creek, the Middle Fork, and the South Fork. These transition points receive unregulated local inflows and regulated releases from "headwaters" locations such as Bowman, Fordyce, Jackson Meadows, Merle Collins, Scotts Flat, and Spaulding reservoirs (not shown in Figure 3-2).

3.2.3 Project Alternatives

The Yuba-Feather Supplemental Flood Control Project will use the Comprehensive Study models and other systems analysis tools to investigate several project alternatives to increase flood protection in the Feather and Yuba River basins. Whitin (2002) summarizes these alternatives as:

- Use flood forecasting to pre-release from Oroville and New Bullard's Bar reservoirs,
- Pre-release from Thermolito afterbay to empty a 45,000 ac-ft space for temporary storage of flood water released from Oroville,

- Install a surcharge rubber bladder on Oroville to raise the dam height and create c. 200,000 ac-ft of additional flood storage space (Countryman 2002). Whitin (2002) comments that the rubber bladder may be difficult to implement because it could make Oroville unable to handle the probable maximum flood event, and
- Revise definitions of the Emergency Spillway Release Diagrams (ESRD) in the Water Control Manuals.

The Comprehensive Study also examined opportunities to conjunctively use storage in aquifers accessible from New Bullard's Bar and Oroville Reservoirs. Additional draw-down of the reservoir conservation pools during the Fall season and transfer of that water into groundwater storage may vacate an additional 100,000 to 138,000 ac-ft for flood storage at Oroville and 73,000 to 120,000 ac-ft at New Bullard's Bar. Transfer of high winter flows through the reservoirs during the flood season into groundwater storage and capture of additional snowmelt runoff during the Spring refill season in the drawn-down conservation pools may also increase water supply by 58,000 to 148,000 ac-ft for Oroville and 55,000 to 131,000 ac-ft for New Bullard's Bar (USACE 2001). The study identifies potential for *dual* water supply and flood protection benefits, and recommends that conjunctive use be investigated further.

3.3 Existing Reservoir Operations

The following section summarizes existing operations at New Bullard's Bar and Oroville for flood management, water supply, hydropower, and minimum flow requirements to maintain fish, wildlife, and environmental habitats. Information was compiled from Water Control Manuals (USACE 1970b; USACE 1972), basin reports (DWR 1985; DWR 1995; USACE and SCRB 2000), and telephone conversations with staff from the Comprehensive Study (Whitin 2002), DWR (Leahigh 2002), and YCWA (Aikens 2002).

3.3.1 Oroville Dam

Flood Management Operations

Flood management operations are specified on the Flood Control Diagram (FCD, Chart A-1) and the Emergency Spillway Release Diagram (ESRD, Chart A-2) of the Oroville Dam Water Control Manual (USACE 1970b). These operations require:

1. Seasonal reservation of a flood pool 750,000 ac-ft in size from October 15th through April 1st (Table 3-2). This pool represents reservoir storage above 2,788,000 ac-ft (848.5 ft). Draw-down to establish the pool must begin by September 15th. The pool may completely refill by June 15st.
2. A release schedule following inflow and rising to a maximum of 150,000 cfs as specified by a function of forecasted or actual inflow and elevation,
3. That releases not increase by more than 10,000 cfs nor decrease by more than 5,000 cfs in any two-hour period,
4. Flow in the Feather River downstream of Oroville not exceed 150,000 cfs,
5. Flow in the Feather River upstream of the confluence with the Yuba River (i.e., at Yuba city) not exceed 180,000 cfs,
6. Feather River flows below the Yuba River confluence not exceed 300,000 cfs,
7. Feather River flows below the Bear River confluence not exceed 320,000 cfs, and
8. Emergency spillway releases larger than operations #1-7 when pool elevation, inflow, and the rate of change in pool elevation endanger the dam. After emergency releases are initiated and reservoir elevation starts to fall, gate openings must be maintained until release falls below 150,000 cfs.

Table 3-2. Base Case Reservoir Zone Definitions

Zone	Date[a]	Oroville		New Bullard's Bar	
		Elevation[b] (ft)	Storage[b] (ac-ft)	Elevation[b] (ft)	Storage[b] (ac-ft)
(1)	(2)	(3)	(4)	(5)	(6)
Top of Dam		922.00	3,870,000	1965.00	1,010,000
Top of Surcharge		916.00	3,801,400	1959.00	980,600
Top of Flood Control		900.03	3,538,000	1955.00	960,000
Top of Conservation	1-Jan	848.48	2,788,000	1916.95	790,000
	31-Mar	848.48	2,788,000	1916.95	790,000
	30-Apr			1939.68	890,000
	31-May			1954.98	959,900
	15-Jun	900.02	3,537,900		
	15-Sep	900.02	3,537,900	1954.98	959,900
	31-Oct	848.48	2,788,000	1916.95	790,000
	31-Dec	848.48	2,788,000	1916.95	790,000
Top of Buffer		640.00	852,200	1731.01	1,731
Top of Inactive		640.00	852,199	1395.00	1,395

Notes:

a. Blanks indicates a static zone definition throughout the water year

b. Blanks indicate values should be linearly interprelated from values for previous and succeeding dates

Minimum Flow Requirements

Minimum flow requirements in the Feather River are mandated by the California State Water Resources Control Board (SWRCB) (DWR 1995; Leahigh 2002) and are listed in Table 3-3. Requirements vary by month and water year type, and can be summarized as (continuing numbers from Flood management operations):

9. 1,700 cfs for the period October through March, and 1000 cfs for April through September following water years classified as Wet, Above, or Below Normal,
10. 1,200 cfs for the period October through February, and 1000 cfs for March through September following water years classified as Dry or Critical (i.e., when runoff between April and July of the previous water year was less than 55% of average), and
11. Requirements #10 and #11 may be reduced by 25% when the Oroville pool level falls below 1,500,000 ac-ft.

Water Supply Operations

Additionally, the following water supply operations were elicited from discussion with and FRSA delivery data provided by Leahigh (2002):

12. Releases to meet contractual obligations with the Feather River Service Area (FRSA). Released water is diverted from the Feather River at Thermolito Afterbay. Average FRSA deliveries from 1985 through 2000 are summarized in Table 3-4.
13. Whenever possible and as permitted by environmental quality constraints and pumping capacity at the Delta, surplus water in the conservation pool is released and routed down the Feather and Sacramento Rivers to the Delta for export to other SWP contractors in Southern California.
14. Whenever reservoir level falls below 1.5 MAF and releases cannot meet both FRSA contract and the minimum environmental flow requirements, shortage is shared equally between the two uses.

Hydropower Operations

Hydropower generation, hydropower peaking, and off-peak pump-back between Oroville and Thermolito afterbay are secondary objectives and operate within the schedule of releases for flood management, water supply, and minimum, in-stream flow requirements. As such, Oroville hydropower operations are not considered further in the study.

Table 3-3. Minimum Required Flow Criteria on the Feather River (DWR 1995; Leahigh 2002)

Condition (1)	**Minimum Required Flow (cfs)** Winter (2)	 Summer (3)
Wet, Above, or Below Normal water year type	Oct - Mar	Apr - Sep
Oroville Pool above 1.5 MAF	1,700	1,000
Oroville Pool below 1.5 MAF	1,275	750
Dry or Critical water year type	Oct - Feb	Mar - Sep
Oroville Pool above 1.5 MAF	1,200	1,000
Oroville Pool below 1.5 MAF	900	750

Table 3-4. Feather Rivers Service Area Water Supply Demands (Computed from data provided by Leahigh 2002)

Month (1)	**Demand** (cfs) (2)	 (ac-ft) (3)
January	165	10,129
February	-	-
March	64	3,922
April	623	37,089
May	2,415	148,462
June	2,467	146,768
July	2,815	173,110
August	2,415	148,521
September	987	58,731
October	870	53,513
November	825	49,096
December	600	36,911

3.3.2 New Bullard's Bar Dam

Flood Management Operations

Flood management operations are specified on the FCD (Chart A-6) and ESRD (Chart A-7) of the New Bullard's Bar Water Control Manual (USACE 1972). These operations require (continuing counting from Oroville operations):

15. Seasonal reservation of a flood pool 170,000 ac-ft in size from November 1st through April 1st (Table 3-2). This pool represents reservoir levels above 790,000 ac-ft (1916.95 ft). Drawdown to establish the pool must begin by September 15th. The pool can completely refill by June 1st.
16. Releases in the North Fork of the Yuba River below the dam not exceed 50,000 cfs,
17. Flow in the Yuba River at Marysville not exceed (i) 120,000 cfs when concurrent flows in the Feather River above the Feather-Yuba confluence are high, or (ii) 180,000 cfs when concurrent flows in the Feather River are low,
18. Releases not increase nor decrease by more than 5,000 cfs per hour, and
19. Emergency spillway releases when pool elevation, inflow, and the rate of change in pool elevation threaten to overtop the dam. After emergency releases are initiated and reservoir elevation starts to fall, gate openings must be maintained until pool level recedes to 1956.0 feet. Afterwards, release may be reduced by 5,000 cfs per hour until outflow is reduced to 50,000 cfs.

Operation #17 effectively requires New Bullard's Bar to maintain flows below 300,000 cfs at the confluence of the Feather and Yuba Rivers. This operation allows Oroville Reservoir the flexibility to make releases as it needs (within its own operational requirements) but forces New Bullard's Bar to operate to meet the confluence flow objective.

Minimum Flow Requirements

Minimum flow requirements in the Yuba River are legally mandated by the State Water Resources Control Board (SWRCB 2001). These require:

20. 5 cfs of flow for the North Fork of the Yuba River below the dam, and
21. Flow at Smartville and Marysville as specified by year type classification and month of the year (Tables 3-5 and 3-6).

Table 3-5. Minimum Environmental in-stream flow requirements at Smartsville in CFS (SWRCB 2001)

Year Type (1)	Oct (2)	Nov (3)	Dec (4)	Jan (5)	Feb (6)	Mar (7)	Apr (8)	May (9)	Jun (10)	Jul (11)	Aug (12)	Sep (13)
Wet, Above, or Below Normal	719	719	719	719	719	719	821	0	0	0	0	505
Dry	571	617	617	617	617	617	753	0	0	0	0	396
Critical	525	617	617	617	617	617	753	0	0	0	0	342
Extremely Critical	525	617	617	617	617	617	583	0	0	0	0	342

Table 3-6. Minimum Environmental in-stream flow requirements at Marysville in CFS (SWRCB 2001)

Year Type (1)	Oct (2)	Nov (3)	Dec (4)	Jan (5)	Feb (6)	Mar (7)	Apr (8)	May (9)	Jun (10)	Jul (11)	Aug (12)	Sep (13)
Wet, Above, or Below Normal	402	518	518	518	518	518	688	1,543	834	276	261	261
Dry	346	415	415	415	415	415	620	1,543	834	276	261	261
Critical	346	415	415	415	415	415	620	1,133	825	276	261	261
Extremely Critical	346	415	415	415	415	415	449	518	518	274	261	261

Table 3-7. Local Water Demand at Marysville in Acre-Feet (Bookman-Edmonston 2002)

Year Type (1)	Oct (2)	Nov (3)	Dec (4)	Jan (5)	Feb (6)	Mar (7)	Apr (8)	May (9)	Jun (10)	Jul (11)	Aug (12)	Sep (13)
Wet or Above Normal	22,353	12,247	7,018	2,500	3,430	6,138	22,963	70,619	66,577	76,524	63,297	22,022
Below Normal, Dry, or Critical	22,353	12,247	7,018	2,500	3,430	7,781	27,568	70,619	66,577	76,524	63,297	22,022

Water Supply Operations

Yuba basin water supply operations are focused on:

22. Delivery to demand at Marysville which is a dependent on both year type classification and month of the year (Table 3-7)(Bookman-Edmonston 2002), and
23. Releasing surplus storage from the conservation pool and routing it down the Yuba, Feather, and Sacramento Rivers to the Delta for export.

Hydropower Generation Operations

YCWA and Pacific Gas and Electric (PG&E) contract so that (Aikens 2002):

24. PG&E can make releases, as necessary, so long as it does not draw reservoir storage below the monthly storage level defined as the bottom of the power pool (Table 3-8, column 2), and
25. YCWA must make releases to generate a firm level of hydropower (Table 3-8, column 3) when reservoir storage is below the level prescribed by operation #24.

Table 3-8. Hydropower Contract Operations for New Bullard's Bar (Aikens 2002)

Month (1)	End-of-Month Storage (ac-ft) (2)	Specified Energy[a] (Kilowatt-hours) (3)
January	600,000	81,700,000
February	600,000	81,700,000
March	685,000	81,500,000
April	825,000	81,700,000
May	930,000	82,000,000
June	890,000	82,100,000
July	830,000	37,000,000
August	755,000	38,200,000
September	705,000	38,900,000
October	660,000	39,300,000
November	645,000	39,500,000
December	645,000	37,800,000

a. Only applies when storage is below level specified in (2)

Chapter 4. Simulation Methods

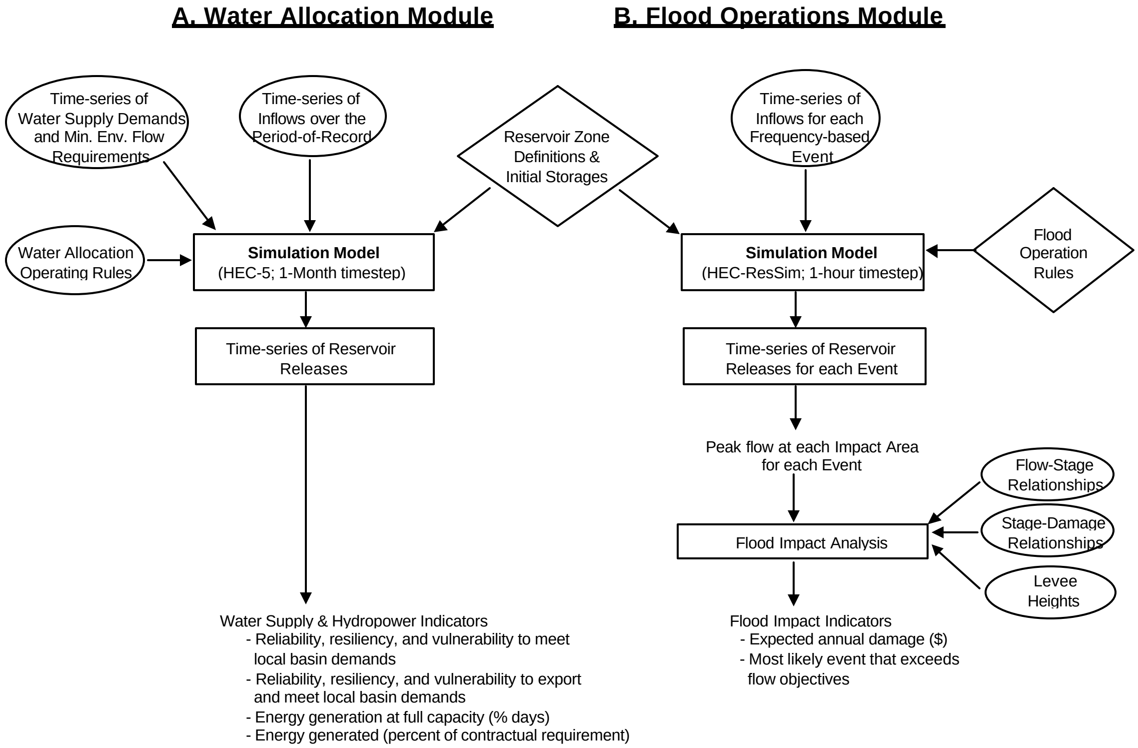
Separate water supply and flood operations modules were developed and used to simulate reservoir operations and quantify results for expected annual flood damages (EAD) and water supply reliability, resiliency, and vulnerability (Figure 4-1). Zone levels and reservoir operations rules defining each project alternative (diamonds in Figure 4-1), and other input data (ovals) were linked to each module. Flood operations were simulated over seven frequency-based, synthetic flood events for a 34-day period on a 1-hour time interval using HEC-ResSim. Using HEC-FIA, simulated reservoir releases and computed down stream, regulated flows were linked with Flow-Stage and Stage-Damage relationships to compute flood impact indicators. Water supply operations were simulated over a 73-year historical period of record (1924 to 1994) on a monthly time interval using HEC-5. Indicators representing hydropower generation and water supply reliability, resiliency, and vulnerability (Hashimoto et al. 1982) were computed directly from HEC-5 simulation model output.

Flood operations and water supply allocations were split into separate modules and simulated on different time steps for the following reasons:

1. A monthly timestep would not provide sufficient resolution to evaluate maximum regulated flows for flood events, which can be as short as 1 – 5 days in duration,
2. It was not computationally feasible—nor was flow data available—to simulate the entire 72-year period of record on a daily or hourly time step, and
3. HEC-ResSim does not yet have the capability to perform simulations on a monthly time-step.

The flood operations module is further described in Section 4.1; descriptions include the simulation model, project alternative parameters, inputs, operation rules, outputs, and

Figure 4-1. Simulation Modules and Evaluation Indicators



procedures for calculating flood impact indicators. The water supply allocation module is likewise detailed in Section 4.2. Use of the simulation modules to define and test project alternatives is explained in Chapter 5. Simulation and study method limitations are discussed in Chapter 6.

4.1 Flood Operations module

Flood operations were simulated using an HEC-ResSim watershed of the Feather and Yuba river basins (Appendix A) over a set of frequency-based flood events (0.5 through 0.002 exceedance probability; i.e., events with a probable reoccurrence interval of 2-, 10-, 20-, 50-, 100-, 200-, and 500-years)(Appendix B). The HEC-ResSim watershed generated time-series of reservoir releases and regulated flows at downstream control points. Flows were then fed into the HEC-FIA module to calculate damage for each event across 45 impact areas delineated in a Flood Damage Assessment (FDA) study of the Sacramento Basin (Cowdin 2002)(see Appendix C). To calculate EAD, damages from each event were aggregated and then weighted by the event frequency.

4.1.1 HEC-ResSim simulation model

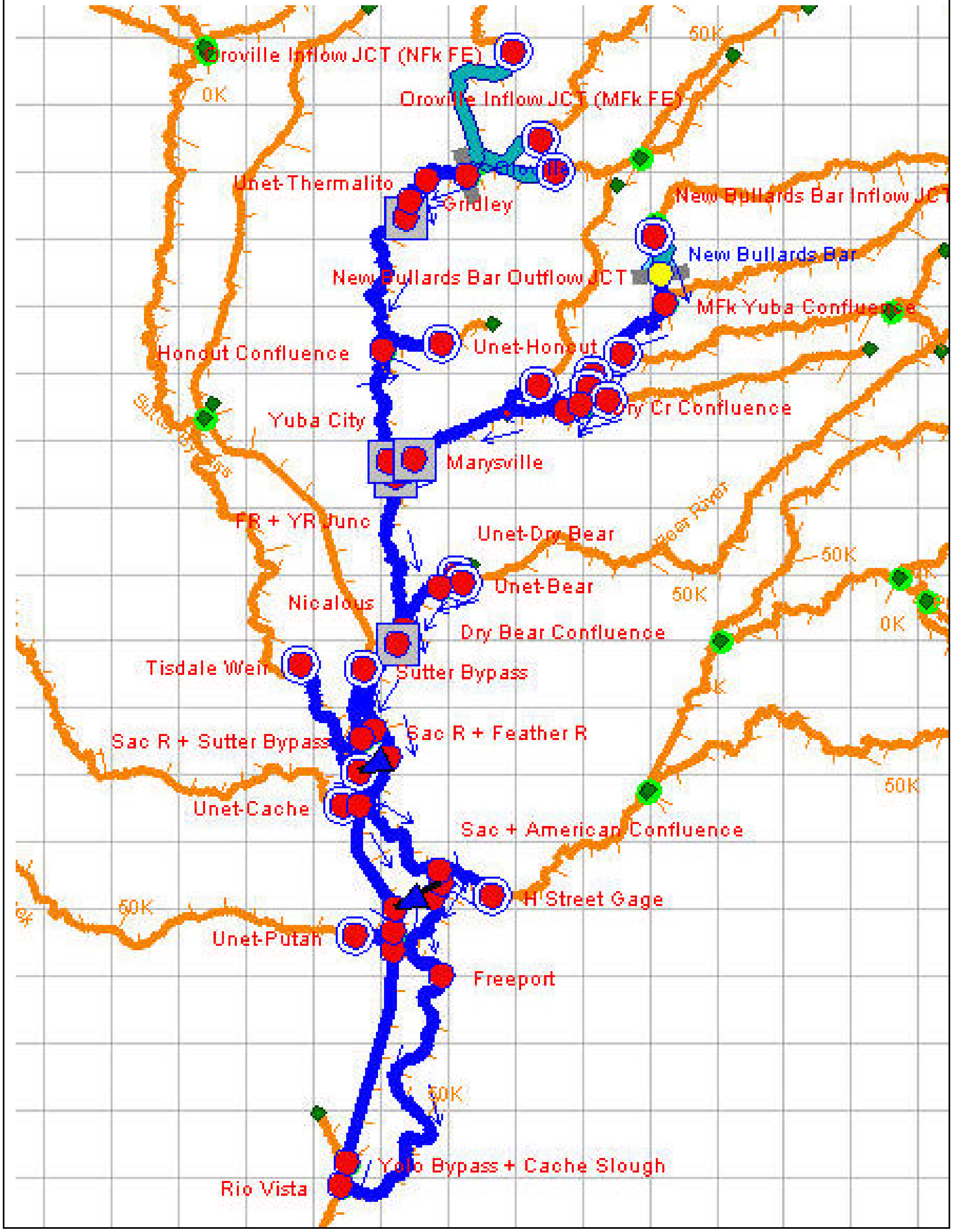
Figure 4-2 shows the HEC-ResSim watershed network of reservoirs, junctions, reaches, and diversions. The network includes Oroville and New Bullard's Bar reservoirs, the Feather and Yuba basins downstream of the reservoirs, the Fremont weir, Yolo Bypass, and Sacramento River down to Rio Vista.

Details regarding the ResSim watershed, including physical reservoir data, reservoir storage zones, reservoir operating rules, starting conditions, and reach routing parameters are presented in Appendix A. Except for the rating curve used at Fremont weir, watershed parameters were based on preexisting physical and operational data contained within a Sacramento District HEC-5 flood operation model of the Sacramento Basin (USACE and SCRB 2000). The Fremont Weir rating curve was calibrated against 1-D unsteady flow UNET model runs for the Sacramento basin as documented in Appendix D. The rating curve verified against a second calibration made using flow data observed during the January 1997 event (Countryman 2003).

4.1.2 Project alternative parameters

Project alternative parameters are indicated by diamonds in Figure 4-1 and include reservoir zone elevations, flood operation rules, and initial starting storage. The first two parameters were entered in the Network Module of HEC-ResSim as "operations sets." Separate operations sets were scripted to represent the unique zone definitions or

Figure 4-2. Flood Operations Model Network in HEC-ResSim



operations of each project alternative. Operations sets were then linked to time-series of flows and lookback starting conditions. Seven, separate inflow scenarios were created for each project alternative and spanned the set of 7 frequency-based flood events.

4.1.3 Input data

As shown in Figure 4-1, module input data is represented by circles and consists of:

1. Synthetic, time-series of hourly flows for 0.5 through 0.002 probability exceedence events for storms centered in the Sacramento basin. Flow locations include: Oroville reservoir, Honcut creek, New Bullard's Bar reservoir, the Middle and South fork confluences of the Yuba River, Deer and Dry creek confluences with the Yuba River, the Bear and Feather River confluence, Sacramento River above Freemont weir, the American River confluence, Cache and Putah creek confluences (see hydrographs in Appendix B).

2. Stage-flow rating curves for the breakout location associated with each of 45 flood-impact areas in the Yuba, Feather, and Sacramento River basins (Cowdin 2002) (see Appendix C, section 2). Rating curves were developed from Sacramento Basin UNET model stage and flow output (Tibbits 2002).

3. Economic damage versus stage relationships for each impact area (Cowdin 2002). Damage functions were invariant with season and aggregated across 8 damage categories (single-family residential, multi-family residential, mobile homes, commercial, industrial, public, farms, and crops). Damage functions are presented in the watershed directory "Yuba-Feather-WS-FDA" (Appendix C).

4. Levee failure height for each impact area. These heights describe the fail-safe stage below which flood damages do not occur. In the FDA study, failure heights

were specified with 3 levels of geo-technical uncertainty. In the flood operations model, failure height was assumed to be the top of the levee (Appendix C, Table C-2, column 3).

4.1.4 Simulation output

In the HEC-ResSim Simulation Module, a simulation was created for each project alternative. Each simulation contained the seven inflow scenarios linked to the operation set defining the project alternative. For each scenario simulated, HEC-ResSim computed a time-series of regulated releases and downstream flows at each model junction and reference location. Time-series were computed on an hourly time interval over the 34-day period of each storm scenario (see the Simulation Module in the watershed "Yuba-Feather-WS-FIA" in Appendix A for examples). Readers should consult the "HEC-ResSim User's Manual" (2002) for explanation of the user interface and the decision logic the program uses to compute reservoir releases.

4.1.5 Evaluation indicators

Two types of indicators were used to evaluate flood operation simulations: (i) expected annual damage (EAD), and (ii) ability to meet downstream operational flow objectives.

EAD was calculated using flood impact analysis by considering 45 impact areas downstream of Oroville and New Bullard's Bar reservoirs (Table C-2 and Figure C-1)(Cowdin 2002). EAD was calculated aggregating impacts in all areas and weighting by the probability-based events simulated. The following procedure summarizes this calculation:

1. For each frequency-based event simulated, determine the peak, maximum regulated flow at each reference location,

2. Calculate the maximum river stage corresponding to each peak flow using the stage-discharge relationship specific to the reference location,
3. At each impact area, calculate the damage value associated with the maximum flood stage,
4. Sum impacts over all areas, and
5. Sum and weight impacts across the set of frequency-based events.

The EAD computation can be expressed mathematically as:

$$EAD_T = \sum_{e=1}^{E} \left[\left(p_e - p_{e-1}\right) \cdot \frac{1}{2} \cdot \sum_{a=1}^{A} \left[d_a\left(S_{l_a}\left(\max\left(f_{l_a,e}\right)\right)\right) + d_a\left(S_{l_a}\left(\max\left(f_{l_a,e-1}\right)\right)\right) \right] \right] \tag{4.1}$$

Where EAD_T is total damage expected every year ($); e and a are indices representing the set of frequency-based event scenarios (0.5, 0.1, 0.04, 0.02, 0.01, 0.005, 0.002, and 0.000) and impact areas over which flooding is considered; E and A are upper bounds for the indices; l_a is the river reference location associated with impact area a; p_e is the probability that event e will occur; $d_a(s)$ is the function relating the damage at impact area a with maximum river stage s; $S_l(f)$ is the function describing the stage expected at location l for flow f, and $f_{l,e}$ is a time-series of regulated flows at location l predicted by simulating the e probability-occurrence event in the Flood Simulation model. Only the $p_1 = 0.5$ through $p_7 = 0.002$ events were simulated. Damage is assumed to linearly decrease to zero for events with likelihood's greater than $p_1 = 0.5$ (i.e., $p_0 = 1.000$; $d_0 = 0$). Damages for events less likely that the $p_7 = 0.002$ event are assumed to equal damage for the p_7 event (i.e., $p_8 = 0.000$; $d_8 = d_7$).

Steps #1 – 3 of the EAD procedure were performed using HEC-FIA while steps # 4 and 5 were computed in Excel. For each scenario of each project alternative, an HEC-FIA table listing total damages for each impact area was saved to a text file. Text files were loaded into Excel and the project alternative EAD was computed from the set of scenarios.

Computations were performed in Excel because HEC-FIA cannot yet perform analysis across multiple scenario runs.

The ability to meet flow objectives was evaluated at 6 separate locations for each scenario by comparing simulation flow output to the flow objective. Locations and flow objectives are listed in Table 4-1; these locations represent critical operation points within the Feather-Yuba basins.

4.2 Period-of-Record, water allocation module

Water supply operations were simulated over a 73-year historical period of record (Oct 1921 to Aug 1994) using an HEC-5 model of the Feather and Yuba river basins. The model computed time-series of reservoir releases, hydropower generated, downstream flows, shortage to water demand, and shortage to hydropower generated. Water supply and hydropower indicators were computed from the shortage time-series.

Table 4-1. Flood Operational Flow Objectives

Location (1)	**Objective Flow** (cfs) (2)	**Operation No.**[a] (3)
1. Feather River below Oroville	150,000	4
2. Yuba City	180,000	5
3. North Fork of Yuba River	50,000	16
4. Marysville	180,000	17
5. Feather + Yuba Rivers Confluence	300,000	6
6. Nicolaus	320,000	7

Note: a- Refers to operation number specified in Chapter 3 Section 3.

4.2.1 Simulation model

HEC-5 simulation model input records (see input data file in part 1 of Appendix E) were adapted from a preexisting HEC-5 flood operations model of the Sacramento basin (USACE and SCRB 2000). Only records for reservoirs and downstream control points located within the Feather-Yuba network and upstream of the Nicolaus operation point were retained.

Key adaptations made were:

- Adding a power pool (zone 4) to each reservoir, defining the top of this zone as the "Guide Curve", and redefining zone 5 as the flood pool rather than the surcharge pool (changed J1, RL 3, RL 4, and RL 5 records),
- Redefining the top of the buffer and conservation zones with monthly rather than seasonal time steps (remove CS records from reservoir data blocks, define RL 3 and RL 4 cards with 12 values)
- Simulate on a monthly time interval over the historical period of record (change BF record)
- Remove all flood operations besides the maximum flow-limit criteria (comment out all RG, RD, CL, CC, and CG records),
- Add minimum required flow criteria to include monthly, varying water supply demands on the Feather and Yuba Rivers and in-stream environmental flow criteria on the Feather River, at Marysville, and Smartsville (added ZR=MR599, ZR=MR660, and ZR=MR601 records below BF record), and
- Add hydropower generation operations as described in Chapter 3 section 3.2 (added P1, P2, and PR records to New Bullard's Bar reservoir data block).

Further details of these adaptations are provided as comments (C records) in the input data file itself (see “PorLBCC1.dat” in Appendix E)

Simulations were then run in a DOS window using the program HEC-5A. The input data record file, input DSS file (containing the time-series of data inputs, see section 4.2.3 below), and output DSS file were specified at the DOS command prompt.
For a simulation, HEC-5 tracked inflows and reservoir storages in each month, and calculated the average monthly release necessary to meet water supply demands, minimum environmental flow requirements, and generate hydropower at New Bullard’s Bar. At the same time, all surplus inflow encroaching into the flood pool were spilled. Also, when reservoir level dropped into the buffer zone, releases were reduced to share shortage equally between water supply and minimum flow requirements. This decision logic was repeated in each successive time period.

4.2.2 Project Alternative Parameters

Storage values defined on the RL 4 cards for each reservoir define the Guide Curve (top of power pool / bottom of flood pool) and were subject to change for different storage reallocation project alternatives. These changes were saved as separate input data files (PorLBCC2.dat, PorLBCC3.dat, etc. in Appendix E).

4.2.3 Input Data

Input data consists of:

1. Time-series of monthly, average flow over the period of record (1921 to 1994) specifying inflow to Oroville reservoir, local inflow from Honcut Creek, inflow to New Bullard’s Bar reservoir, and local inflow to the Yuba River from Deer Creek, Dry Creek, and the Middle and South Forks of the Yuba River (Jenkins et al. 2001). Jenkins et. al’s data already incorporated evaporative storage losses.

The time-series were converted into an average monthly flow and linked to the HEC-5 simulation model.

2. Time-series of monthly local water supply demands in the Feather and Yuba basins. Local Feather basin demands are summarized in Table 3-4 and were computed by averaging monthly deliveries to the FRSA contractors from 1985 through 1990 and 1993 through 2000 (DWR 1985; Leahigh 2002). Deliveries in 1991 and 1992 were significantly below average due to drought conditions and not factored into the calculations. Local Yuba demands are summarized in Table 3-7 as reported for Daguerre Point diversion requirements (DWR 1985; Leahigh 2002). Yuba demands were adjusted over the period of record based on year-type classifications reported by DWR (2002). Both time-series represent unit demand levels in the respective basins. Unit levels were multiplied by demand factors (0.5, 1, 2, 3, 4, and 5) to generate additional demand levels.

3. Time-series of monthly, minimum in-stream flow requirements for the Feather River, the Yuba River at Smartville (below the confluence with Deer creek), and the Yuba River at Marysville. Feather river minimum flow requirements are listed in Table 3-3 as reported by Leahigh (2002) and DWR (1985). Smartville and Marysville minimum flow requirements are listed in Tables 3-4 and 3-5; requirement for each month of the 73-year period of record were adjusted based on water-year-type classifications reported at DWR (2002).

4. For the Feather River and Marysville, the local basin water supply demand and the minimum in-stream flow requirement were added to generate time-series of total demand-requirement at each of those locations.

4.2.4 Simulation output

The HEC-5 water allocation model outputted time-series of monthly reservoir releases, hydropower generated, and total river flow at the downstream points of interest. The model also calculated time-series of shortages to required energy and water supply demand at appropriate locations. Shortages were calculated by subtracting the hydropower generated (or total river flow) from the required energy (or the total demand) in each time-period of the simulation.

4.2.5 Evaluation criteria

The six water supply and two hydropower indicators used to evaluate simulation output were:

(i) Reliability, (ii) vulnerability, and (iii) resilience to meet local basin water supply demand,
(iv) Reliability, (v) vulnerability, and (vi) resilience to meet two times the local basin water supply demand,
(vii) percentage of days able to generate maximum power, and
(viii) percentage of required hydropower generated.

Water supply indicators (i) through (vi) were computed separately for the Feather and Yuba basins. Indicators (iv) through (vi) were used to express the reliability, resilience, and vulnerability to which an additional quantity of water could be exported south of the delta. In this application, reliability (R), vulnerability (V), and resiliency (S) are used as defined by Hashimoto et al (1982) and were calculated as:

$$R = \text{Reliability} = \frac{N_{zeros\,shortage}}{T} = \text{Percent time of no shortage} \tag{4.2}$$

$$V = \text{Vulnerability} = \frac{\sum_{t=1}^{T} s_t}{T - N_{zeroshortage}} = \text{Average magnitude of shortage} \tag{4.3}$$

$$S = \text{Resiliency} = \frac{T - N_{zero\,shortage}}{N_{Droughts}} = \text{Average legnth of shortage} \tag{4.4}$$

Where $N_{\text{zero shortage}}$ = total number of instances (months) where the time-series of shortage to demand is zero; T = total months in the 73-year period of record simulation (870); s_t = amount of shortage in month t of the time-series record; and N_{Droughts} = number of droughts in the shortage time-series, i.e., where shortage changes from zero to some positive value in successive time-periods ($s_t = 0 \cup s_{t+1} > 0$).

Hydropower generation indicators (vii) and (viii) were evaluated only for New Bullard's Bar reservoir. Since hydropower indicators could not be calculated explicitly in simulation runs, a DSS macro was written to post-process the time-series of simulation results. The macro computed the indicators as follows:

$$PD_S = \frac{\sum_{y=1}^{Y}\left[\sum_{m=M_S} g\left(\frac{f_{y,m}}{P_{\max}}\right)\cdot d_{y,m}\right]}{\sum_{y=1}^{Y}\sum_{m=M_S} d_{y,m}}; \qquad g(x) = \begin{cases} x, & x < 1 \\ 1, & x \geq 1 \end{cases} \tag{4.5}$$

Where PD_S is the percentage of days able to generate full power in season S; y and m are indexes representing water years and months; Y is the last year of the simulation period; M_S is the set of months in season S (Summer = May -- September; Winter = October -- April); $f_{y,m}$ is the release in CFS from New Bullard's Bar in month m of year y; $P_{\max}$ is the maximum hydropower generation capacity for the Colgate power house and equals 3,400 cfs (USACE 1972); and $d_{y,m}$ is the number of days in month m of water year y.

Likewise, percentage of required hydropower generated (PRH_S) was calculated as:

$$PRH_S = \frac{\sum_{y=1}^{Y}\sum_{m=M_S}\frac{EG_{y,m}}{ER_{y,m}}}{\sum_{y=1}^{Y}\sum_{m=M_S}1} \tag{5.7}$$

Where $EG_{y,m}$ is the energy generated in month m of water year y, $ER_{y,m}$ is the energy required in month m of water year y, and y, m, Y, M_S, and S are as defined previously.

Chapter 5. Study Methods

The water supply allocation and flood operations modules discussed in Chapter 4 were used to simulate and evaluate the base case project, 18 control runs, and all project alternatives (Table 5-1). These aspects of the study are described as follows.

5.1 Base Case

The base case project consisted of reservoir zone levels for Oroville and New Bullard's Bar as defined in the Comprehensive Study Sacramento basin model (see definitions in Table 3-2) (USACE and SCRB 2000) and flood and water supply operations as listed in Chapter 3 Section 3. In the flood operations module, zone level elevations and operations rules were entered as an operations set (Figure A-3, Appendix A). Seven separate flow scenarios (representing 0.5, 0.1, 0.04, 0.02, 0.01, 0.005, and 0.002 likelihood events) for the Sacramento storm centering were linked to base case operations set (Figure A-4, Appendix A shows an example for the 200-year event). Then, each base case scenario was simulated in HEC-ResSim.

In the Water Supply allocation module, base case flood and conservation pool levels were defined on the RL 3 and RL 4 records for each reservoir in the input data file "SacLBCC1.dat." Within the input data file, time-series representing the unit-level of local water demands in the Feather and Yuba basins (see Chapter 3 section 3) were defined on ZR=MR599 and ZR=MR601 records. The input data file and time-series data were linked to the HEC-5 executable. Simulation output was written to DSS.

5.2 Verification and Control Runs

Control runs were made to further test and verify base case project results using:

Table 5-1. List of Project Alternatives

Project Alternative Description (1)	Type (2)
(a) 1st Round of researcher-initiated alternatives	
1. Base Case	Existing storage alloc.
2. Raise Oroville wintertime guide curve 40 TAF	Storage reallocation
3. Lower Oroville wintertime guide curve 40 TAF	Storage reallocation
4. Raise Oroville wintertime guide curve 200 TAF	Storage reallocation
5. Lower Oroville wintertime guide curve 200 TAF	Storage reallocation
6. Raise New Bullard's Bar wintertime guide curve 45 TAF	Storage reallocation
7. Lower New Bullard's Bar wintertime guide curve 45 TAF	Storage reallocation
8. Raise New Bullard's Bar wintertime guide curve 100 TAF	Storage reallocation
9. Lower New Bullard's Bar wintertime guide curve 100 TAF	Storage reallocation
10. Raise New Bullard's Bar top of buffer 50 TAF	Storage reallocation
11. Lower New Bullard's Bar top of buffer 50 TAF	Storage reallocation
12. Raise Oroville wintertime guide curve 300 TAF	Storage reallocation
13. Raise Oroville wintertime guide curve 400 TAF	Storage reallocation
14. Lower Oroville wintertime guide curve 300 TAF	Storage reallocation
15. Lower Oroville wintertime guide curve 400 TAF	Storage reallocation
(b) 2nd Round of participant solicited project alternatives	
16. Lower Oroville wintertime guide curve 100 TAF (conjunctive use study alternative #2)	Storage reallocation
17. Lower Oroville wintertime guide curve 138 TAF (conjunctive use study alternative #1)	Storage reallocation
18. Lower New Bullard's Bar wintertime guide curve 120 TAF (conjunctive use study alternative #1)	Storage reallocation
19. New Bullard's Bar operates for flow objective of 180,000 cfs at Marysville (rather than 300,000 cfs at Feather – Yuba confluence)	Re-operation
20. Increase New Bullard's Bar objective release to 75,000 cfs (from 50,000 cfs)	Re-operation
21. Combine Alternatives #19 and #20	Re-operation
22. Decrease Feather –Yuba River confluence flow objective to 270,000 cfs (rather than 300,000 cfs).	Re-operation

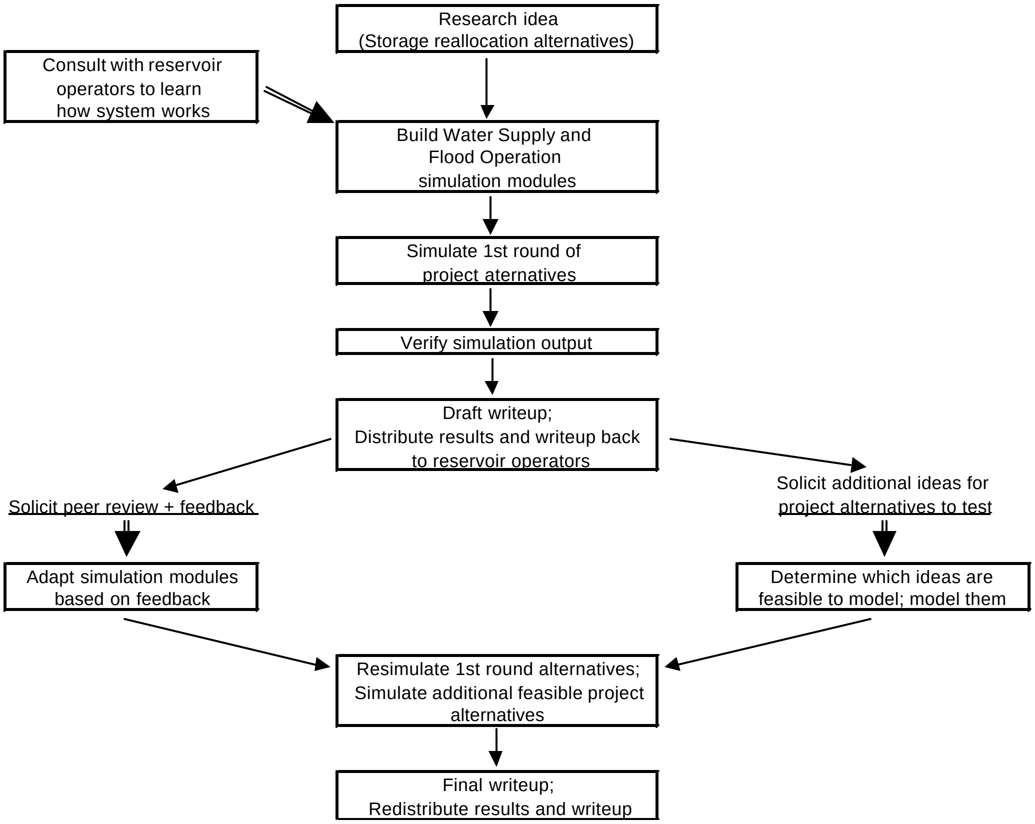
(i) inflow from synthetic storms centered in Feather basin, the Yuba basin, and at Shanghai Bend (located 1 mile downstream of the confluence of the Feather and Yuba rivers)(Whitin 2003); (ii) a second impact area set of breakout locations and stage-damage relationships delineated in a Flood Impact Analysis (FIA) study of the Sacramento Basin (Dunn 1999)(Appendix F); (iii) reservoir releases routed with travel times as simulated in the UNET model of the Sacramento Basin (Tibbits 2002); and (iv) varying levels of local water demand. A further explanation of how control runs were defined in the flood operations and water allocation modules and simulated is provided as Appendix G. Control run results were used to select the Sacramento storm centering, FDA impact area set, and twice the unit-level of demand in both the Feather and Yuba basins as the conditions under which all project alternatives were eventually simulated and evaluated.

5.3 Project Alternatives

Project alternatives (Table 5-1) were developed and tested using a research and semi-participatory modeling approach as outlined in Figure 5-1. Fourteen storage-reallocation project alternatives were simulated and evaluated in a first round of modeling using the Sacramento storm centering, FIA study impact area set delineated by Dunn (1999)(Appendix F), unit level demand in the Yuba basin, and twice the unit level demand in the Feather basin. Reallocation alternatives involved either raising (or lowering) the wintertime definition of the guide curve at one reservoir while holding the guide curve at the other reservoir to its base case definition.

Next, simulation results and draft documentation were distributed to 3 water resources professionals. Each professional was asked to review the manuscript and suggest additional project alternatives to simulate and evaluate. Feedback was received from

Figure 5-1. Semi-Participatory Approach to Simulation Modeling and Project Alternative Development



Countryman (2003) and Whitin (2003) and clarified through follow-up telephone calls or in-person discussion. Table 5-2 summarizes participant feedback and how feedback was addressed.

As noted in column (1), participants suggested project alternatives for:

- Three additional storage reallocations encapsulating winter-season draw-down volumes calculated in a Conjunctive Use study (USACE 2001),
- Three new reservoir re-operation policies,

Table 5-2. Proposed Project Alternatives and Feedback Solicited from Participants

Proposed Project Alternatives			Additional Feedback or Comments		
Description	Addressed?		Description	Addressed?	
	Yes	No		Yes	No
(1)	(2)	(3)	(4)	(6)	(7)
(a) Whitin, Sacramento District, USACE (2003)					
1. Lower Guide Curves by draw-down volumes calculated in Conjunctive Use study	Yes		1. Minor text edits	Yes	
2. New Bullard's Bar operates only for 180,000 cfs flow objective at Marysville (not 300,000 cfs flow objective at Feather - Yuba confluence)	Yes		2. When Oroville guide curve is raised 200 TAF, is reservoir still able to pass 0.005 probability event?	Yes	
3. Use Shanghai Bend storm event centered at confluence of Feather and Yuba Rivers	Yes				
4. Add 40 TAF additional flood storage project at Englebright reservoir		No[a]			
5. Lengthen travel time from Oroville down to Yuba City to 16 hours (from 8 hours)		No[b]			
(b) Countryman, MBK Associates (2003)					
1. New Bullard's Bar operates only for 180,000 cfs flow objective at Marysville	Yes		1. EAD calculations and conclusion regarding ability to raise Oroville guide curve 200 TAF with little change to EAD look suspect. Why large damages for high likelihood (low return period) events? Appropriate levee heights?	Yes[c]	
2. Increase New Bullard's Bar release objective to 75,000 cfs (from 50,000 cfs)	Yes		2. Verify Freemont Weir rating curve against January 1997 flow calibration	Yes	
3. Decrease Feather - Yuba confluence flow objective to 270,000 cfs (from 300,000 cfs)	Yes		3. Honcut Creek local inflow looks to high		No
4. Prerelease 40 TAF from Thermolito afterbay to increase flood storage in Oroville		No[a]			

Notes:

a. Not feasible to add an additional reservoir to HEC-ResSim watershed network
b. Not feasible to change routing times in HEC-ResSim watershed network and resimulate
c. Developed 2nd impact area set as defined by Cowdin (2002)

- An additional control run for a synthetic storm centered 1 mile downstream of the confluence of the Feather and Yuba rivers at Shanghai Bend (Whitin 2003), and
- Two additional downstream flood protection projects and altered routing times.

The last three project suggestions required extensive modifications to the network layout of the HEC-ResSim flood operations model. These suggestions were not simulated.

Key comments regarding simulations and results are noted in Table 5-2, column 4. The most challenging comment concerned the validity of EAD calculations using the FIA impact area set. Countryman (2003) asked, why were large damages for high likelihood (i.e., low return period) events observed when the reservoirs were operating within objective flow criteria? Did the FIA impact area set use appropriate levee heights? To address this concern, a second impact area set was delineated using breakout locations, levee heights, and stage-damage relationships used for a Flood Damage Assessment (FDA) study in the Sacramento Basin (Cowdin 2002)(Appendix C). The FDA study was based on a more recent and complete inventory of structures in the impact areas and site-specific levee heights. A description of the FDA results and their improvement over FIA results is given in Chapter 7, section 1.

In a second round of modeling, the new project alternatives were defined, and all project alternatives were re-simulated and evaluated using the Sacramento storm centering, FDA impact area set, and twice the unit-level of demand in the Feather and Yuba basins. Appendix H explains how storage reallocation and reservoir re-operation project alternatives were defined in the simulation modules. Final results were redistributed to each participant.

Chapter 6. Limitations

Generally, the methods outlined in Chapters 4 and 5 are limited by the assumptions that:

1. Evaluation of alternatives is limited to flood and water supply impacts only. This evaluation does not consider recreation, navigation, legal, or institutional aspects and only considers hydropower and environmental aspects as required to meet minimum hydropower generation requirements at New Bullard's Bar reservoir and in-stream flows in both the Feather and Yuba basins, and
2. Model networks and simulated operations are assumed to represent all the important inflow, storage, water demand, flood impact areas, connectivity, and timing required to move water within the basins.

Limitations specific to the event-based flood operation simulation and HEC-FIA are:

3. Damage weighting is based on simulation of frequency-based synthetic hydrology representing a Sacramento storm centering. Synthetic flow-frequency relationships may be different for storms centered in different basins,
4. Reservoir release decisions to meet downstream flow objectives are made considering perfect, limited foresight of intermediary local inflows. This foresight ignores flood forecasting, operator uncertainty, or other real-time operations.
5. Diversions and operations for water supply are ignored while routing flood operational releases,
6. Out-of-bank flow is not considered,
7. Flooding or damage at one impact area does not affect flooding or damage at other, downstream impact areas,
8. Both flood impacts and the frequency of flood events are the same across all months of the flood season,

9. Flood damage at a location corresponds to the peak regulated discharge (and corresponding stage) observed for the flood event,
10. Regulated flows will not change the discharge-stage relationship in any reach,
11. Additional regulated and non-regulated inflows to the Sacramento basin below the confluence of the Feather and Yuba rivers are modeled as static,
12. Expected Annual Damage (EAD) is calculated ignoring uncertainties in the regulated flow-frequency relationship, stage-discharge relationship, stage-damage relationship, and levee failure stage.

Limitations for the period-of-record, water supply simulation and evaluation are:

13. Water supply allocations are 100% consumptive (no water returns to the river) while allocations for hydropower and to meet minimum in-stream flow requirements are 100% non-consumptive (all water ends up in the Delta),
14. All water spilled during the flood season to maintain the flood pool and above minimum water supply requirements is allocated down the rivers to the Delta. This spill represents 100% non-consumptive flow,
15. FRSA and Marysville water supply demands are specified by month, and
16. The 73-year past historical record will represent possible future hydrology.

Chapter 7. Results

Selected flood impact, water supply, and hydropower generation indicators are presented for the existing storage allocation scheme (base case), base case control runs (Table 7-1), and 19 additional project alternatives (Table 7-2; Figures 7-1 through 7-3; Appendix I).

7.1 Base case and control runs

In Table 7-1A, flood impact indicators of expected annual damage (EAD, columns 5 through 7) and the return period for the largest (i.e., least likely) event that meets flow objectives at six locations (columns 8 through 13) are reported for each base case control run. EAD is reported for all impact areas (column 5), impact areas located in just the Feather and Yuba basins (column 6), and impact areas in the Lower Sacramento basin downstream of the Feather and Sacramento River confluence. Total EAD calculated from the FDA study impact area set generally agrees with EAD calculated from the FIA study impact area set (column 5, rows 1A through 1D compared to rows 1E through 1H). However, the two sets show different distributions of damages between the Feather-Yuba and Lower Sacramento Basins (same rows, columns 6 and 7). Also, 70 to 90% of EAD calculated from the FIA study impact area set is attributed to high likelihood events with re-occurrence intervals *less* than 100 years (results not shown). This result indicates that FIA impact area delineations predict significant damages even as downstream flow objectives are being met. FDA study impact area set delineation results show that events with re-occurrence intervals less than 100-years contribute no more than 50% to total EAD (results also not shown). FDA impact area data was compiled from a more recent land-use, building, and crop inventory. Therefore, the FDA study impact area set—rather than the FIA set—is subsequently used as the basis for calculating EAD.

Table 7-1. Simulation Results for Base Case and Control Runs

A. Flood Impact Indicators

Base Case Control Run				Expected Annual Damage ($)			Return Period for Largest Event that Meets Flow Objective at					
Description (1)	Inflow hydrology (2)	Impact area set (3)	Demand level (4)	Total (5)	In Feather - Yuba basin (6)	In Lower Sacramento basin (7)	Oroville reservoir (8)	New Bullard's Bar reservoir (9)	Yuba City (10)	Marysville (11)	Feather+Yuba confluence (12)	Nicolaus (13)
1A. Base Case	Sacramento basin centering	FIA	1	$182,602,869	$ 90,203,450	$ 92,399,463						
1B. Base Case	Feather basin centering	FIA	1	$176,307,485	$ 83,941,062	$ 92,366,947						
1C. Base Case	Yuba basin centering	FIA	1	$171,820,819	$ 79,909,584	$ 91,911,231						
1D. Base Case	Shanghai Bend A centering	FIA	1	$156,371,058	$ 12,717,268	$ 143,653,791						
1E. Base Case	Sacramento basin centering	FDA	1	$156,991,356	$ 13,329,174	$ 143,662,182	200-year	100-year	200-year	100-year	100-year	25-year
1F. Base Case	Feather basin centering	FDA	1	$116,981,906	$ 12,328,143	$ 104,653,763	100-year	100-year	100-year	100-year	100-year	50-year
1G. Base Case	Yuba basin centering	FDA	1	$151,378,185	$ 9,003,313	$ 142,374,872	200-year	100-year	200-year	100-year	100-year	50-year
1H. Base Case	Shanghai Bend A centering	FDA	1	$119,831,771	$ 14,123,720	$ 105,708,051	100-year	50-year	100-year	100-year	100-year	25-year
1I. Base Case	Unet - Sacramento centering	FIA	1	$166,377,197	$ 81,806,724	$ 84,570,557						
1J. Base Case	Unet - Feather centering	FIA	1	$168,941,842	$ 83,779,983	$ 85,161,863						
1K. Base Case	Unet - Yuba centering	FIA	1	$166,468,660	$ 81,066,007	$ 85,402,610						
1L. Base Case	Unet - Sac centering	FDA	1	$164,907,977	$ 21,619,832	$ 143,288,202	NA	NA	200-year	100-year	100-year	50-year
1M. Base Case	Unet - Feather centering	FDA	1	$146,374,966	$ 4,246,901	$ 142,128,096	NA	NA	100-year	200-year	100-year	50-year
1N. Base Case	Unet - Yuba centering	FDA	1	$113,114,201	$ 7,691,551	$ 105,422,657	NA	NA	200-year	100-year	100-year	100-year
1O. Base Case	Sacramento basin centering	FIA	0.5									
1P. Base Case	Sacramento basin centering	FIA	2									
1Q. Base Case	Sacramento basin centering	FIA	3									
1R. Base Case	Sacramento basin centering	FIA	4									
1S. Base Case	Sacramento basin centering	FIA	5									

Notes:

a. Blanks indicate value does not deviate from base case run (#1E) because control run is focused on a parameter manipulation unrelated to the indicator. For example, with run #1A, manipulating the impact area set does not change the return period for which flow objectives are met in the HEC-ResSim simulation model. Demand levels do not change flood impact indicators.

Table 7-1 (continued)

B. Water Supply Indicators

Base Case Control Run				Reliability [%][b]		Vulnerability [ac-ft/month][b]		Resiliency [months][b]	
Description (1)	Inflow hydrology (2)	Impact area set (3)	Demand level (4)	At Marysville (14)	At FRSA (15)	At Marysville (16)	At FRSA (17)	At Marysville (18)	At FRSA (19)
1O. Base Case	Sacramento basin centering	FIA	0.5	98.3%	100.0%	18,128	0	3.0	0.0
1A. Base Case	Sacramento basin centering	FIA	1	91.9%	100.0%	27,318	0	4.2	0.0
1P. Base Case	Sacramento basin centering	FIA	2	72.0%	95.8%	48,071	110,324	5.3	4.6
1Q. Base Case	Sacramento basin centering	FIA	3	61.4%	82.9%	77,145	183,612	5.3	4.8
1R. Base Case	Sacramento basin centering	FIA	4	52.5%	68.6%	106,076	264,423	5.7	5.3
1S. Base Case	Sacramento basin centering	FIA	5	46.1%	57.6%	139,273	344,126	5.8	5.9

Notes:

b. to meet unit-level local basin demand

C. Hydropower Generation Indicators

Base Case Control Run				Percent of Days at Full Generation at New Bullard's Bar			Percent of Required Energy Generated at New Bullard's Bar		
Description (1)	Inflow hydrology (2)	Impact area set (3)	Demand level (4)	Winter[c] (20)	Summer[d] (21)	Total over year (22)	Winter[c] (23)	Summer[d] (24)	Total over year (25)
1O. Base Case	Sacramento basin centering	FIA	0.5	46.3%	51.9%	48.7%	8.8%	10.2%	9.4%
1A. Base Case	Sacramento basin centering	FIA	1	43.2%	56.5%	48.8%	7.6%	10.7%	8.9%
1P. Base Case	Sacramento basin centering	FIA	2	40.0%	60.9%	48.8%	6.6%	10.0%	8.0%
1Q. Base Case	Sacramento basin centering	FIA	3	39.2%	61.7%	48.6%	6.2%	10.2%	7.8%
1R. Base Case	Sacramento basin centering	FIA	4	38.2%	60.7%	47.6%	5.8%	10.0%	7.6%
1S. Base Case	Sacramento basin centering	FIA	5	37.8%	59.6%	46.9%	5.6%	9.5%	7.2%

Notes:

c. October through April

d. May through September

Simulation results show that the system is able to safely pass synthetic flows up to and including the 200-year event below flow objectives for storms centered in the different basins (rows 1E through 1H and columns 8 through 13). Oroville reservoir and Yuba City show a slightly higher level of protection against storms centered in the Sacramento and Yuba basins than to storms centered in the Feather basin or at Shanghai Bend. However, this difference does not translate into lower damages at Feather and Yuba basin impact areas (column 6). Storms centered at Shanghai Bend and in the Sacramento basin have the highest damages at Feather and Yuba basins impact areas (column 6). Sacramento and Yuba storms have the largest damages concentrated in the lower Sacramento basin impact areas (column 7). Therefore, the Sacramento storm center hydrology was selected for further study because it showed large damages in both impact area locations.

Comparisons between UNET-model routing times (rows 1L through 1N) and flood operations model routings (rows 1E through 1G) show similar ability to meet flow objectives (columns 10 through 13). UNET represents more realistic modeling of flow routing than the muskingum and null routing methods used in flood operations module. For UNET routings, Marysville was able to pass a larger storm event under the Oroville centering; likewise at Nicolaus for the Yuba centering. Both events significantly lower EAD at Feather – Yuba impact areas (column 6, rows 1M and 1N) compared to EAD calculated from regulated releases routed through the flood operations model (rows 1F and 1G). At lower Sacramento Basin impact areas, the combination of storm center and routing time seem to jointly influence the magnitude of EAD (column 7). These results identify the need to further investigate routing methods and travel times used.

In Table 7-1B, water supply indicators for reliability (columns 14 and 15), vulnerability (columns 16 and 17), and resiliency (columns 18 and 19) are reported for all base case control runs where the demand level was changed. Each indicator is reported as ability to meet demand in the Yuba basin at Marysville (e.g., column 14) and in the Feather Basin at FRSA (column 15). With increasing demand level, the control runs show decreasing reliability, increasing vulnerability, and increasing resiliency to meet demand in both basins. In the Yuba basin, shortages (reliability < 100%; vulnerability > 0; and resiliency > 0) are observed for all demand levels. In the Feather basin, shortages are first observed when demand exceeds 2 times the unit level (Run 1P). Therefore, 2 times the unit demand is level used as a basis for further study.

Hydropower generation indicators representing percentage of days New Bullard's Bar can generate at full capacity (Table 7-1C, columns 20 through 22) and percent of required hydropower generated at New Bullard's Bar (columns 23 through 25) are reported for all base case control runs where the demand level was changed. Each indictor is reported for winter months between October and April (e.g., column 20), summer months between May and September (column 21), and the total over the year (column 22). With increasing demand level, percentage of days operating at full capacity generation decreases in winter months, but increases in summer months. The overall change is less than 2%. Required energy generation shows a noticeable, but small decrease with increasing demand level. Even for the base case, NBB seems only able to generate less than 10% of contracted energy requirements. Required energy generation is not examined further in the study.

7.2 Project Alternatives

Selected simulation results for storage reallocation and reservoir re-operation project alternatives are reported in Figures 7-1 through 7-3 and Table 7-2. Storage reallocations involved raising or lowering the wintertime definition of the guide curve in one reservoir

Table 7-2. Selected Simulation Results for Project Alternatives

A. Flood Impact Indicators

Project Alternative	Return Period for Largest Event that Meets Flow Objective at					
	Oroville reservoir	New Bullard's Bar reservoir	Yuba City	Marysville	Feather + Yuba confluence	Nicolaus
(1)	(2)	(3)	(4)	(5)	(6)	(7)
(a) Storage reallocations at Oroville Reservoir						
2. Lower TOC 400 TAF in Oroville	200-year	100-year	200-year	200-year	200-year	25-year
3. Lower TOC 300 TAF in Oroville	200-year	100-year	200-year	100-year	200-year	25-year
4. Lower TOC 200 TAF in Oroville	200-year	100-year	200-year	100-year	100-year	25-year
5. Lower TOC 138 TAF in Oroville (Conj Use Alts #1,3)	200-year	100-year	200-year	100-year	100-year	25-year
6. Lower TOC 100 TAF in Oroville (Conj Use Alts #2,4)	200-year	100-year	200-year	100-year	100-year	25-year
7. Lower TOC 40 TAF in Oroville	200-year	100-year	200-year	100-year	100-year	25-year
1E. Base Case (0 TAF)	200-year	100-year	200-year	100-year	100-year	25-year
8. Raise TOC 40 TAF in Oroville	100-year	100-year	200-year	100-year	100-year	25-year
9. Raise TOC 200 TAF in Oroville	100-year	100-year	100-year	100-year	100-year	25-year
10. Raise TOC 300 TAF in Oroville	50-year	50-year	50-year	100-year	50-year	25-year
11. Raise TOC 400 TAF in Oroville	50-year	50-year	50-year	100-year	50-year	25-year
(b) Storage Reallocations at New Bullard's Bar Reservoir						
12. Lower TOC 120 TAF at NBB (Conj Use Alts #1,3)	200-year	100-year	100-year	100-year	100-year	25-year
13. Lower TOC 100 TAF at NBB	200-year	100-year	200-year	100-year	100-year	25-year
14. Lower TOC 45 TAF at NBB	200-year	100-year	200-year	100-year	100-year	25-year
1E. Base Case (0 TAF)	200-year	100-year	200-year	100-year	100-year	25-year
15. Raise TOC 45 TAF at NBB	100-year	50-year	200-year	100-year	100-year	25-year
16. Raise TOC100 TAF at NBB	50-year	25-year	200-year	100-year	100-year	25-year
(c) Re-operations						
17. Base Case - NBB operates only for Marysville	200-year	100-year	200-year	200-year	50-year	25-year
18. Base Case - NBB outlet capacity is 75,000 cfs	200-year	100-year	200-year	100-year	100-year	25-year
19. Base Case - Combination of #19 & #20	200-year	200-year	200-year	100-year	50-year	25-year
20. Base Case - Lower Confluence CC to 270,000 cfs	200-year	100-year	200-year	200-year	25-year	50-year

Notes:

a. All project alternatives simulated using Sacramento Basin storm centering, FDA Study impact area set, and demand level = 2.

B. Water Supply and Hydropower Generation Indicators

Project Alternative	Reliability^{b,c} [%]	Vulnerability^{b,c} [ac-ft/month]	Resiliency^{b,c} [months]	Percent of Days at Full Generation at New Bullard's Bar^{d}		
				Winter^{e}	Summer^{f}	Total over year
(1)	(8)	(9)	(10)	(11)	(12)	(13)
(a) Storage reallocations at Oroville Reservoir						
2. Lower TOC 400 TAF in Oroville	94.4%	113,165	4.5			
3. Lower TOC 300 TAF in Oroville	94.7%	111,596	4.2			
4. Lower TOC 200 TAF in Oroville	95.2%	113,164	4.7			
7. Lower TOC 40 TAF in Oroville	95.8%	113,935	4.6			
1E. Base Case (0 TAF)	95.8%	110,324	4.6			
8. Raise TOC 40 TAF in Oroville	96.0%	112,789	4.4			
9. Raise TOC 200 TAF in Oroville	96.6%	113,632	4.3			
10. Raise TOC 300 TAF in Oroville	96.9%	115,197	4.5			
11. Raise TOC 400 TAF in Oroville	97.3%	118,851	4.8			
(b) Storage Reallocations at New Bullard's Bar Reservoir						
13. Lower TOC 100 TAF at NBB	71.9%	47,920	5.2	56.2%	48.6%	7.6%
14. Lower TOC 45 TAF at NBB	72.0%	48,071	5.3	56.3%	48.7%	7.6%
1E. Base Case (0 TAF)	72.0%	48,071	5.3	56.5%	48.8%	7.6%
15. Raise TOC 45 TAF at NBB	72.0%	48,071	5.3	56.5%	48.8%	7.6%
16. Raise TOC100 TAF at NBB	72.0%	48,071	5.3	56.6%	48.8%	7.6%

Notes:

b. to export water through the delta and meet unit demand at FRSA from storage reallocations at Oroville reservoir

c. to export water through the delta and meet unit demand at Marysville from storage reallocations at New Bullard's Bar reservoir

d. blanks mean indicator is not applicable to reallocation at Oroville reservoir

e. October through April

f. May through September

while holding the other reservoir to the base case storage allocation. Re-operation alternatives changed objective flow criteria at one or more locations. All project alternatives were simulated and evaluated using a synthetic storm centered in the

Figure 7-1. Expected Annual Damage at Feather and Yuba Basin Impact Areas for Reallocation Project Alternatives

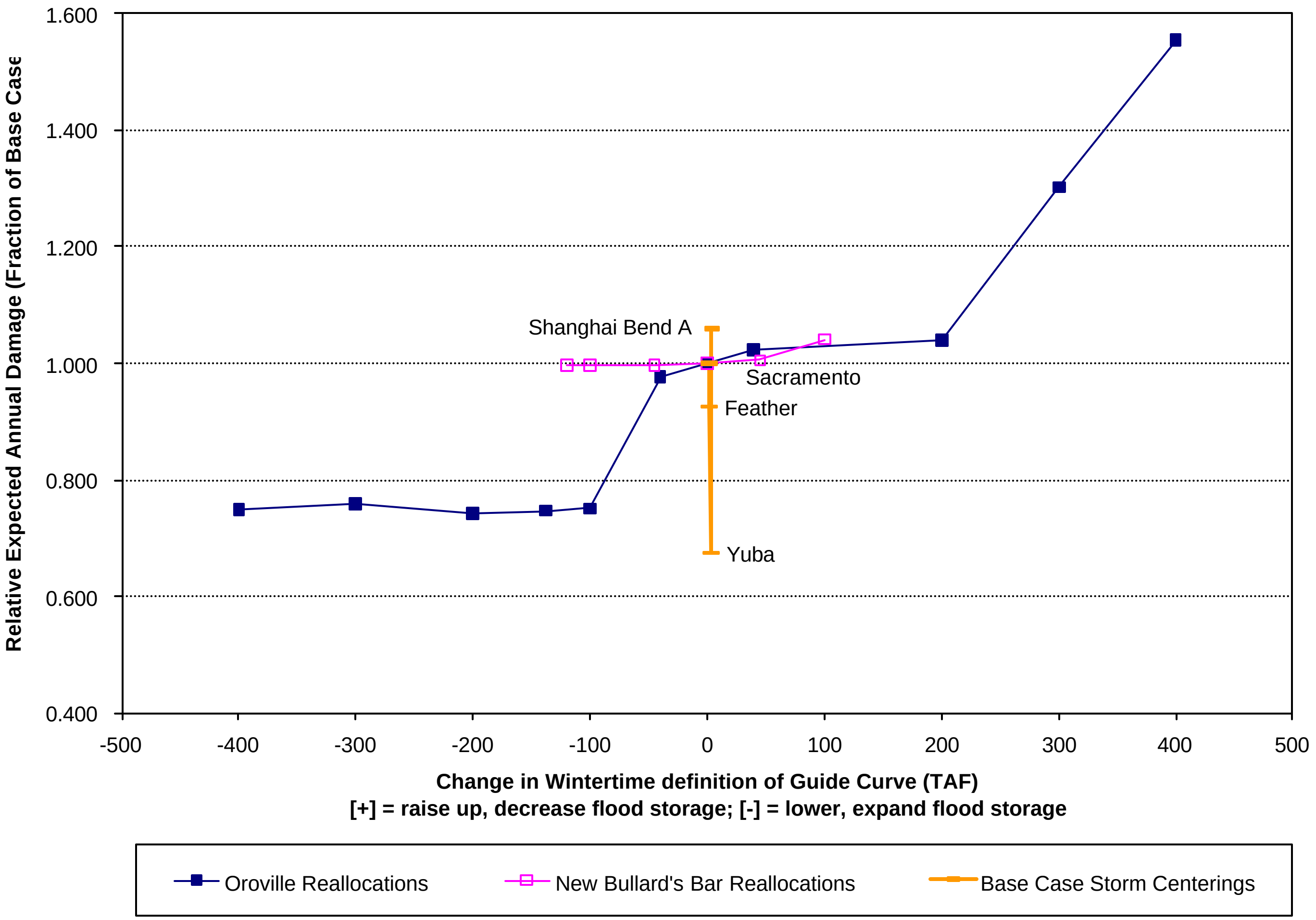


Figure 7-2. Expected Annual Damage at Lower Sacramento Impact Areas for Reallocation Project Alternatives

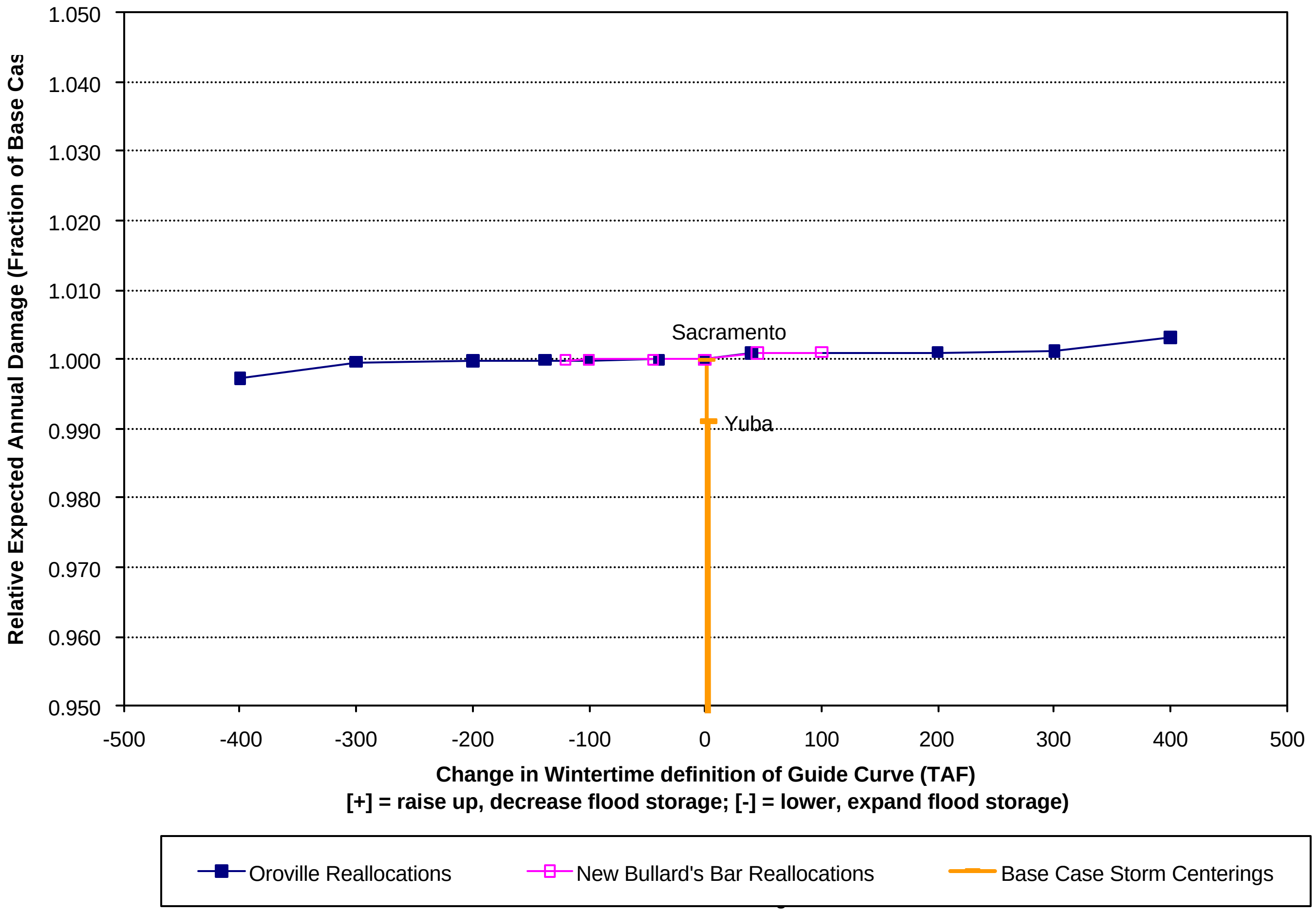
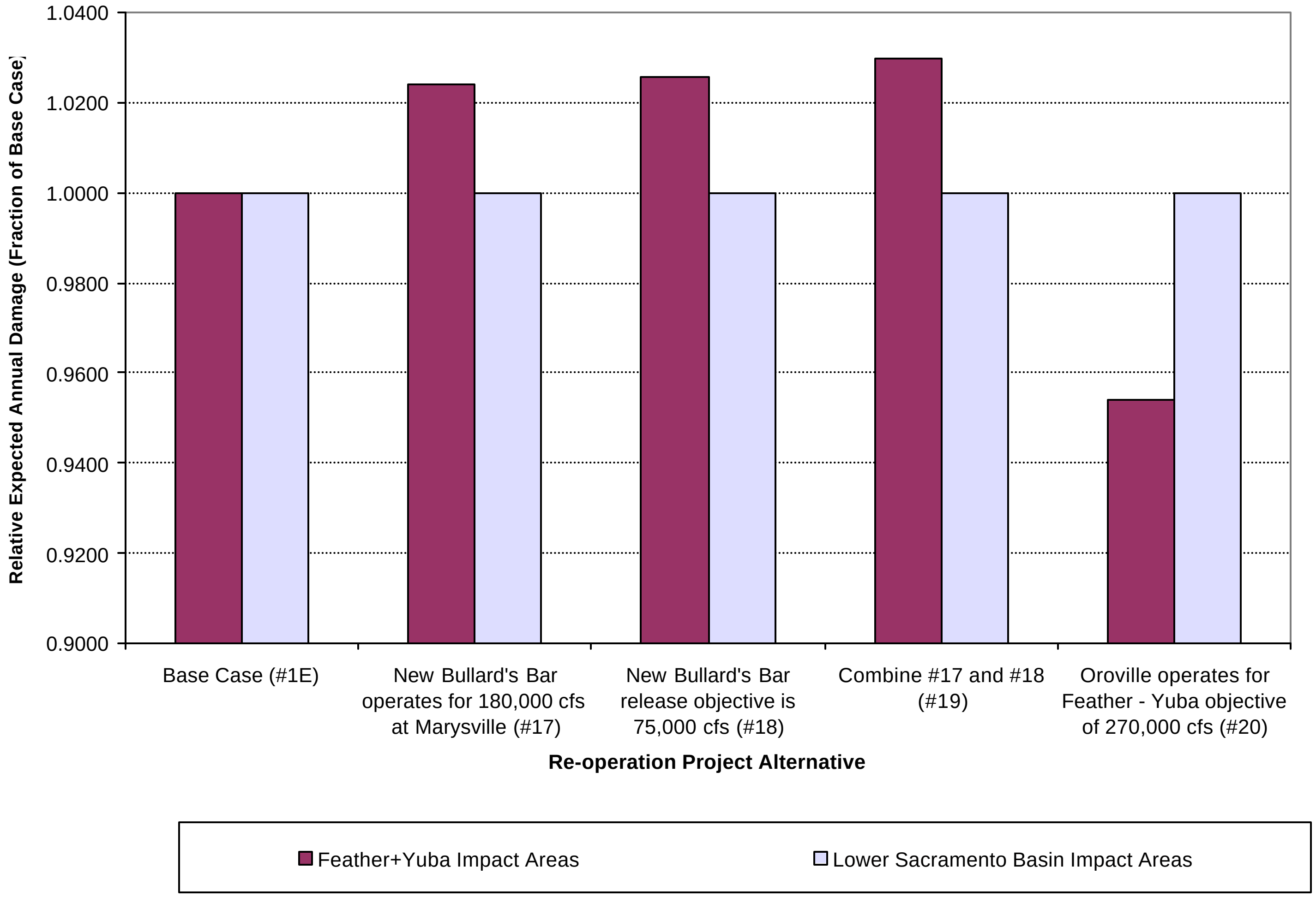


Figure 7-3. Expected Annual Damage for Reservoir Re-operation Project Alternatives



Sacramento basin, FDA study impact area set, and 2-times the unit level of water demand in both the Feather and Yuba basins.

Figure 7-1 shows the influence of sequentially raising the wintertime definition of the guide curve at New Bullard's Bar and Oroville reservoir on the expected annual damage (EAD) in Feather and Yuba basin impact areas. Damages are reported as fractions relative to damage for the base case (0 change), Sacramento storm centering. The figure shows that:

- Reallocating additional storage to the flood pool at New Bullard's Bar does not change EAD at Feather and Yuba impact areas. However, reallocating 100 TAF to flood storage at Oroville does reduce EAD by more than 25%.
- Additional flood damage reductions are not achieved when more than 100 TAF is reallocated to flood storage at Oroville,
- Total EAD remains essentially constant even as Oroville flood storage is decreased (the guide curve is raised by 200,000 ac-feet), and
- Changes in EAD due to storage reallocations are comparable to changes observed when simulating different storm events (centered in the different basins).

Figure 7-2 shows the influence of sequentially raising the wintertime definition of the guide curve at New Bullard's Bar and Oroville reservoirs on EAD in lower Sacramento basin impact areas. Reallocations at both reservoirs show little influence on EAD at these impact areas. Also, changes observed when simulating storm events centered in different basins are orders of magnitude larger than changes in EAD resulting from storage reallocations. Across all alternatives, lower Sacramento basin impact areas damages were observed to remain constant between $US 143 and 144 million per year (Appendix I).

These Sacramento metropolitan and delta agricultural areas see approximately 90 to 93% of total Feather, Yuba, and lower Sacramento basin damages.

Figure 7-3 shows the influence of re-operation project alternatives on EAD. Reducing the flow objective to 270,000 cfs at the Feather – Yuba River confluence (from 300,000 cfs) is the only re-operation alternative that reduces EAD. This reduction is only seen for Feather-Yuba impact areas. No re-operation alternatives change EAD at lower Sacramento basin impact areas.

Table 7-2 summarizes selected additional flood impact, water supply, and hydropower generation indicators for each project alternative. Ability to meet objective flow criteria is reported for six locations (Table 7-2A, columns 2 through 7). Most Oroville storage reallocations safely pass 200-year Feather River flows below objective criteria established at the reservoir (column 2) and Yuba City (column 4). When the guide curve is raised 200 TAF, only the 100-year event passes safely. For all project alternatives, only the 25-year event safely passes at Nicolaus (column 7). An exception is the last re-operation project alternative (row 20). Here, the 50-year event passes safely. However, this gain is traded for a loss at the Feather – Yuba confluence. There, only the 25-year event passes safely (column 6).

When Oroville storage is reallocated to conservation purposes, results demonstrate an ability to more reliably export water through the delta and meet local Feather Basin demand (Table 7-2B, column 8). However, under such reallocations, water demands still remain vulnerable to drought shortages of between 110 and 118 TAF/month (column 9). These shortages last 4 – 5 months on average (column 10). Across all reallocation alternatives, New Bullard’s Bar reservoir can consistently export water through the delta and meet Yuba Basin water demands with 72% reliability. Water demands remain vulnerable to drought shortages of between 47.7 and 48.1 TAF/month lasting 5.1 to 5.3 months. Storage reallocations also do not influence total hydropower generation at New Bullard's Bar (column 13).

Additional flood operation module results should be accessed electronically (Appendix A and Appendix D). These results include: (i) time-series of reservoir inflows, (ii) storages, (iii) releases, (iv) downstream flows, (v) stages, and (vi) damages at each model control point and impact area for the matrix of basin storm centers and return-period events. Additional water supply module results should also be accessed electronically (Appendix E). Results include: (i) time-series of reservoir inflows over the entire 72-year period-of-record simulation, (ii) required hydropower generation, (iii) storages, (iv) releases, (v) generated hydropower, (vi) downstream flows, (vii) downstream water supply demand, and (viii) shortage to that demand.

Chapter 8. Conclusions

1. Storage reallocations have a small, but noticeable influence on the overall magnitude of expected annual damages (EAD) in the Sacramento Basin.
2. Lowering the operational flow objective to 270,000 cfs at the Feather – Yuba Rivers confluence shows promise to reduce flood damages in Feather and Yuba impact areas.
3. Upwards of approximately 200,000 ac-feet of flood storage in Oroville reservoir appears to serve flood protection purposes beyond current desired levels of protection. This statement is made given the current understanding of the frequency curve at Oroville. Oroville reservoir can still safely pass 100-year events for reallocations up to 200,000 ac-feet.
4. Reallocations in Oroville reservoir serve a greater flood damage reduction purpose than similar magnitude reallocations in New Bullard's Bar reservoir. These results fit with the observations that (i) New Bullard's Bar is a smaller reservoir than Oroville, (ii) it influences a smaller portion of Yuba River flood flows arriving at the Marysville / Feather River confluence, while (iii) Oroville reservoir influences a larger portion of Feather River flood flow arriving at the Yuba City / Yuba River confluence.
5. Reallocations or re-operations most influence EAD at Feather and Yuba Basin impact areas rather than lower Sacramento Basin areas.
6. Base case control runs show significant changes in EAD related to storm center and routing time. These results identify a need to investigate operations, timing, and coordination of operations between the reservoirs as additional flood protection strategies in both basins.

7. Verification runs also show that EAD was particularly sensitive to: (i) flow at Marysville, (ii) flow at Natomas, and (iii) levee failure stage at Natomas. Small flood improvement projects at these areas could show significant flood damage reduction benefits.
8. No project alternatives studied significantly improved ability to meet operational flow objectives at Nicolaus.
9. Hydropower generation, water supply reliability, and EAD indicators appear insensitive to storage reallocations at New Bullard's Bar reservoir.
10. Reallocations that raise the Oroville guide curve increase the reliability with which Feather River water can be exported south of the delta.
11. The results discussed above demonstrate a successful integration of (i) reservoir system simulation and (ii) flood impact analysis for large planning studies within the Corps Water Management Software suite.

Chapter 9. Recommendations

The methods, results, and conclusions presented in Chapters 4 through 9 represent a successful merging of reservoir simulation and flood impact analysis tools for a storage reallocation and re-operation planning study within CWMS. Recommendations for further study of flood protection strategies in the Feather, Yuba, and Sacramento Basins are highlighted in section 9.1. Section 9.2 lists recommendations to guide further development of HEC-ResSim, HEC-FIA, CWMS, and HEC-WAT software tools for planning study and analysis.

In part, the recommendations and needs for further study described in Section 9.1 are borne out of current limitations of the modeling software encountered while performing work for this thesis. These issues limited analysis to the current scope of the thesis.

9.1 Recommendations for further study

To improve flood protection in the Feather, Yuba, and Sacramento basins, the following topics merit further study:

1. Examine the ability to meet flow objectives considering different routing methods and times between reservoirs and downstream objective flow locations. One basis for analysis could include calibrating routing times to travel times observed in UNET model runs,
2. Assess the influence of additional flood storage not represented in the current model, including (i) 40,000 TAF in Engelbright reservoir (downstream of New Bullard's Bar on the Yuba River), and (ii) 45,000 TAF in Thermolito afterbay (on the Feather River). Incorporating these storages as explicit, separate flood

protection projects would serve to maintain outlet capacity at Oroville and New Bullard's Bar reservoirs (this behavior was not explicitly modeled in storage reallocation alternatives #7 and #15),

3. Identify alternative strategies for joint or staggered releases for downstream operation at the Yuba City-Marysville-Feather and Yuba Rivers Confluence,
4. Flood forecasting and pre releases at both reservoirs,
5. Channel and levee improvements around Natomas (both levee height and geotechnical reliability), and
6. Investigate additional re-operations for Nicolaus or additional flood management upstream in the Bear River.

9.2 Recommendations to guide further development of HEC-ResSim, HEC-FIA, CWMS, and HEC-WAT

This section provides an evaluation of HEC-ResSim, HEC-FIA, and CWMS for planning study analysis based on the work presented in Chapters 4 through 8. Software strengths and weaknesses are listed. Recommended future capabilities are described for the existing software programs as well as the proposed HEC-WAT tool.

9.2.1 Strengths

1. The CWMS geo-spatial visual user interface allows the user to base all aspects of the planning analysis under a common representation of and nomenclature in the watershed—using the stream alignment and configuration. This representation readily carries across all CWMS software tools.
2. Data Storage System (DSS), DSS-Vue, and DSS-Vue time-series selection editors allows ready sharing of time-series data across software tools and external data

sources. These features permitted linking output from one software tool to input for a second software tool, and

3. Plotting tools built into the simulation modules allow ready evaluation of simulation results within an individual scenario run and easy comparison between multiple geographic locations in the scenario run.

9.2.2 Weaknesses

1. HEC-ResSim cannot perform simulations on a monthly time interval. This limits ability to make period-of-record analysis for water supply and hydropower operations.
2. A cumbersome CWMS user interface forces the user to delineate alternatives for hydrology, initial conditions, and operations for each scenario of each project alternative in each software tool environment. This inefficiency multiplies opportunities for data entry error, increases the time and difficulty in tracking down errors, increases the user time required to setup and evaluate a project alternative, and requires the user to aggregate results from multiple scenario runs for a project alternative in a computational environment outside of CWMS. Likewise, project alternative evaluation and evaluation between project alternatives must be made outside the CWMS environment. Together, these weaknesses make it difficult to reproduce project alternative analysis in CWMS using multiple software tools. This weakness also forces the user to repeat the setup and evaluation task across multiple scenarios for additional project alternatives.
3. There is no way to easily define, setup, and simulate scenarios representing changes to sets of hydrological flow conditions, physical reservoir characteristics, diversion operating rules, routing parameters, impact area sets, levee heights,

reference location rating curves, levee setbacks, and other user defined scenarios. In Version 1.1.5 of HEC-ResSim, scenario-based analysis is only available for reservoir zone definitions and operating rules using "operations sets" (selected within the Alternative Editor). All other scenario changes must be implemented as child networks. Then, additional program alternatives must be newly defined for those network(s). This setup exponentially exacerbates the problems described for weakness #2.

4. There is no ability to dynamically link input and output among multiple software tools. Re-computes in an earlier module require updating in subsequent modules followed by re-computes. Updating must be done individually for each scenario in each simulation. This setup forces the user to shuffle between the various software modules and increases the time and effort needed to re-generate results.

9.2.3 Recommended Future Capabilities

1. In HEC-ResSim, ability to (i) compute on a monthly time interval, and (ii) define release function or downstream control function reservoir operation rules based on level of flood pool encroachment. "Encroachment" should be another reservoir model variable available for user selection similar to "Elevation," "Storage", "Inflow", etc.
2. In HEC-ResSim, additional "set" capabilities should be developed to handle changes to sets of hydrological flow conditions, lookback conditions, physical reservoir characteristics, diversion operating rules, routing parameters, impact area sets, levee heights, reference location rating curves, levee setbacks, and other user defined scenarios within a single reservoir network. These sets would be analogous to the existing reservoir "operation sets." Sets should be available for user selection on a Set Tab (i.e., expanded Operations Tab) within the Alternative

Editor. If only one "set" is defined for a network, then the alternative should default to that selection.

3. Ability to easily replicate setup of multiple project alternatives across a consistent set of scenarios (operations sets). This feature should automate the process for creating program alternatives for each scenario. This feature could be implemented using either: (i) a project alternative scenario editor that allows the user to define the scenarios (sets and permutations of sets) under which all project alternatives will be simulated, (ii) scripts and user-defined scripting capabilities for navigating through the CWMS graphical-user-interface, or (iii) vertically integrated file management system across all software tools.
4. Ability to easily replicate simulation and evaluation of multiple project alternatives across a consistent set of scenarios and multiple software tools. This feature should automate the process for simulating and evaluating all scenarios in a particular project alternative. These features could be implemented using a project alternative evaluation editor that allows the user to define the algorithm used to simulate and evaluate results.
5. Consistent with recommendation #4, capability for users to define their own evaluation indicators (e.g., firm water supply yield, reliability, vulnerability, resilience, EAD, percent encroachment, peak flow, flow criteria met at location x, duration of inundation, etc.) and ability to post-process these user-defined evaluation indicators using time-series results from multiple scenario runs. All indicators need to be dynamically computed as part of the project alternative simulation and evaluation algorithm. This feature could be implemented using some kind of DSS-MathLogic editor or extension to DSS-Vue.
6. Import features that allow users to integrate parts or all of preexisting standalone HEC-FIA or HEC-ResSim watersheds (for example watershed network

information such as physical and operational reservoir data, diversion operational data, reach parameters, etc and flood impact area data such as impact area delineations, reference rating curves, and damage functions) into the planning analysis tool.

7. Ability to, if desired, dynamically link reservoir simulation with unsteady flow routing of regulated releases (i.e. blending HEC-ResSim with HEC-Ras or UNET). This capability would allow dynamic reservoir release decisions based on unsteady flow routing, stages, or damages.

References

Aikens, C. (October 25, 2002). Yuba County Water Agency. Personal communication. Telephone: 530-741-6278. Email: caikens@ycwa.com.

Bookman-Edmonston. (2002). "Review and Modification of the Calsim Yuba River Basin Model." Department of Water Resources, State of California, Sacramento, California.

Bower, B. T., Hufschmidt, M. M., and Reedy, W. W. (1966). "Operating Procedures: Their Role in the Design of Water-Resource Systems by Simulation Analysis." Design of Water Resource Systems, e. al, ed., Harvard University Press, 443-458.

Coe, J. J. (1989). "Conjunctive Use--Advantages, Constraints, and Examples." *Journal of Irrigation and Drainage Engineering*, 116(3), 427 - 443.

Countryman, J. (2002). "Yuba-Feather Supplemental Flood Control Project." Yuba County Water Agency, Sacramento, California.

Countryman, J. (February, 2003). MBK Engineers. Personal communication. 2450 Alhambra Blvd., 2nd Floor, Sacramento, CA 95817. Phone: 916-456-4400, Email: countryman@mbkengineers.com.

Cowdin, S. (September 23, 2002). Sacramento District, USACE. Personal communication. 1325 J Street, Sacramento CA 95814-2922, Phone: (916-557-7720), E-mail: Stephen.W.Cowdin@usace.army.mil.

Dunn, C. N. (1999). "Development of Hec-Fia Models for Teh Phase I Sacramento Aand San Joaquin Rivers Basin Study." *PR-41*, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

Department of Water Resources, State of California (DWR). (1985). "Yuba River Watershed Model." Division of Planning, 15

Department of Water Resources, State of California (DWR). (1995). "Calsim Preliminary Draft Report." Sacramento, California, http://modeling.water.ca.gov/hydro/studies/assumptions/calfed/assum514.html.

Department of Water Resources, State of California (DWR). (2002). "Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices." California Data Exchange Center, http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

Feldman, A. D. (1981). "Hec Models for Water Resources System Simulation: Theory and Experience." Advances in Hydroscience, Academic Press, San Francisco, California, 297-423.

Ford, D. T. (1990). "Reservoir Storage Reallocation Analysis with Pc." *Journal of Water Resources Planning and Management*, 116(3), 402-416.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). "Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation." *Water Resources Research*, 18(1), 14-20.

Hydrologic Engineering Center (HEC). (1998). "Hec-5: Simulation of Flood Control and Conservation Systems." User's Manual: Version 8.0. Davis, CA, http://www.hec.usace.army.mil.

Hickey, J. T., Collins, R. F., High, H. M., Richardson, K. A., White, L. L., and Pugner, P. E. (2002). "Synthetic Rain Flood Hydrology for Sacramento and San Joaquin River Basins." *Journal of Hydraulic Engineering*(May/June).

Hinks, R. W., and Eichinger, R. A. "Conjunctive Water Use Planning." *Water Forum '86 : world water issues in evolution*, Long Beach, Calif, 1829-1836.

Hirsch, R. M., Cohon, J. L., and ReVelle, C. S. (1977). "Gains from Joint Operation of Multiple Reservoir Systems." *Water Resources Research*, 13(2), 239-245.

Institute for Water Resources (IWR). (1988). "Opportunities of Reservoir Storage Reallocation." Policy Study 88-PS-2. Davis, California

Jenkins, M. W., Howitt, R. E., and Lund, J. R. (2001). "Improving California Water Management: Optimizing Value and Flexibility." University of California, Davis, Davis. http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

Johnson, W. K., Wurbs, R. A., and Beegle, J. E. (1990). "Opportunities for Reservoir-Storage Reallocation." *Journal of Water Resources Planning and Management*, 116(4), 550-566.

Labadie, J. W. (1997). "Reservoir System Optimization Models." *Water Resources Update*, 108(Summer), 83-110.

Leahigh, J. (September 30, 2002). California, Department of Water Resources. Personal communication. Telephone: 916-574-2666. Email: Leahigh@water.ca.gov.

Loucks, D. P., Stedinger, J. R., and Haith, D. A. (1981). *Water Resources Systems Planning and Analysis*, Prentice-Hall Inc., Engelwood Cliffs, New Jersey.

Lund, J. R. (1996). "Developing Seasonal and Long-Term Reservoir System Operations Plans Using Hec-Prm." *RD-40*, Hydrologic Engineering Center, Davis.

Lund, J. R., and Guzman, J. (1999). "Derived Operating Rules for Reservoirs in Series or in Parallel." *Journal of Water Resources Planning and Management*, 125(3), 143-153.

Maknoon, R., and Burges, S. J. (1978). "Conjunctive Use of Ground and Surface Water." *Journal of the American Water Works Association*, 70(8), 419 - 424.

Needham, J. T., David W. Watkins, J., Lund, J. R., and Nanda, S. K. (2000). "Linear Programming for Flood Control on the Iowa and Des Moines Rivers." *Journal of Water Resources Planning and Management*, 126(3), 118-127.

Palmer, R. N., Smith, J. A., Cohon, J. L., and ReVelle, C. S. (1982). "Reservoir Management in Potomac River Basin." *Journal of the Water Resources Planning* *and Management Division, Proceedings of the American Society of Civil Engineers*, 108(Wr1), 47-66.

Sand, G. M. (1984). "An Analytical Investigation of Operating Policies for Water-Supply Reservoirs in Parallel," Ph.D. Dissertation, Cornell University, Ithaca, NY.

Sarkaria, G. S. (1968). "California's Yuba River Development." *Water Power*, 20(1), 5-16.

Sen, Z., and Kadioglu, M. (2000). "Simple Daily Dynamic Adaptive Operation Rules for Water Resources Optimization." *Water Resources Management*, 14(5), 349-368.

Simonovic, S. P. (1992). "Reservoir Systems Analysis: Closing the Gap between Theory and Practice." *Water Resources Planning and Management*, 118(3), 262-280.

State Water Resources Control Board (SWRCB). (2001). "Decision 1644: Fishery Resources and Water Right Issues of the Lower Yuba River." http://www.waterrights.ca.gov/hearings/decision1644.pdf.

Tibbits, D. (October 13, 2002). Sacramento District, USACE. Personal communication. Telephone: (916)557-7372, Email: Dan.P.Tibbitts@usace.army.mil.

U.S. Army Corps of Engineers (USACE). (1970a). "Design Memorandum No. 2. Hydrology." Marysville Reservoir, Yuba River, California. Sacramento, California

U.S. Army Corps of Engineers (USACE). (1970b). "Report on Reservoir Regulation for Flood Control." Oroville Dam and Lake, Feather River, California. Sacramento, California

U.S. Army Corps of Engineers (USACE). (1972). "Report on Reservoir Regulation for Flood Control." New Bullard's Bar Dam and Reservoir, North Yuba River, California. Appendix V to Master Manual of Reservoir Regulation, Sacramento River Basin, California. Sacramento, California

U.S. Army Corps of Engineers (USACE). (1991). "Arial Atlas." Sacramento River, Sloughs, and Tributaries, California. S. District, Sacramento, California

USACE. (2001). "Conjunctive Use for Flood Protection." *PR-49*, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

U.S. Army Corps of Engineers and State of California, Reclamation Board (USACE, and SCRB). (2000). "In Progress Review Document." Sacramento and San Joaquin River Basins Comprehensive Study. Sacramento, California

Whitin, B. (October 13, 2002). Sacramento District, USACE. Personal communication. Telephone: 916-557-7103. Email: Brett.J.Whitin@usace.army.mil.

Whitin, B. (February 13, 2003). Sacramento District, USACE. Personal communication. Telephone: 916-557-7103. Email: Brett.J.Whitin@usace.army.mil.

Williams, P. A. (1994). "Flood Control Vs. Flood Management." *Civil Engineering--ASCE*, 64(5), 51-54.

Wurbs, R. A. (1993). "Reservoir System Simulation and Optimization Models." *Water Resources Planning and Management*, 119(4), 455-472.

Wurbs, R. A., and Cabezas, L. M. (1987). "Analysis of Reservoir Storage Reallocation." *Journal of Hydrology*, 92, 77-95.

Wurbs, R. A., and Carriere, P. E. (1988). "Evaluation of Storage Reallocation and Related Strategies for Optimizing Reservoir System Operations." *TR-145*, Texas Water Resources Institute, College Station, Texas. http://twri.tamu.edu/reports/1988/145.html.

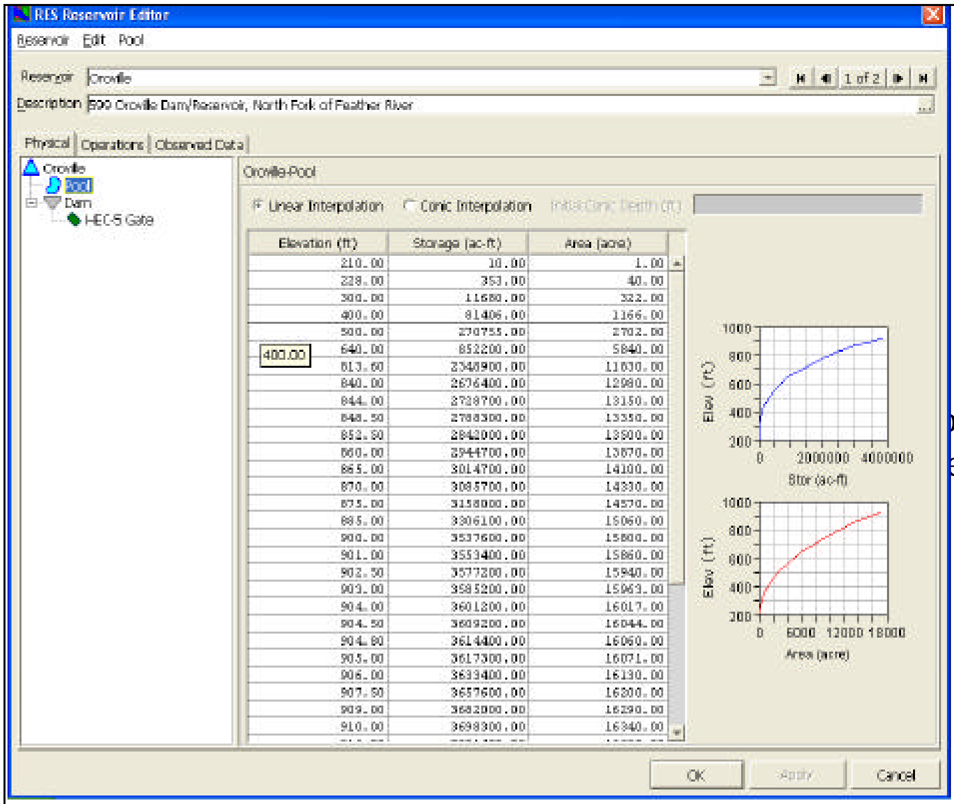
Yeh, W. W. G. (1985). "Reservoir Management and Operations Models: A State of the Art Review." *Water Resources Research*, 21(12), 1797-1818.

Appendix A. Description of HEC-ResSim Flood Operations Model

This appendix presents reservoir physical data (Figures A-1 and A-2), reservoir operation data (Figures A-2), and how operational data is linked to flow hydrology and lookback starting conditions (Figure A-4). The screen captures show data as it was entered into the graphical user interface of HEC-ResSim in the flood operations model. Further details should be accessed electronically through the watershed directory "Yuba-Feather-WS-FIA".

Parameter values for diversion specifications, physical reservoir data (storage-elevation and elevation-physical capacity relationships), reservoir storage zones, and routing times were taken from values used in a preexisting HEC-5 model of the basin (USACE and SCRB 2000). In ResSim, reservoir zone definitions and the prioritized stack of operating rules within each zone define an operations set. Flow hydrology is linked to the operations sets for each flow scenario (i.e., 2-, 10-, … 500- year event, see Figure A-4 for example with the 200-year event).

Scenarios were simulated on a 1-hour time step over circa 34-day duration of the synthetic events. HEC-ResSim uses end-of-period storage, current inflow, and current period release to update reservoir level, storage, and allowable release in each time interval. The model calculates the allowable release according to a "guide-curve operation" but subject to physical capacity limits and the maximum allowable release imposed by the prioritized set of rules defined for the flood pool. Please refer to the HEC-ResSim User's Manual for a more detailed discussion of guide-curve operation, the available operating rules, prioritizing rules, and constraints imposed by rules and rule-priority combinations.



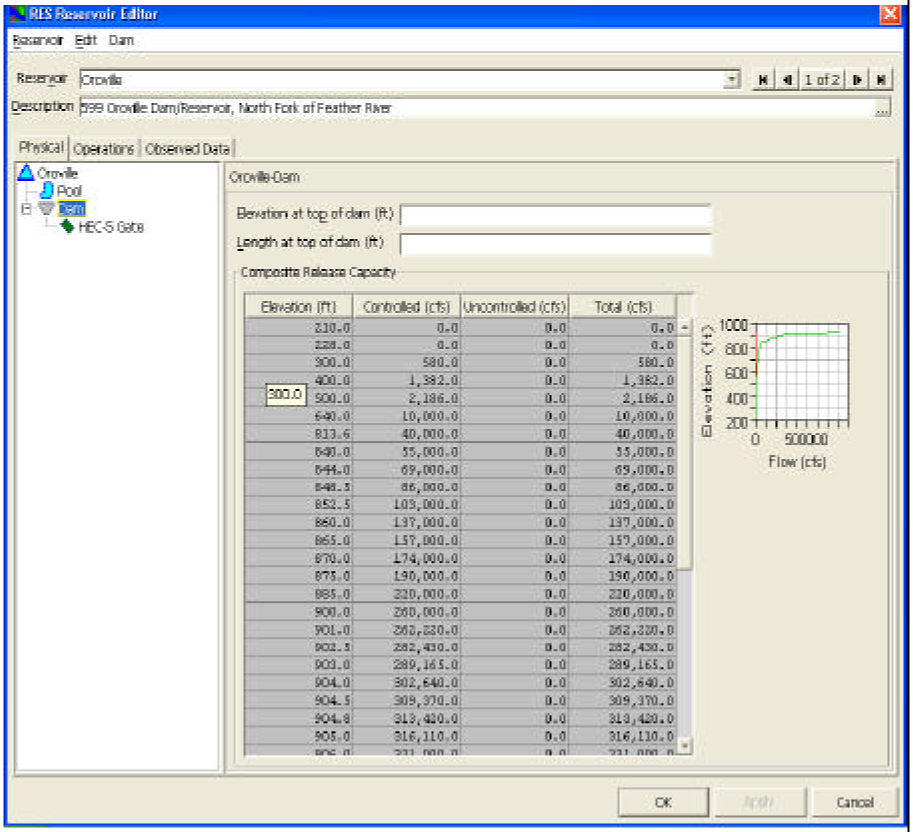
Reservoir: Oroville

Description: 599 Oroville Dam/Reservoir, North Fork of Feather River

● Linear Interpolation ○ Conic Interpolation

Elevation (ft)	Storage (ac-ft)	Area (acre)
210.00	10.00	1.00
228.00	353.00	40.00
300.00	11680.00	322.00
400.00	81406.00	1166.00
500.00	270755.00	2702.00
640.00	852200.00	5840.00
813.60	2348900.00	11830.00
840.00	2676400.00	12980.00
844.00	2728700.00	13150.00
848.50	2788300.00	13350.00
852.50	2842000.00	13500.00
860.00	2944700.00	13870.00
865.00	3014700.00	14100.00
870.00	3085700.00	14330.00
875.00	3158000.00	14570.00
885.00	3306100.00	15060.00
900.00	3537600.00	15800.00
901.00	3553400.00	15860.00
902.50	3577200.00	15940.00
903.00	3585200.00	15963.00
904.00	3601200.00	16017.00
904.50	3609200.00	16044.00
904.80	3614400.00	16060.00
905.00	3617300.00	16071.00
906.00	3633400.00	16130.00
907.50	3657600.00	16200.00
909.00	3682000.00	16290.00
910.00	3698300.00	16340.00

Elevation,
rage, and
ea Curves



Reservoir: Oroville

Description: 599 Oroville Dam/Reservoir, North Fork of Feather River

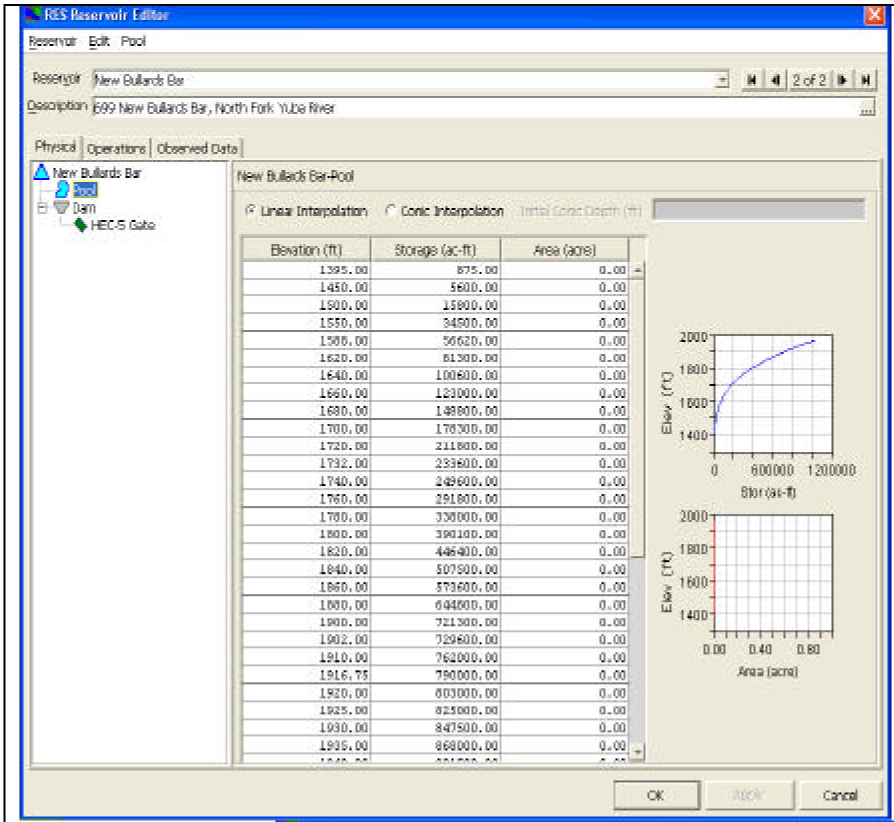
Elevation at top of dam (ft)

Length at top of dam (ft)

Elevation (ft)	Controlled (cfs)	Uncontrolled (cfs)	Total (cfs)
210.0	0.0	0.0	0.0
228.0	0.0	0.0	0.0
300.0	580.0	0.0	580.0
400.0	1,382.0	0.0	1,382.0
500.0	2,186.0	0.0	2,186.0
640.0	10,000.0	0.0	10,000.0
813.6	40,000.0	0.0	40,000.0
840.0	55,000.0	0.0	55,000.0
844.0	69,000.0	0.0	69,000.0
848.5	86,000.0	0.0	86,000.0
852.5	103,000.0	0.0	103,000.0
860.0	137,000.0	0.0	137,000.0
865.0	157,000.0	0.0	157,000.0
870.0	174,000.0	0.0	174,000.0
875.0	190,000.0	0.0	190,000.0
885.0	220,000.0	0.0	220,000.0
900.0	260,000.0	0.0	260,000.0
901.0	262,220.0	0.0	262,220.0
902.5	282,430.0	0.0	282,430.0
903.0	289,165.0	0.0	289,165.0
904.0	302,640.0	0.0	302,640.0
904.5	309,370.0	0.0	309,370.0
904.8	313,420.0	0.0	313,420.0
905.0	316,110.0	0.0	316,110.0

B. Elevation and Maximum Release Capacity Curve

Figure A-1. Physical Data for Oroville Reservoir



Reservoir: New Bullards Bar 2 of 2

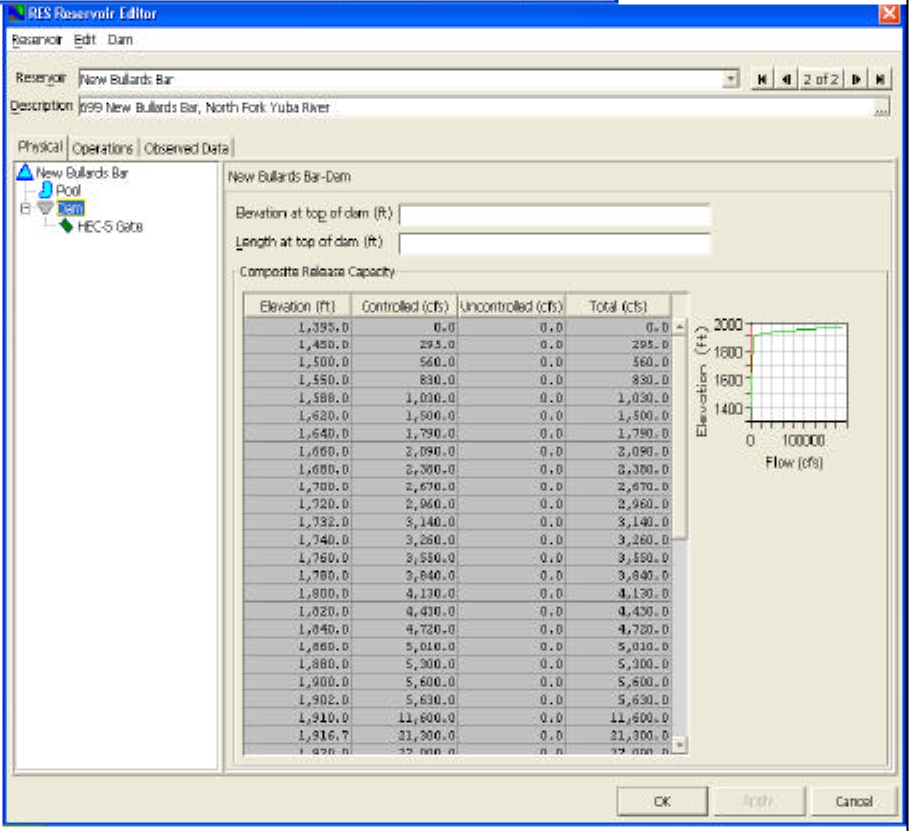
Description: 699 New Bullards Bar, North Fork Yuba River

New Bullards Bar-Pool

● Linear Interpolation ○ Conic Interpolation Initial Conic Depth (ft)

Elevation (ft)	Storage (ac-ft)	Area (acre)
1395.00	875.00	0.00
1450.00	5600.00	0.00
1500.00	15800.00	0.00
1550.00	34500.00	0.00
1588.00	56620.00	0.00
1620.00	81300.00	0.00
1640.00	100600.00	0.00
1660.00	123000.00	0.00
1680.00	148800.00	0.00
1700.00	178300.00	0.00
1720.00	211800.00	0.00
1732.00	233600.00	0.00
1740.00	249600.00	0.00
1760.00	291800.00	0.00
1780.00	338000.00	0.00
1800.00	390100.00	0.00
1820.00	446400.00	0.00
1840.00	507500.00	0.00
1860.00	573600.00	0.00
1880.00	644800.00	0.00
1900.00	721300.00	0.00
1902.00	729600.00	0.00
1910.00	762000.00	0.00
1916.75	790000.00	0.00
1920.00	803000.00	0.00
1925.00	825000.00	0.00
1930.00	847500.00	0.00
1935.00	868000.00	0.00

A. Elevation, Storage, and Area Curves



Reservoir: New Bullards Bar 2 of 2

Description: 699 New Bullards Bar, North Fork Yuba River

New Bullards Bar-Dam

Elevation at top of dam (ft):

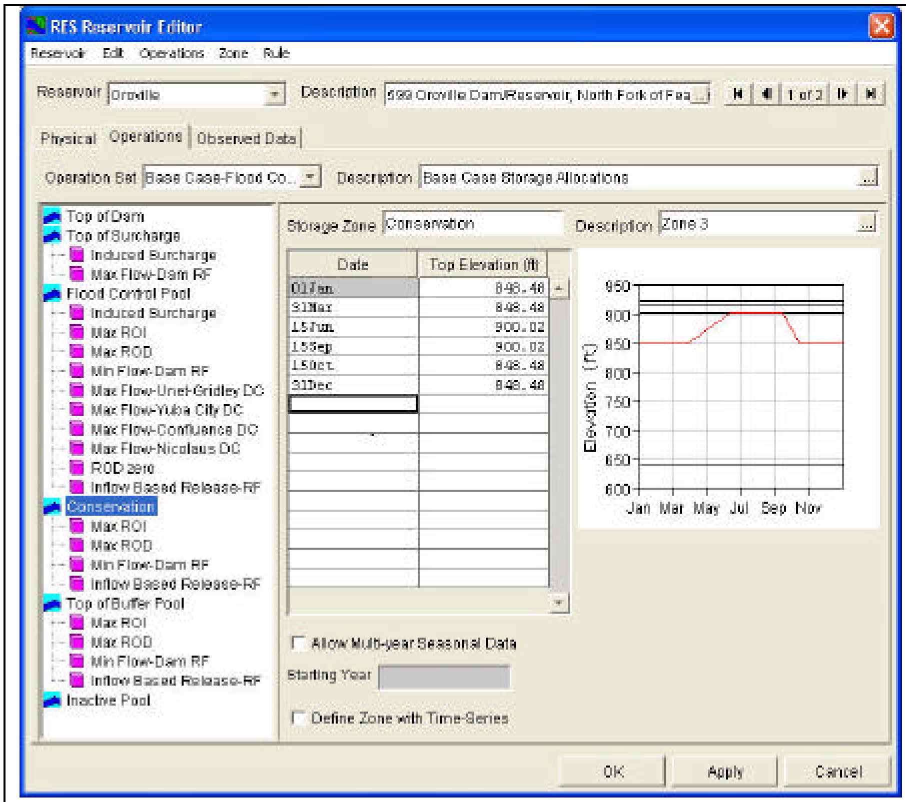
Length at top of dam (ft):

Composite Release Capacity

Elevation (ft)	Controlled (cfs)	Uncontrolled (cfs)	Total (cfs)
1,395.0	0.0	0.0	0.0
1,450.0	295.0	0.0	295.0
1,500.0	560.0	0.0	560.0
1,550.0	830.0	0.0	830.0
1,588.0	1,030.0	0.0	1,030.0
1,620.0	1,500.0	0.0	1,500.0
1,640.0	1,790.0	0.0	1,790.0
1,660.0	2,090.0	0.0	2,090.0
1,680.0	2,380.0	0.0	2,380.0
1,700.0	2,670.0	0.0	2,670.0
1,720.0	2,960.0	0.0	2,960.0
1,732.0	3,140.0	0.0	3,140.0
1,740.0	3,260.0	0.0	3,260.0
1,760.0	3,550.0	0.0	3,550.0
1,780.0	3,840.0	0.0	3,840.0
1,800.0	4,130.0	0.0	4,130.0
1,820.0	4,430.0	0.0	4,430.0
1,840.0	4,720.0	0.0	4,720.0
1,860.0	5,010.0	0.0	5,010.0
1,880.0	5,300.0	0.0	5,300.0
1,900.0	5,600.0	0.0	5,600.0
1,902.0	5,630.0	0.0	5,630.0
1,910.0	11,600.0	0.0	11,600.0
1,916.7	21,300.0	0.0	21,300.0

B. Elevation and Maximum Release Capacity Curve

Figure A-2. Physical Data for New Bullard's Bar Reservoir

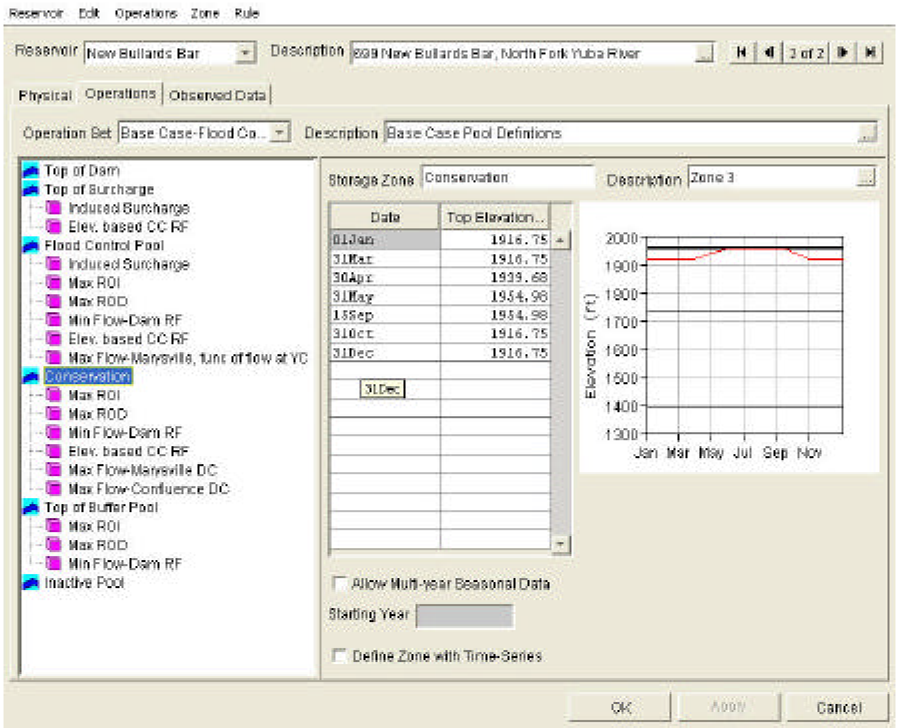


Reservoir: Oroville
Description: 599 Oroville Dam/Reservoir, North Fork of Fea...
Operation Set: Base Case-Flood Co...
Description: Base Case Storage Allocations
Storage Zone: Conservation
Description: Zone 3

Date	Top Elevation (ft)
01Jan	848.48
31Mar	848.48
15Jun	900.02
15Sep	900.02
15Oct	848.48
31Dec	848.48

☐ Allow Multi-year Seasonal Data
Starting Year
☐ Define Zone with Time-Series

A. Oroville Reservoir with Conservation Pool definition tabulated



Reservoir: New Bullards Bar
Description: 599 New Bullards Bar, North Fork Yuba River
Operation Set: Base Case-Flood Co...
Description: Base Case Pool Definitions
Storage Zone: Conservation
Description: Zone 3

Date	Top Elevation...
01Jan	1916.75
31Mar	1916.75
30Apr	1939.68
31May	1954.98
15Sep	1954.98
31Oct	1916.75
31Dec	1916.75

☐ Allow Multi-year Seasonal Data
Starting Year
☐ Define Zone with Time-Series

B. New Bullard's Bar Reservoir with Conservation Pool definition tabulated

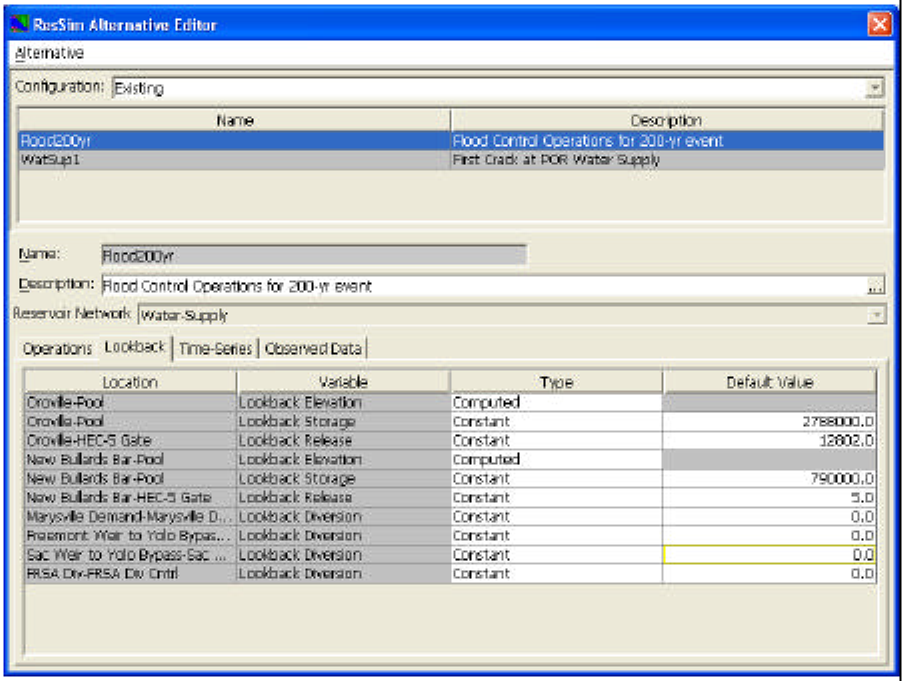
Figure A-3. Reservoir Operational Data

Figure A-4. Linking Operations to Lookback starting storage and Inflow Hydrology

Reservoir	Operation Set
New Bullards Bar	Flood Control Ops
Oroville	Flood Control Operations

A. Operations Sets

B. Lookback info. for starting storage and release in first time interval



Configuration: Existing

Name	Description
Flood200yr	Flood Control Operations for 200-yr event
WatSup1	First Crack at POR Water Supply

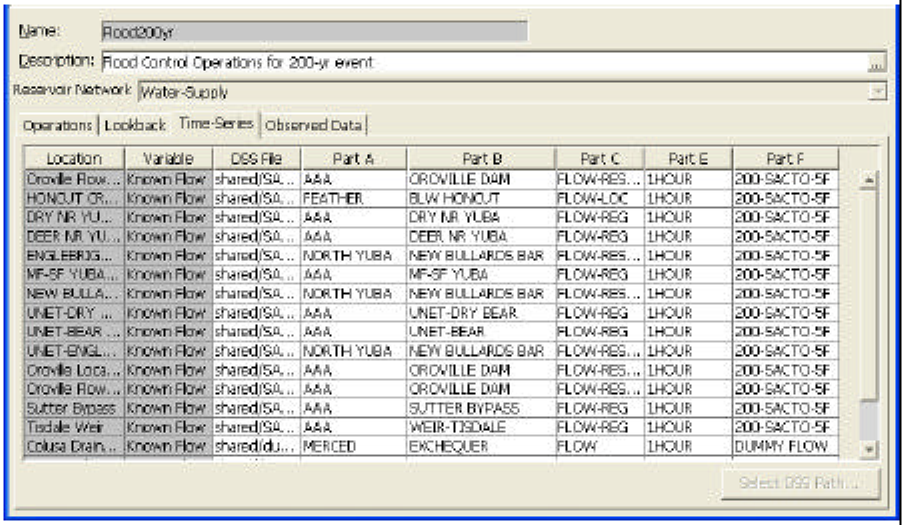
Name: Flood200yr

Description: Flood Control Operations for 200-yr event

Reservoir Network: Water-Supply

Location	Variable	Type	Default Value
Oroville-Pool	Lookback Elevation	Computed	
Oroville-Pool	Lookback Storage	Constant	2788000.0
Oroville-HEC-5 Gate	Lookback Release	Constant	12802.0
New Bullards Bar-Pool	Lookback Elevation	Computed	
New Bullards Bar-Pool	Lookback Storage	Constant	790000.0
New Bullards Bar-HEC-5 Gate	Lookback Release	Constant	5.0
Marysville Demand-Marysville D...	Lookback Diversion	Constant	0.0
Freemont Weir to Yolo Bypas...	Lookback Diversion	Constant	0.0
Sac Weir to Yolo Bypass-Sac ...	Lookback Diversion	Constant	0.0
FRSA Div-FRSA Div Cntrl	Lookback Diversion	Constant	0.0

C. Paths specifying Time-series of inflows



Name: Flood200yr

Description: Flood Control Operations for 200-yr event

Reservoir Network: Water-Supply

Location	Variable	DSS File	Part A	Part B	Part C	Part E	Part F
Oroville Flow...	Known Flow	shared/SA...	AAA	OROVILLE DAM	FLOW-RES...	1HOUR	200-SACTO-SF
HONCUT CR...	Known Flow	shared/SA...	FEATHER	BLW HONCUT	FLOW-LOC	1HOUR	200-SACTO-SF
DRY NR YU...	Known Flow	shared/SA...	AAA	DRY NR YUBA	FLOW-REG	1HOUR	200-SACTO-SF
DEER NR YU...	Known Flow	shared/SA...	AAA	DEER NR YUBA	FLOW-REG	1HOUR	200-SACTO-SF
ENGLEBRIG...	Known Flow	shared/SA...	NORTH YUBA	NEW BULLARDS BAR	FLOW-RES...	1HOUR	200-SACTO-SF
MF-SF YUBA...	Known Flow	shared/SA...	AAA	MF-SF YUBA	FLOW-REG	1HOUR	200-SACTO-SF
NEW BULLA...	Known Flow	shared/SA...	NORTH YUBA	NEW BULLARDS BAR	FLOW-RES...	1HOUR	200-SACTO-SF
UNET-DRY ...	Known Flow	shared/SA...	AAA	UNET-DRY BEAR	FLOW-REG	1HOUR	200-SACTO-SF
UNET-BEAR ...	Known Flow	shared/SA...	AAA	UNET-BEAR	FLOW-REG	1HOUR	200-SACTO-SF
UNET-ENGL...	Known Flow	shared/SA...	NORTH YUBA	NEW BULLARDS BAR	FLOW-RES...	1HOUR	200-SACTO-SF
Oroville Loca...	Known Flow	shared/SA...	AAA	OROVILLE DAM	FLOW-RES...	1HOUR	200-SACTO-SF
Oroville Flow...	Known Flow	shared/SA...	AAA	OROVILLE DAM	FLOW-RES...	1HOUR	200-SACTO-SF
Sutter Bypass	Known Flow	shared/SA...	AAA	SUTTER BYPASS	FLOW-REG	1HOUR	200-SACTO-SF
Tisdale Weir	Known Flow	shared/SA...	AAA	WEIR-TISDALE	FLOW-REG	1HOUR	200-SACTO-SF
Colusa Drain...	Known Flow	shared/du...	MERCED	EXCHEQUER	FLOW	1HOUR	DUMMY FLOW

Appendix B. Time-series of Flows for the Flood Operations Module

This appendix presents the synthetic time-series of flows linked to the flood operation simulation module (example hydrographs in Figures B-1 through B-3)(Hickey et al. 2002). Flows are specified as hourly time-series. Table B-1 presents a further description of the 13 model locations (columns 1 and 2), the dss file and path names from which flow data was linked (columns 3 and 4), and a description of the source of flow upstream from the point where the time-series is linked to the flood operations simulation model (column 5). "Unregulated flow" refers to unimpaired Hickey et al (2002) synthetic hydrology; "regulated flow" refers to the flow computed by the HEB-5 Sacramento flood operation models after routing the unimpaired synthetic storm event through the "Headwaters" and "Lower Basin" models and down to the location (Apart = "AAA", Bpart = location name in Column 4)(USACE and SCRB, 2000). Hydrographs B-1 through B-3 show flows for locations #1-3 for the 2-, 10-, 25-, 50-, 100-, 200-, and 500-year recurrence interval events of the Sacramento Basin storm centering.

Figure B-1. Synthetic Hydrographs of Regulated and Unregulated Inflow to Oroville Reservoir

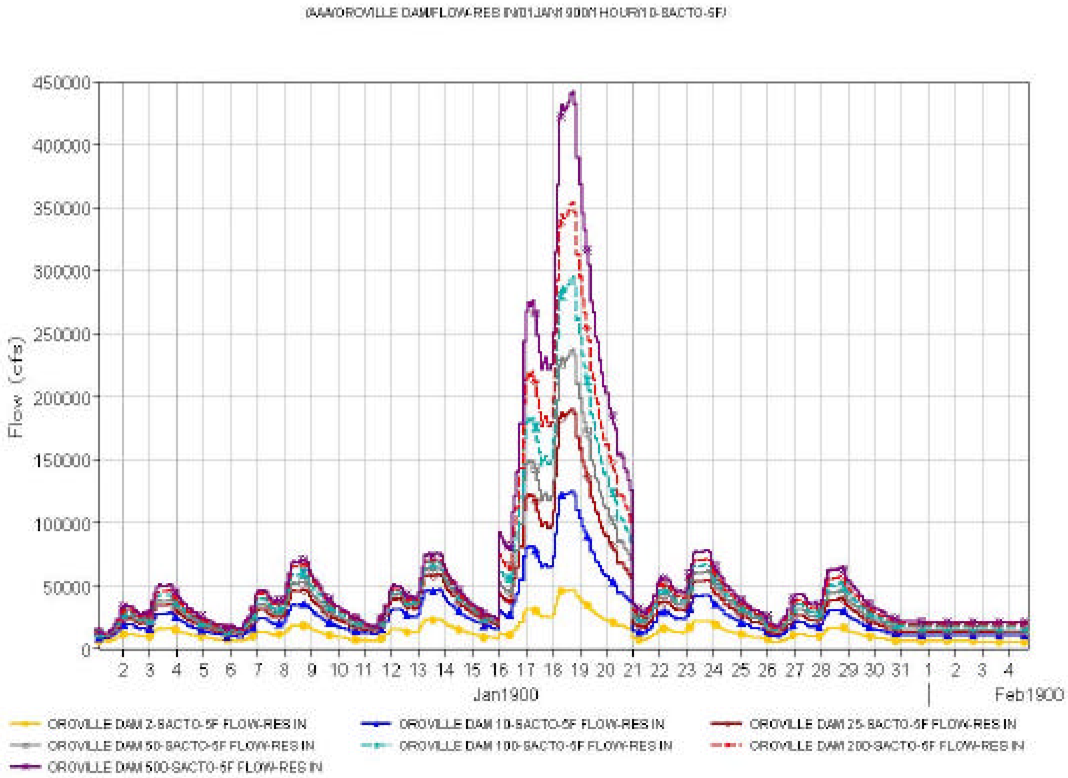


Figure B-2. Synthetic Hydrographs of Unregulated Inflow from Honcut Creek

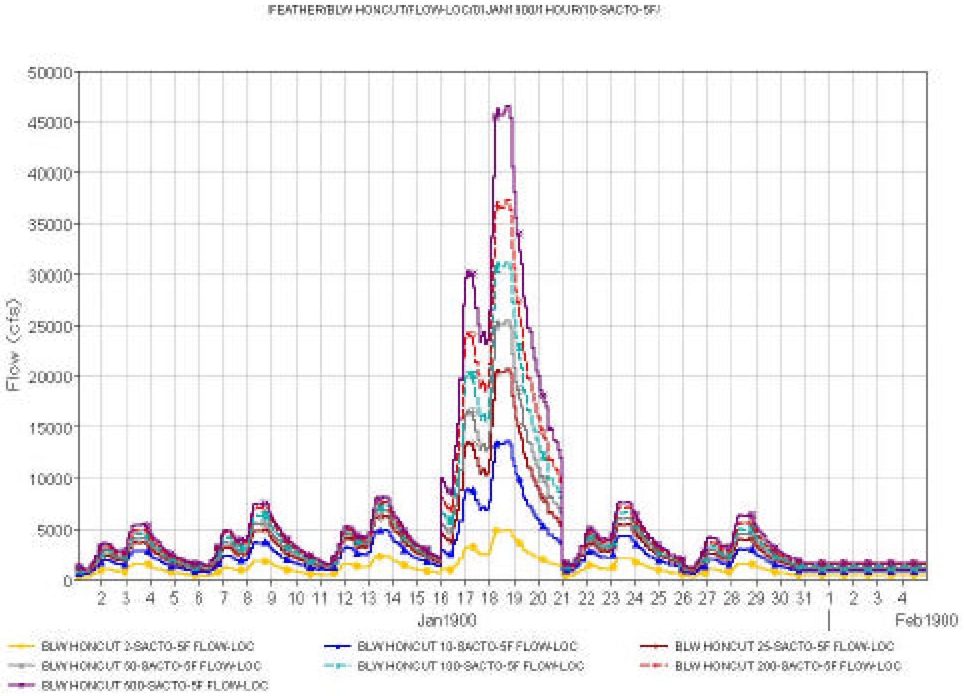


Figure B-3. Synthetic Hydrographs of Unregulated Inflow from North Fork of Yuba River to New Bullard’s Bar Reservoir

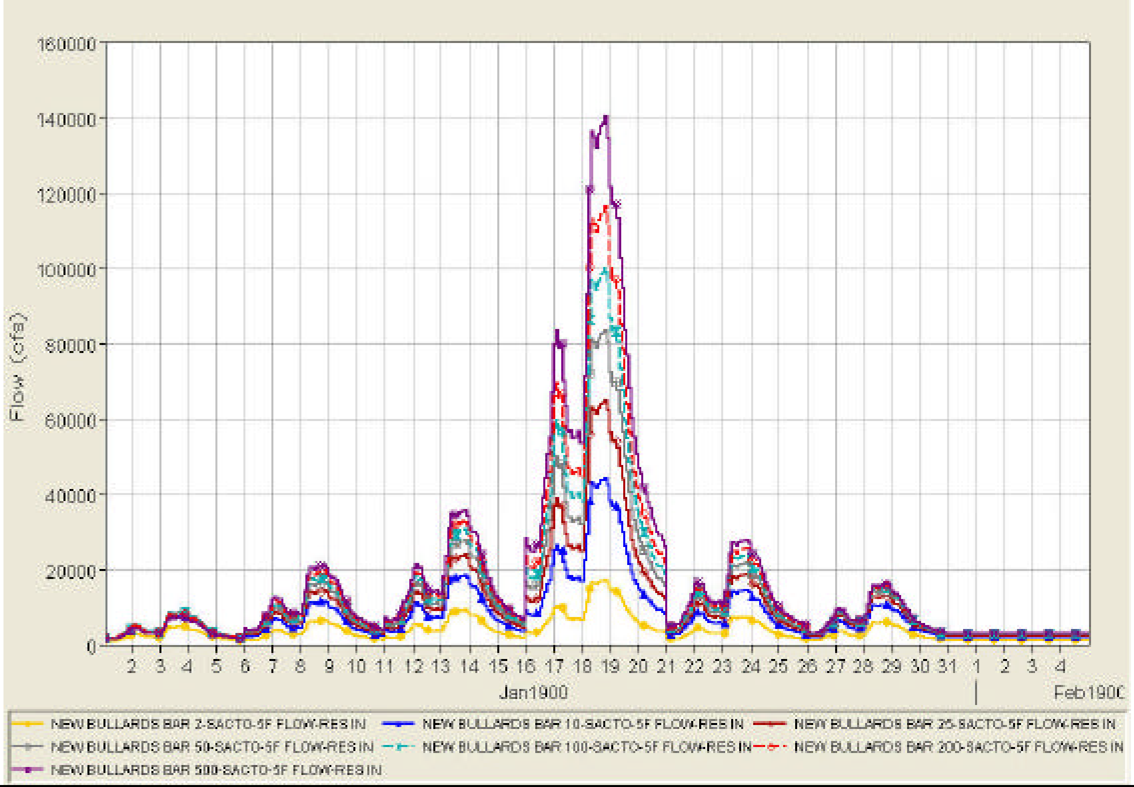


Table B-1. Description of Flow Input Data for Locations in Feather-Yuba Basin

Location (1)	**Basin** (2)	**DSS File**[a] (3)	**DSS Path (Apart/Bpart/Cpart)**[b] (4)	**Description** (5)
B-1 Oroville Reservoir	Feather River	SAC5F2.dss	/AAA/OROVILLE DAM/FLOW-RES IN/	All regulated and unregulated flow from above Oroville Reservoir
B-2 Honcut Creek	Feather River	SAC5F.dss	/FEATHER/BLW HONCUT/FLOW-LOC/	Unregulated local inflow below Oroville Reservoir
B-3 New Bullard's Bar Reservoir	Yuba River	SAC5F.dss	/NORTH YUBA/NEW BULLARDS BAR/FLOW-RES IN/	Unregulated inflow from the North Fork of the Yuba River above New Bullard's Bar Reservoir
4 South Fork Confluence	Yuba River	SAC5F.dss	/AAA/MF-SF YUBA/FLOW-REG/	Regulated and Unregulated local inflow from the Middle and South Forks of the Yuba River
5 Deer Creek Confluence	Yuba River	SAC5F.dss	/AAA/DEER NR YUBA/FLOW-REG/	Regulated and Unregulated local Inflow from Deer Creek
6 Dry Creek Confluence	Yuba River	SAC5F.dss	/AAA/DRY NR YUBA/FLOW-REG/	Regulated and Unregulated local Inflow from Dry Creek
7 UNET-Bear	Bear River	SAC5F2.dss	/AAA/UNET-BEAR/FLOW-REG/	Regulated and Unregulated Inflow from Bear River
8 UNET-Dry Bear	Bear River	SAC5F2.dss	/AAA/UNET-DRY BEAR/FLOW-REG/	Unregulated Inflow from Dry Creek to Bear River
9 Tisdale Weir	Sacramento River	SAC5F2.dss	/AAA/WEIR-TISDALE/FLOW-REG/	Regulated and unregulated flows from the Sacramento River
10 Sutter Bypass	Sacramento River	SAC5F2.dss	/AAA/SUTTER BYPASS/FLOW-REG/	Regulated and Unregulated flows through the Sutter Bypass
11 UNET-Cache	Cache Creek	SAC5F2.dss	/AAA/UNET-CACHE/FLOW-REG/	Regulated and Unregulated flow from Cache Creek
12 UNET-Putah	Putah Creek	SAC5F2.dss	/AAA/UNET-PUTAH/FLOW-REG/	Regulated flow from Putah Creek
13 H Street Gate	Americanr	SAC5F2.dss	/AAA/H ST.GAGE/FLOW-REG/	Regulated flow from Folsom Dam

Notes:

a. Sacramento Basin storm centering file. Substitute "OROV5B" or "YUBA5B" for "SAC5F" to access Oroville or Yuba Storm centerings.

b. D part = "01Jan1900"; E part = "1HOUR"; and F part = "x-SACTO-5F" for Sacramento storm centering, "x-OROV-5B" for Oroville storm centering, or "x-YUBA-5F" for Yuba storm centering, where *x* is return period of event scenario (2, 10, 25, 50, 100, 200, or 500)

Appendix C. Impact Area Set Delineated in Flood Damage Assessment Study of Sacramento Basin

This appendix presents the data input to and results generated by the Flood Impact Analysis (HEC-FIA) component of the Flood Operations Module using an impact area set delineated for the Sacramento Basin in a Flood Damage Assessment (FDA) made by the Comprehensive Study (Cowdin 2002). Input data consisted of (i) impact area delineations, (ii) stage-flow rating curves for the breakout locations to which flood impacts in the impact areas were tied, (iii) stage-damage relationships for the impact areas, and (iv) levee failure height for each impact area. Output consists of damages resulting from simulation of all scenarios for all project alternative runs. Table C-1 lists the electronic files associated with the FDA impact area set input and output data.

C.1 Delineating Impact Areas

Forty-five impact areas were selected for use (Cowdin 2002)(Table C-2 and Figure C-1). These impact areas were located either within the Feather and Yuba basins, or the Sacramento basin downstream of the Feather-Sacramento River confluence. One Bear River basin impact area (Sac 28), one area in the lower Sacramento Basin (Sac 59), and impact areas on the Sacramento River upstream of the Feather River confluence (Sac 1 through Sac 12) were excluded. Table C-2 also lists reference flow locations in the HEC-ResSim flood operation model to which impact area damages were tied (column 4), and the location(s) in the UNET model of the Sacramento basin (Tibbits 2002) from which the stage-flow rating curve for the breakout location was developed (columns 5 through 8).

C.2 Developing Rating Curves

Rating curves for breakout locations were developed using two separate methods.

For breakout locations situated on main reaches that were modeled in the flood operations simulation model (i.e., blank entries in columns 5 and 6 of Table C-2), a flow-stage rating curve was constructed from the upper envelope of all paired flow and stage Sacramento Basin UNET model output aggregated across all storm centering and recurrence frequency scenarios (Tibbits 2002). Figure C-2 shows the rating curve for Yuba City (Sac 25) and the aggregated UNET data from which the curve was developed.

This aggregation was performed as follows. For each scenario, UNET output consisted of time-series of paired, flow-stage data. For most reference locations, when time series of pairs were examined for particular scenarios, multiple stages were observed for many flow values (loops). These loops seemed to be caused by backwater effects and different peak flow timings within and across scenarios. Therefore, at each reference location, a composite stage-flow rating curve was defined from the upper envelope of the aggregated stage-flow pairs.

This upper envelope was identified using the following algorithm. First, the aggregated set of stage-flow pairs from all scenarios for the reference location was sorted by increasing flow value. Then, a flow interval (generally 10,000 or 20,000 cfs) was selected as the basis to iterate through the sorted flow values. In each flow interval, the largest stage (paired with any flow value occurring in the current flow range) was the stage selected for use on the composite rating curve. The flow value paired with that stage was also used to define the composite rating curve point along the flow interval. After iterating through all flow values, rating curve points were screened to make the composite rating curve increase monotonically. Points were removed for instances where the stage decreased from the previous stage value.

A second method was used to develop rating curves for UNET breakout locations situated on tributary reaches that were not modeled in the HEC-ResSim flood operations model (i.e., impact areas with flow entries in columns 5 and 6 of Table C-2). In this case the rating curve was constructed by correlating peak stage observed at the side channel, breakout location (Table C-2, columns 7 and 8) with peak flow observed at a nearby main channel location (columns 5 and 6). Peak flow-stage pairs for all storm centers and frequencies were sorted by increasing flow. Events with inconsistent stages were removed. Figure C-3 shows the rating curve for Marysville impact area (Sac 26). Essentially, stage at Jack Slough reach 25 is a function of flow on the Yuba River in reach 27.

C.3 HEC-FIA tool, input data, damage functions, setup, and output

FDA impact area set delineations, stage-flow rating curves, damage functions, and levee failure heights were entered into the Impact Area Setup Module of the HEC-FIA software tool (see watershed directory “Yuba-Feather-WS-FDA”). Damage functions were those described by Cowdin (2002) and were invariant with season and aggregated across multiple damage categories including single-family residential, multi-family residential, mobile homes, commercial, industrial, public, farms, and crops. Levee failure height was selected as the top levee elevation (Table C-2, column 3). This height ignored geo-technical uncertainties that were specified in the original FDA study. Together, this information comprised the “impact area set.”

Runs were set up by linking the impact area set to the flow hydrology (i.e., output from the flood operations simulation model as described in Appendix A). Figure C-4 shows an example setup for the base case project, Sacramento storm centering, 500-year event scenario. Setup was repeated for each additional frequency-based flow scenario. Flow scenarios were grouped in a simulation and then evaluated.

Table C-1. Electronic Files used for Flood Impact Analysis

File Name (1)	Description (2)
“Sac 13”, “Sac 14” … “Sac 62”	Directory of FDA study database files containing stage-damage functions and levee height input for impact areas.
“FlowStageFDAIndexpts.xls” “FlowStageFDAIndexpts2.xls” “FlowStageFDAIndexpts3.xls” “FlowStageFDAIndexpts4.xls”	UNET model time-series data organized by breakout location. Includes stage-flow rating curves developed for each location. See Figures C-2 and C-3 for examples.
“Yuba-Feather-WS-FDA”	HEC-FIA watershed of FDA impact areas containing all input data and HEC-FIA output for all scenarios runs of every project alternative.

Table C-2. FDA Study Impact area set Delineated by Cowdin (2002)

Impace Area	FDA Comp Study ID[a]	Levee Height (feet)	Damage tied to flow at HEC-ResSim Flood Ops model junction[b]	Unet Model locations used to construct Flow-Stage Rating Curve[c,d,e] Flow Location[f,g]		Stage Location[h]	
(1)	(2)	(3)	(4)	A part (5)	B part (6)	A part (7)	B part (8)
(a) Feather and Yuba Basin Impact Areas							
1. Honcut	SAC18	93.00	Honcut Confluence			YUBA RIVER R27	IP 4 DA SAC18
2. Sutter Buttes North	SAC19	106.00	Honcut Confluence			FEATHER RIVER R24	IP 4 DA SAC19
3. Gridley	SAC20	106.00	Honcut Confluence			FEATHER RIVER R24	IP 4 DA SAC19
4. Sutter Buttes East	SAC21	89.00	Honcut Confluence			FEATHER RIVER R25	IP 4 DA SAC20
5. Live Oak	SAC22	89.00	Honcut Confluence			FEATHER RIVER R24	IP 4 DA SAC19
6. District 10	SAC23	88.00	Yuba City			FEATHER RIVER R24	IP 4 DA SAC23
7. Levee Dist. #1	SAC24	54.20	Nicolaus			FEATHER RIVER R38	IP 4 DA SAC24
8. Yuba City	SAC25	82.20	Yuba City			FEATHER RIVER R26	IP 4 DA SAC25
9. Marysville	SAC26	80.70	Marysville	YUBA RIVER R27	IP 4 DA SAC27	JACK SLOUGH REACH 25	IP 4 DA SAC26
10. Linda-Olivehurst	SAC27	90.90	Marysville			YUBA RIVER R27	IP 4 DA SAC27
11. Best Slough	SAC29	68.80	Dry Bear Confluence			BEAR RIVER R29	IP 4 DA SAC29
12. Rec Dist 1001	SAC30	52.50	Nicolaus			FEATHER RIVER R38	IP 4 DA SAC30
(b) Lower Sacramento Basin Impact Areas							
13. Knight's Landing	SAC13	40.50	Tisdale Weir			SAC RIVER R21	IP 4 DA SAC14
14. Ridge Cut (North)	SAC14	42.80	Tisdale Weir			SAC RIVER R21	IP 4 DA SAC14
15. Ridge Cut (South)	SAC15	38.90	Yolo Bypass + Cache Slough	YOLO BYPASS R66	IP 4 DA SAC16	KNGHTS LNDNG RDG CUT R63	IP 4 DA SAC15
16. Rec Dist 2035	SAC16	32.80	Yolo Bypass + Cache Slough			YOLO BYPASS R66	IP 4 DA SAC16
17. East of Davis	SAC17	46.30	Yolo Bypass + Putah	YOLO BYPASS R72	YOLO BP DS PUTAH CR	PUTAH CREEK R71	IP 4 DA SAC17
18. Rec Dist 1500 West	SAC34	42.80	Nicolaus	SAC RIVER R57	IP 4 DA SAC35	SAC RIVER R21	IP 4 DA SAC34
19. Elkhorn	SAC35	40.20	Freemont Weir			SAC RIVER R57	IP 4 DA SAC35
20. Natomas	SAC36	41.00	Freemont Weir			SAC RIVER R57[i]	IP 4 DA SAC36[i]
21. Rio Linda	SAC37	46.10	H Street Gage			AMERICAN RIV R60	IP 4 DA SAC37
22. West Sacramento	SAC38	37.40	I Street Gage			SAC RIVER R61	IP 4 DA SAC38
23. Rec Dist 900	SAC39	37.90	I Street Gage			SAC RIVER R61	IP 4 DA SAC39
24. Sacramento	SAC40	55.10	H Street Gage			AMERICAN RIV R60	IP 4 DA SAC40
25. Rec Dist 302	SAC41	31.80	Freeport			SAC RIVER R61	IP 4 DA SAC41
26. Rec Dist 999	SAC42	22.90	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT	SUTTER SLOUGH R89	IP 4 DA SAC42
27. Clarksburg	SAC43	22.90	Freeport			SAC RIVER R61	IP 4 DA SAC44
28. Stone Lake	SAC44	25.40	Freeport			SAC RIVER R61	IP 4 DA SAC44
29. Hood	SAC45	25.40	Freeport			SAC RIVER R61	IP 4 DA SAC44
30. Merritt Island	SAC46	26.30	Freeport			SAC RIVER R61	IP 4 DA SAC46
31. Rec Dist 551	SAC47	25.80	Freeport			SAC RIVER R61	IP 4 DA SAC47
32. Courtland	SAC48	25.80	Freeport			SAC RIVER R61	IP 4 DA SAC47
33. Sutter Island	SAC49	25.30	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT	SUTTER SL R92	IP 4 DA SAC49
34. Grand Island	SAC50	22.80	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT	SAC RIVER R98	IP 4 DA SAC50
35. Locke	SAC51	22.90	Freeport			SAC RIVER R96	IP 4 DA SAC51
36. Walnut Grove	SAC52	21.20	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT	GEORGIANA SL R97	IP 4 DA SAC52
37. Tyler Island	SAC53	10.50	Freeport			GEORGIANA SL R97	IP 4 DA SAC53
38. Andrus Island	SAC54	10.90	Freeport			GEORGIANA SL R97	IP 4 DA SAC54
39. Ryer Island	SAC55	25.40	Freeport			SUTTER SL R92	IP 4 DA SAC55
40. Prospect Island	SAC56	10.50	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA	MINER SLOUGH R90	IP 4 DA SAC56
41. Twitchell Island	SAC57	13.37	Freeport			THREE MILE SLOUGH R101	IP 4 DA SAC57
42. Sherman Island	SAC58	16.30	Freeport			THREE MILE SLOUGH R101	IP 4 DA SAC58
43. Cache Slough	SAC60	17.30	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA	CACHE SL R83	IP 4 DA SAC60
44. Hastings	SAC61	17.80	Freeport			CACHE SL R85	IP 4 DA SAC61
45. Lindsey Slough	SAC62	17.90	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA	LINDSEY SL R86	IP 4 DA SAC62

Notes:

a. As used by Cowdin (2002)
b. Reference index location in HEC-ResSim Flood Operations model
c. DSS output file path parts from Unet model simulation of Sacramento Basin
d. DSS file = "BSIxxxyy.dss" where *xxx* is a 3-character number (010, 025, 050, 100, 200, or 500) representing the return period of the flood event and yy is a 2-character abbreviation representing the storm centering (OV, YU, SC)
e. D part = "01Jan1900"; E part = "1Hour", and F part = "BSEIxxxyyyy" where *xxx* is as in note a, and *yyyy* is a 3 or 4 character abbreviation representing the storm centering (OROV, YUBA, SAC)
f. C part = "Flow"
g. Blank entry indicates rating curve was constructed from upper envelope of flows observed at the same Unet model location as stages (Cols 7 and 8). When separate locations were used, rating curve was constructed by correlating peak stage observed at side channel, breakout location (cols 7 and 8) with peak flow observed at main channel lcoation (cols 5 and 6). for each event. Peak flow and peak stage pairs for each event were then sorted by increasing flow. Events with inconsistent stages were removed. Separate flow and stage locations were used because breakout (stage) location for impact area was on a tributary strea. Those flows were not modeled in HEC-ResSim Flood Operations model.
h. C part = "Stage"
i. Upper envelope rating curve was constructed ignoring 200-year event centered in American basin

Figure C-1. Delineation of FDA Impact Areas in HEC-FIA Watershed

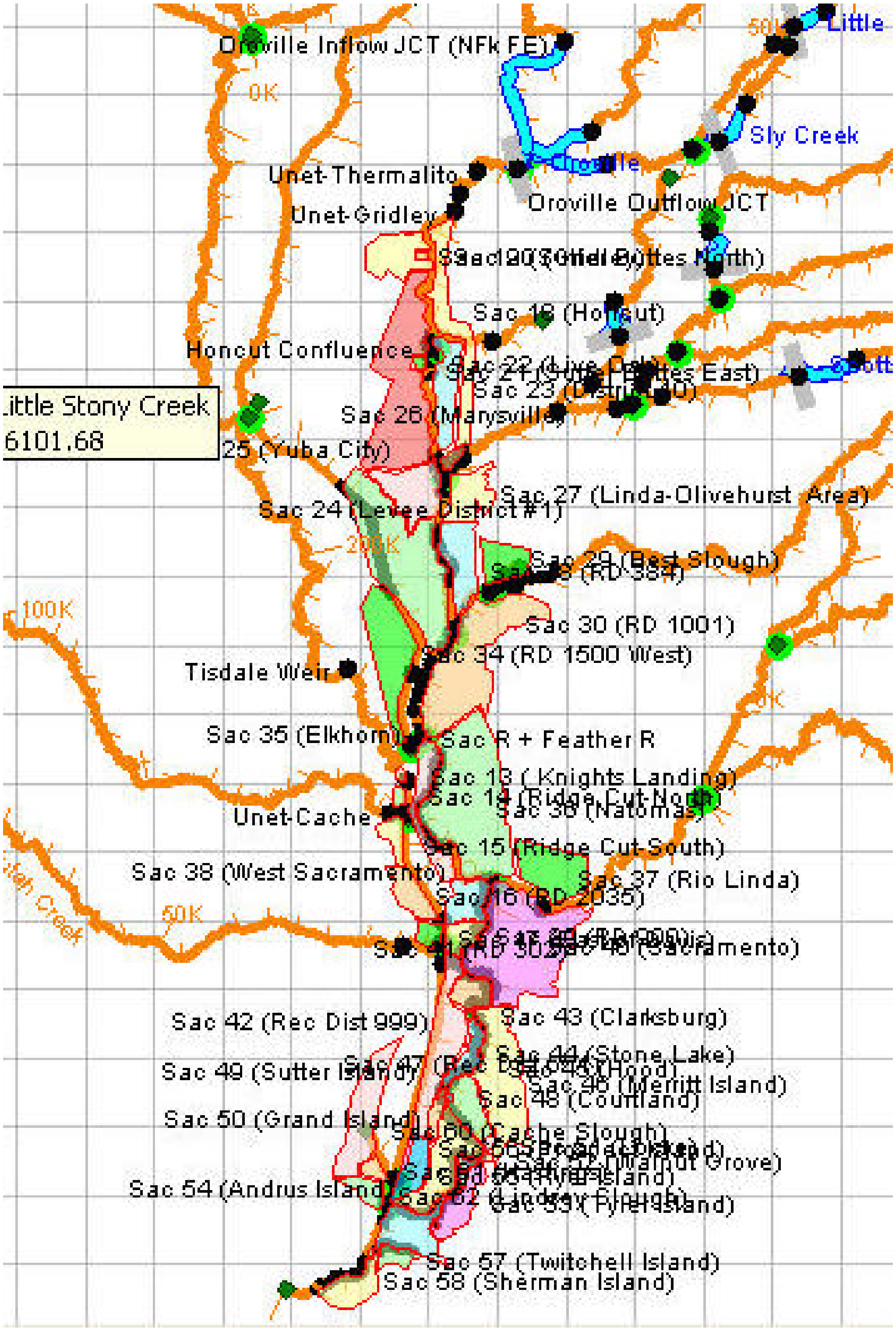


Figure C-2. Rating Curve for Yuba City (Sac 25)

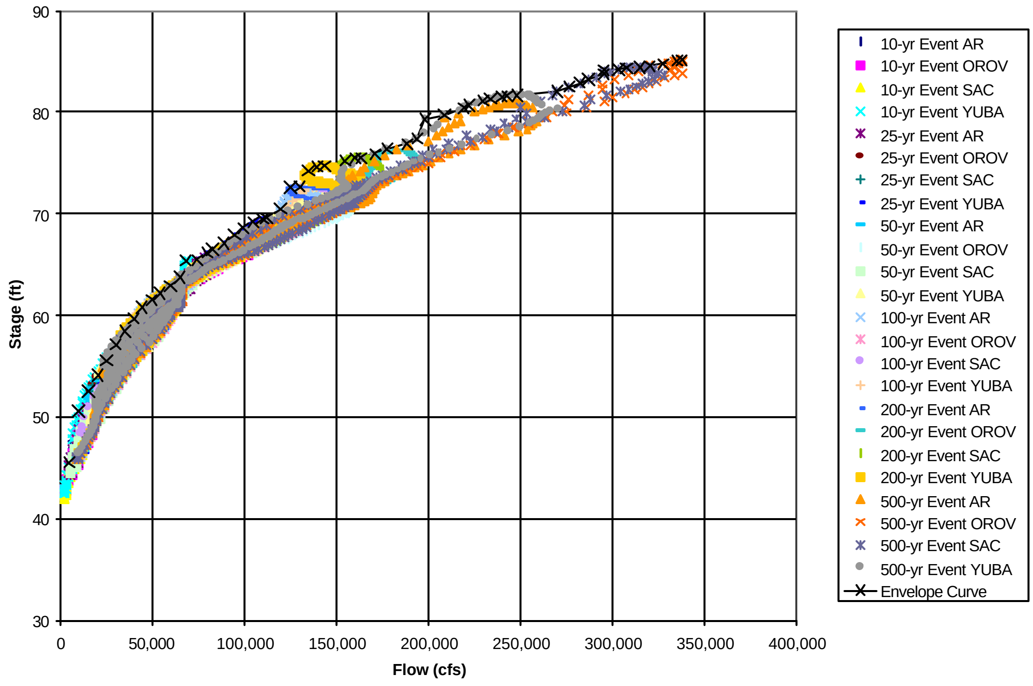


Figure C-3. Rating Curve for Marysville (Sac 26). Stage at Jack Slough as a function of Flow at Marysville

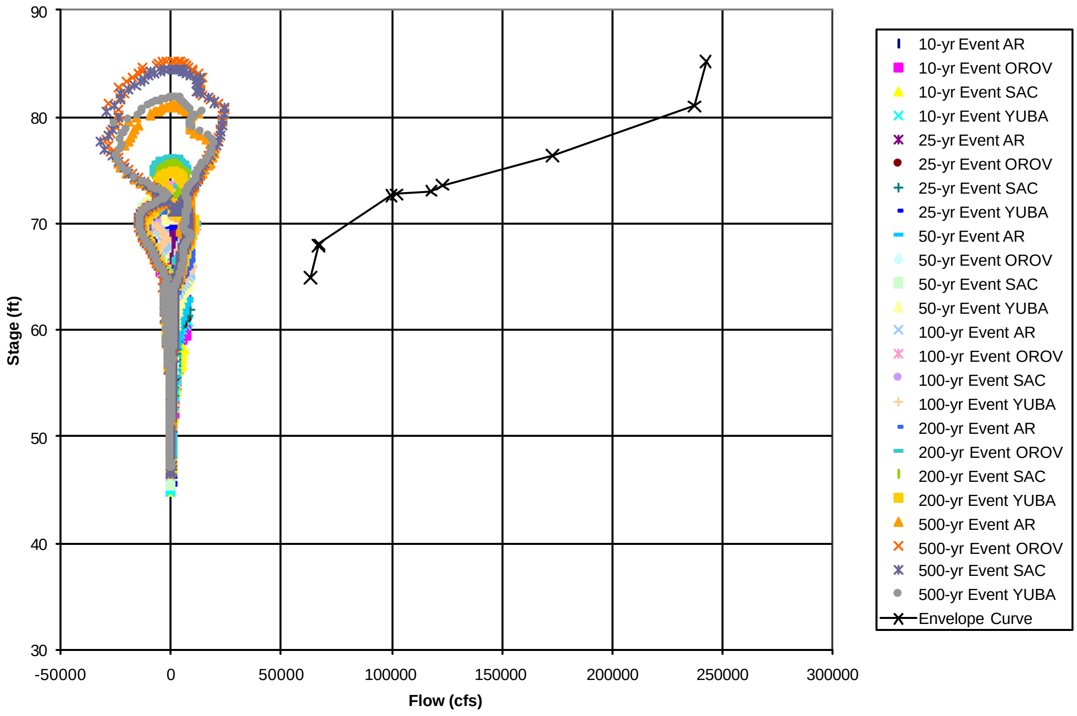
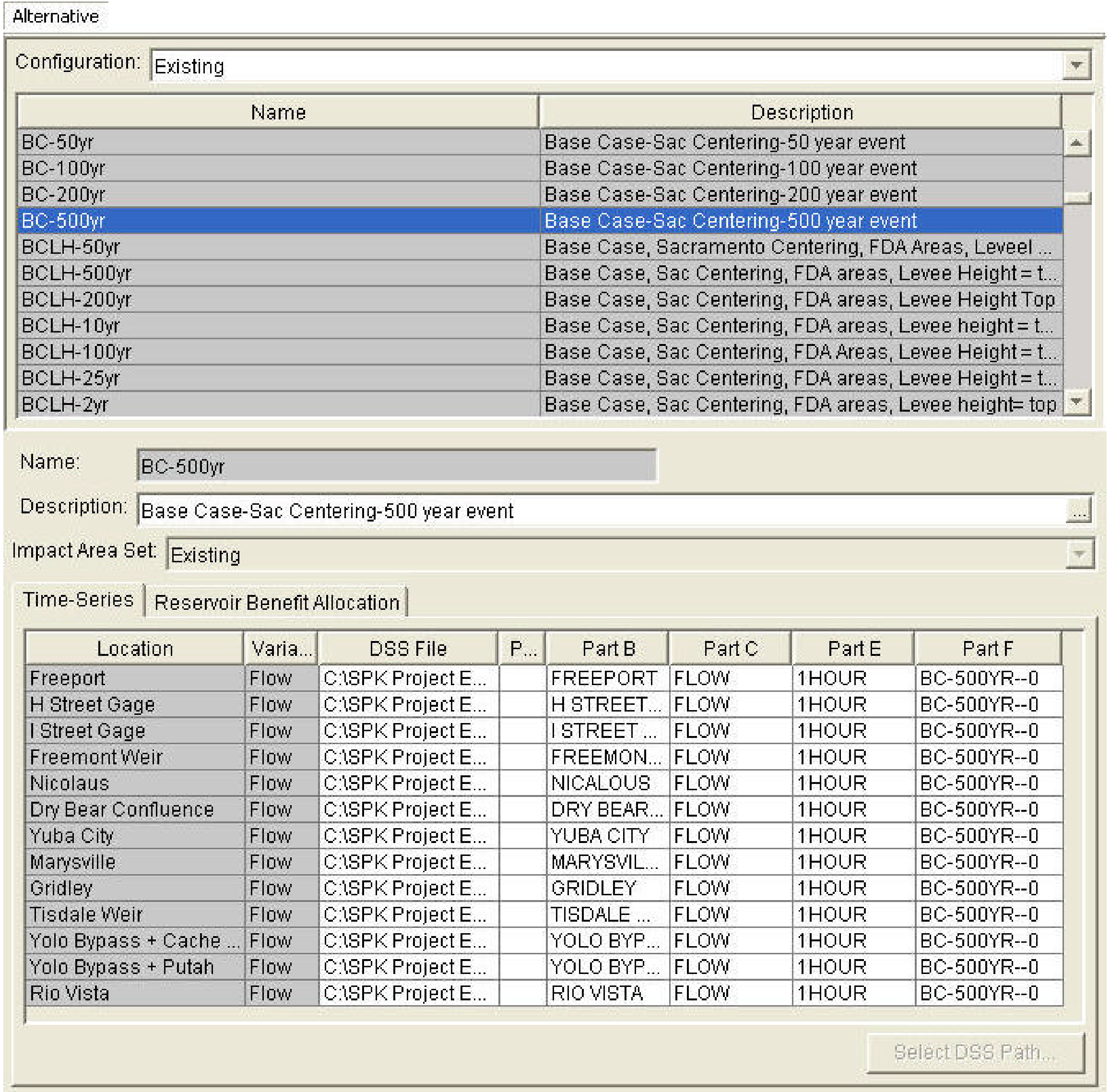


Figure C-4. FIA Setup for Base Case project, Sacramento storm center, 500-year event.



Configuration: Existing

Name	Description
BC-50yr	Base Case-Sac Centering-50 year event
BC-100yr	Base Case-Sac Centering-100 year event
BC-200yr	Base Case-Sac Centering-200 year event
BC-500yr	Base Case-Sac Centering-500 year event
BCLH-50yr	Base Case, Sacramento Centering, FDA Areas, Leveel ...
BCLH-500yr	Base Case, Sac Centering, FDA areas, Levee Height = t...
BCLH-200yr	Base Case, Sac Centering, FDA areas, Levee Height Top
BCLH-10yr	Base Case, Sac Centering, FDA areas, Levee height = t...
BCLH-100yr	Base Case, Sac Centering, FDA Areas, Levee Height = t...
BCLH-25yr	Base Case, Sac Centering, FDA areas, Levee Height = t...
BCLH-2yr	Base Case, Sac Centering, FDA areas, Levee height= top

Name: BC-500yr

Description: Base Case-Sac Centering-500 year event

Impact Area Set: Existing

Location	Varia...	DSS File	P...	Part B	Part C	Part E	Part F
Freeport	Flow	C:\SPK Project E...		FREEPORT	FLOW	1HOUR	BC-500YR--0
H Street Gage	Flow	C:\SPK Project E...		H STREET...	FLOW	1HOUR	BC-500YR--0
I Street Gage	Flow	C:\SPK Project E...		I STREET ...	FLOW	1HOUR	BC-500YR--0
Freemont Weir	Flow	C:\SPK Project E...		FREEMON...	FLOW	1HOUR	BC-500YR--0
Nicolaus	Flow	C:\SPK Project E...		NICALOUS	FLOW	1HOUR	BC-500YR--0
Dry Bear Confluence	Flow	C:\SPK Project E...		DRY BEAR...	FLOW	1HOUR	BC-500YR--0
Yuba City	Flow	C:\SPK Project E...		YUBA CITY	FLOW	1HOUR	BC-500YR--0
Marysville	Flow	C:\SPK Project E...		MARYSVIL...	FLOW	1HOUR	BC-500YR--0
Gridley	Flow	C:\SPK Project E...		GRIDLEY	FLOW	1HOUR	BC-500YR--0
Tisdale Weir	Flow	C:\SPK Project E...		TISDALE ...	FLOW	1HOUR	BC-500YR--0
Yolo Bypass + Cache ...	Flow	C:\SPK Project E...		YOLO BYP...	FLOW	1HOUR	BC-500YR--0
Yolo Bypass + Putah	Flow	C:\SPK Project E...		YOLO BYP...	FLOW	1HOUR	BC-500YR--0
Rio Vista	Flow	C:\SPK Project E...		RIO VISTA	FLOW	1HOUR	BC-500YR--0

Appendix D. Developing a Rating Curve for Freemont Weir

Initial flood operation module runs showed poor verification between the HEC-5 and UNET Sacramento basin models for regulated flows in the lower Sacramento River and Yolo Bypass. Further examination showed that the error involved poor partitioning (diversion) of flow at the Freemont weir (i.e. diversion rating curve) in the HEC-5 model. Therefore, it was decided to calibrate the HEC-ResSim Fremont Weir rating curve to UNET model flow output generated from synthetic hydrology (Tibbits 2002). Figure D-1 shows the calibration as well as the old HEC-5 rating curve. With the HEC-ResSim curve calibrated from the UNET model data, up to 40,000 cfs of additional flow is directed over the weir and into the Yolo Bypass rather than down the main Sacramento River channel. This calibration was shown to fit with a similar Freemont Weir flow-split calibration made from the January, 1997 flood event and reported by MBK Engineers (Countryman, 2003)(Light blue crosses in Figure D-1). Additional background information regarding the weir and the calibration steps are discussed below.

D.1 Additional Background Information

Figure D-2 shows the map of the Sacramento and Feather Rivers and Sutter and Yolo Bypasses in the neighborhood of Fremont Weir (USACE 1991, plate #12). An important physical characteristic of the system to observe is that the Weir (located between Sacramento River miles #82 and 84) is actually upstream of the confluence of the Feather and Sacramento Rivers (river mile #80). But, high flows in the Feather and Sacramento Rivers can raise the river stage at Verona higher than the stage at the weir and create a hydraulic gradient that directs significant Feather River, Sutter Bypass, and Natomas cross-canal flows across the weir. Upriver flow behavior cannot be modeled in the HEC-ResSim watershed due to limitations with hydraulic routings; therefore, the Fremont Weir was modeled as immediately downstream of the Feather and Sacramento Rivers confluence (Figure D-3).

D.2 Calibration Steps

All time-series of flows in the UNET model in the neighborhood of Fremont Weir were examined (Table D-1; numbers in the table correspond to circled number locations in Figure D-2) for each of the 10-, 4.0-, 2.0-. 1.0-, 0.5-, and 0.2 % probability exceedance events simulated in UNET. These flows represent mass balance for a control volume around the Fremont weir and can be partitioned into flows into (#1 through #4) and out of (#5 and #6) the control volume. Figure D-3 shows the time-series of flows for the 500-year, Sacramento storm centering event as well as the total inflows and outflows.

Total inflows (brown diamonds in Figure D-3) nearly equal total outflows (light green crosses in Figure D-3) (or are lagged by travel time between in the inflow locations and the outflow locations) at every time-step for each exceedance event. This represents conservation of mass.

Table D-1. List of UNET Time-series[a,b,c,d] for Mass Balance on Flow in the Neighborhood of Fremont Weir

TS A part (2)	**B part** (2)	**C part** (3)
Inflows		
1. Sac River R21	Sacramento River @ Wilkens Slough	Flow
2. Sutter BP R23	Sutter BP DS Tisdale BP	Flow
3. Feather River R38	Feather R @ Nicolaus	Flow
4. Natomas Cross CNL R56	Crss Cnl @ Sac Riv	Flow
Outflows		
5. Yolo Bypass R62	Yolo Bypass @ Fremont Weir	Flow
6. Sac River R57	Sac River @ Verona	Flow

Notes:

a. DSS file = “BSIxxxyy.dss” where *xxx* is a 3-character number (010, 025, 050, 100, 200, or 500) representing the return period of the flood event and *yy* is a 2-character abbreviation representing the storm centering (OV, YU, SC).

b. D part = “01Jan1900””

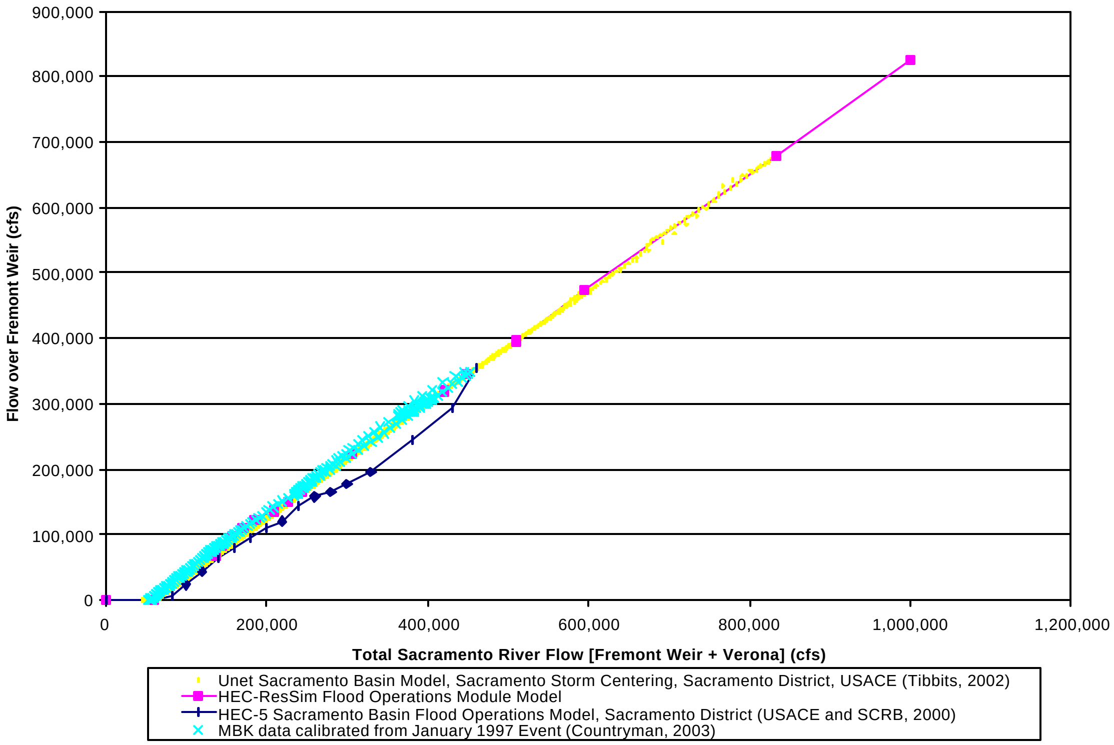
c. E part = “1Hour”

d. F part = “BSEIxxxyyyy”, where *xxx* is as in note a, and *yyyy* is a 3 or 4 character abbreviation representing the storm centering (OROV, YUBA, SAC)

Flow over the weir (#5) was compared against total outflow (#5 + #6) for each time step. These pairs were plotted in aggregate for all probability events (small, yellow crosses in Figure D-1). This paired comparison assumes negligible routing time between the weir and Verona gaging station (expected to be less than 1 hour).

Points for the rating curve were pulled from the aggregate data by identifying the weir flow corresponding to local-maximum outflow for each event (pink squares in Figure D-1). These points correspond to flow peaks occurring on Jan 10, Jan 15, Jan 21, and Jan 26.

Figure D-1. Flow-split Rating Curves for Fremont Weir



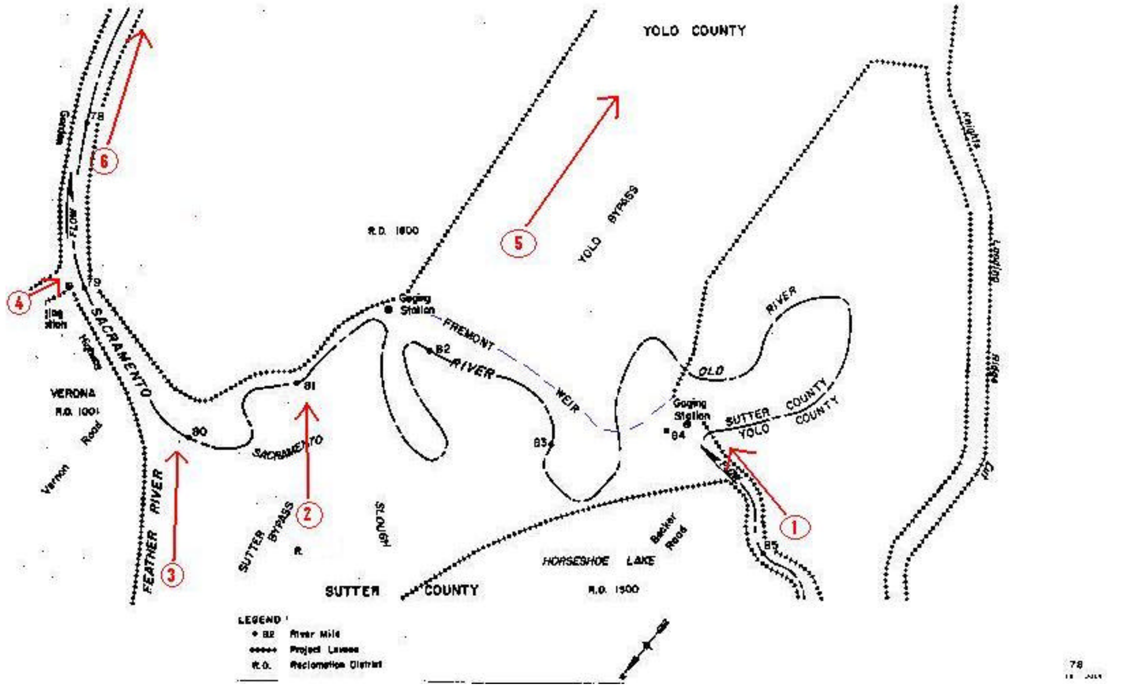


Figure D-2. Sacramento River in Neighborhood of Fremont Weir

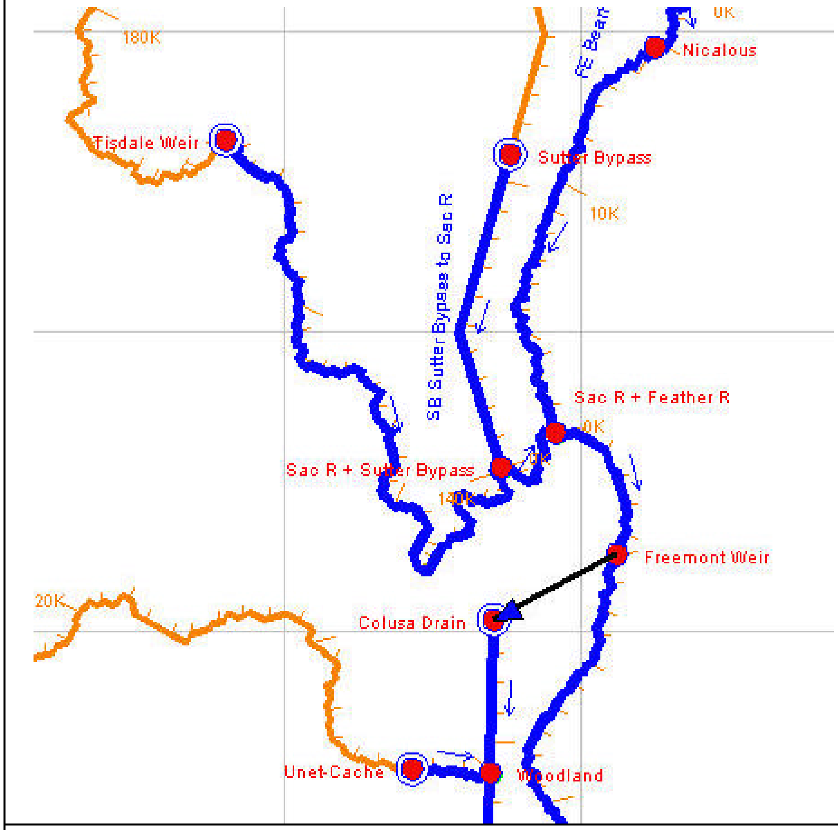
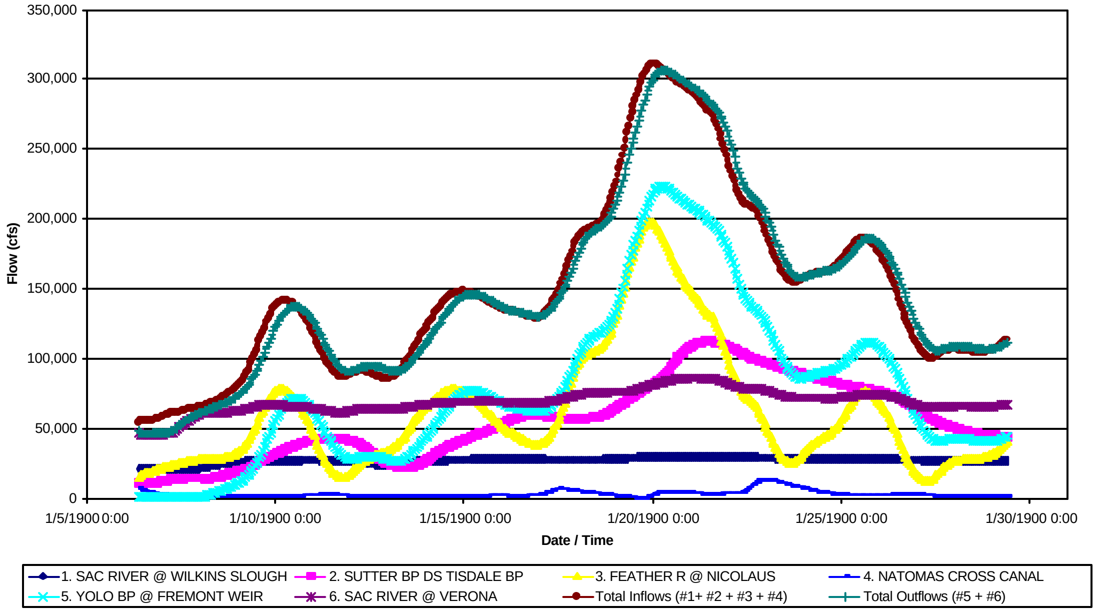


Figure D-3. Schematic of Fremont Weir in HEC-ResSim Watershed

Figure D-4. Flows Into and Out of Fremont Weir 10-year Event, Sacramento Storm Centering



Appendix E. Water Supply Allocation Module Files

This appendix presents the electronic files which were used to run the water supply allocation modules. Files were of three types:(i) input data files containing the HEC-5 records describing each storage reallocation project alternative, (ii) HEC-5 simulation executable files, and (iii) the DSS file from which period-of-record flows, demands, and in-stream flow requirements for each simulation were read and to which output time-series were written. File names are summarized in Table F-1. For all storage reallocation alternatives, input and output time-series were written to the same DSS file, "POR_FEYU.dss." Contents of the executable batch file "HEC5ALL.bat" are also listed below.

Table E-1. Electronic Files used for Water Supply Allocation Module

File Name	Description
HEC-5 Input data files	
1. PorLBCC1.dat	Base Case
2. PorLBCC2.dat	Raise Oroville guide curve 40 TAF
3. PorLBCC3.dat	Lower Oroville guide curve 40 TAF
4. PorLBCC4.dat	Raise Oroville guide curve 200 TAF
5. PorLBCC5.dat	Lower Oroville guide curve 200 TAF
6. PorLBCC6.dat	Raise New Bullard's Bar guide curve 45 TAF
7. PorLBCC7.dat	Lower New Bullard's Bar guide curve 45 TAF
8. PorLBCC8.dat	Raise New Bullard's Bar guide curve 100 TAF
9. PorLBCC9.dat	Lower New Bullard's Bar guide curve 100 TAF
10. PorLBC10.dat	Raise New Bullard's Bar top of buffer 50 TAF
11. PorLBC11.dat	Lower New Bullard's Bar top of buffer 50 TAF
12. PorLBC12.dat	Raise Oroville guide curve 300 TAF
13. PorLBC13.dat	Raise Oroville guide curve 400 TAF
14. PorLBC14.dat	Lower Oroville guide curve 300 TAF
15. PorLBC15.dat	Lower Oroville guide curve 400 TAF
Simulation Run Files	
1. HEC5ALL.bat	Batch file to execute all input data files at once
2. HEC5A.exe	HEC-5 executable
Input and Output file	
1. POR_FEYU.dss	file from which period-of-record flows, demands, and in-stream flow requirements were read and to which output time-series were written

Contents of batch file “HEC5ALL.bat”

```
HEC5A I=PorLBCC1.DAT O=PorLBCC1.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC2.DAT O=PorLBCC2.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC3.DAT O=PorLBCC3.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC4.DAT O=PorLBCC4.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC5.DAT O=PorLBCC5.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC6.DAT O=PorLBCC6.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC7.DAT O=PorLBCC7.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC8.DAT O=PorLBCC8.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBCC9.DAT O=PorLBCC9.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC10.DAT O=PorLBC10.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC11.DAT O=PorLBC11.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC12.DAT O=PorLBC12.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC13.DAT O=PorLBC13.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC14.DAT O=PorLBC14.OUT DSS=POR_FEYU.DSS
HEC5A I=PorLBC15.DAT O=PorLBC15.OUT DSS=POR_FEYU.DSS
```

Appendix F. Impact Area Set delineated for Flood Impact Analysis Study of the Sacramento Basin

Analogous to Appendix D, this appendix presents the input and output data for delineating Sacramento Basin impact areas based on data compiled in an FIA study made by Dunn (1999). Damage results were outputted for all scenarios associated with all project alternative runs. Table F-1 lists the electronic files associated with the FIA study impact area set.

The FIA study impact area delineation was used as a basis for comparing and validating EAD calculated from the impact area set delineated in the FDA study (Appendix D). Key differences between the two impact area sets regarded the (i) delineation of impact areas and breakout locations, (ii) stage-damage functions, and (iii) levee heights.

D.1 Delineating Impact Areas

Impact areas located within the Feather, Yuba, and Bear River basins, or the Sacramento River basin downstream of the Feather-Sacramento River confluence were used (Table F-2 and Figure F-1). Table F-2 also lists levee heights (column 3), the reference flow locations in the HEC-ResSim flood operation model to which impact area damages were tied (column 4), and the location in the UNET model of the Sacramento basin (Tibbits 2002) from which the stage-flow rating curve for the impact area was developed (columns 5 and 6).

D.2 Developing Rating Curves

All reference locations were located on the main river reaches that were represented in the flood operations modul. Therefore, all reference location rating curves were developed using the upper envelope of UNET model flow and stage time-series data as described in Appendix D, section 2.

D.3 HEC-FIA tool, input data, damage functions, and output data

Impact area delineations, stage-flow rating curves, damage functions, and levee heights were entered into the Impact Area Setup Module of the HEC-FIA software tool (see watershed directory “Yuba-Feather-WS-FIA”) using data described by Dunn (1999). Damage functions were invariant with season and aggregated across 8 damage categories (single-family residential, multi-family residential, mobile homes, commercial, industrial, public, farms, and crops). Levee failure heights were specified as the top levee height described by Dunn (1999). Using the FIA impact area set, damage was calculated for each event scenario of each project alternative.

Table F-1. Electronic Files used for Flood Impact Analysis

File Name (1)	Description (2)
Flow-Stage.xls	UNET model time-series data organized by reference location. Includes rating curves developed for each location.
Yuba-Feather-WS-FIA	HEC-FIA watershed directory containing input data (impact area delineations, stage-flow rating curves, damage functions, and levee heights) and HEC-FIA output for all scenarios run for each project alternative.

Table F-2. FIA Study Impact Area Set

Impace Area (1)	FIA Study ID[a] (2)	Levee Height (feet) (3)	Reference Flow Location Junction[b] (4)	Flow-Stage Rating Curve Location in Unet Model[c,d,e] A part (5)	B part (6)
(a) Feather and Yuba Basin Impact Areas					
1. Area between Sutter Bypass and Feather River	Sac 13	51.2	Nicolaus	FEATHER RIVER R38	FEATHER R @ NICOLAUS
2. Yuba City	Sac 14	80.5	Yuba City	FEATHER RIVER R26	FEATHER R @ YUBA CITY
3. Marysville	Sac 16	77.0	Marysville	YUBA RIVER R27	YUBA R @ MARYSVILLE
4. North of Marysville	Sac 17	92.4	Honcut Creek Confluence	FEATHER RIVER R24	IP 4 DA SAC21
5. Olivehurst_Linda Area	Sac 18	78.5	FR + YR Junction	FEATHER RIVER R28	FEATHER R DS YUBA R
6. Feather River South of Oliverhurst/Linda Area	Sac 19	68.0	FR + YR Junction	FEATHER RIVER R28	FEATHER R DS YUBA R
7. Wheatland	Sac 20	98.2	Unet Bear	FEATHER RIVER R38	FEATHER R DS BEAR R
8. Feather River South of Bear River	Sac 21	51.2	Bear Confluence	FEATHER RIVER R38	FEATHER R DS BEAR R
9. Sacramento River at Feather River Confluence	Sac 22	48.6	Nicolaus	FEATHER RIVER R38	FEATHER R @ NICOLAUS
(b) Lower Sacramento Basin Impact Areas					
10. Sacramento River Below Verona	Sac 29		Freemont Weir	SAC RIVER R57	SAC RIVER @ VERONA
11. Local Area North of West Sacramento	Sac 30	34.3	Freemont Weir	SAC RIVER R57	SAC RIVER @ VERONA
12. West Sacramento	Sac 31	34.0	I Street Gage	SAC RIVER R61	SAC RIVER @ I STREET
13. Lisbon Area South of West Sacramento	Sac 32	38.3	Lisbon	YOLO BYPASS R72	YOLO BP @ LISBON
14. Rural area South of West Sacramento	Sac 33	38.3	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT
15. Natomas	Sac 35	40.8	Freemont Weir	SAC RIVER R57	SAC RIVER @ VERONA
16. Sacramento City	Sac 38	34.0	I Street Gage	SAC RIVER R61	SAC RIVER @ I STREET
17. Rural West Bank Area South of Sacramento	Sac 39	28.3	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT
18. East Bank Sacramento River South of Sacramento	Sac 40	28.3	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT
19. Sacramento River Levee South of Sacramento	Sac 41	28.3	Freeport	SAC RIVER R61	SAC RIVER @ FREEPORT
20. Local Area Sacramento River	Sac 46	23.7	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
21. Sacramento River Local Area	Sac 47	19.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
22. Local Area Sacramento River	Sac 48	23.7	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
23. Sacramento River Across from Rio Vista	Sac 49	19.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
24. Small Local Area Sacramento River	Sac 50	18.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
25. Small Local Area Sacramento River Levee	Sac 51	18.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
26.	Sac 52	18.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
27.	Sac 53	18.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
28. Local Area Sacramento River	Sac 54	19.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA
29. Lower Sacramento Area Below Rio Vista	Sac 55	19.0	Rio Vista	SAC RIVER R100	SAC RIVER @ RIO VISTA

Notes:

a. As used by Dunn (1999)

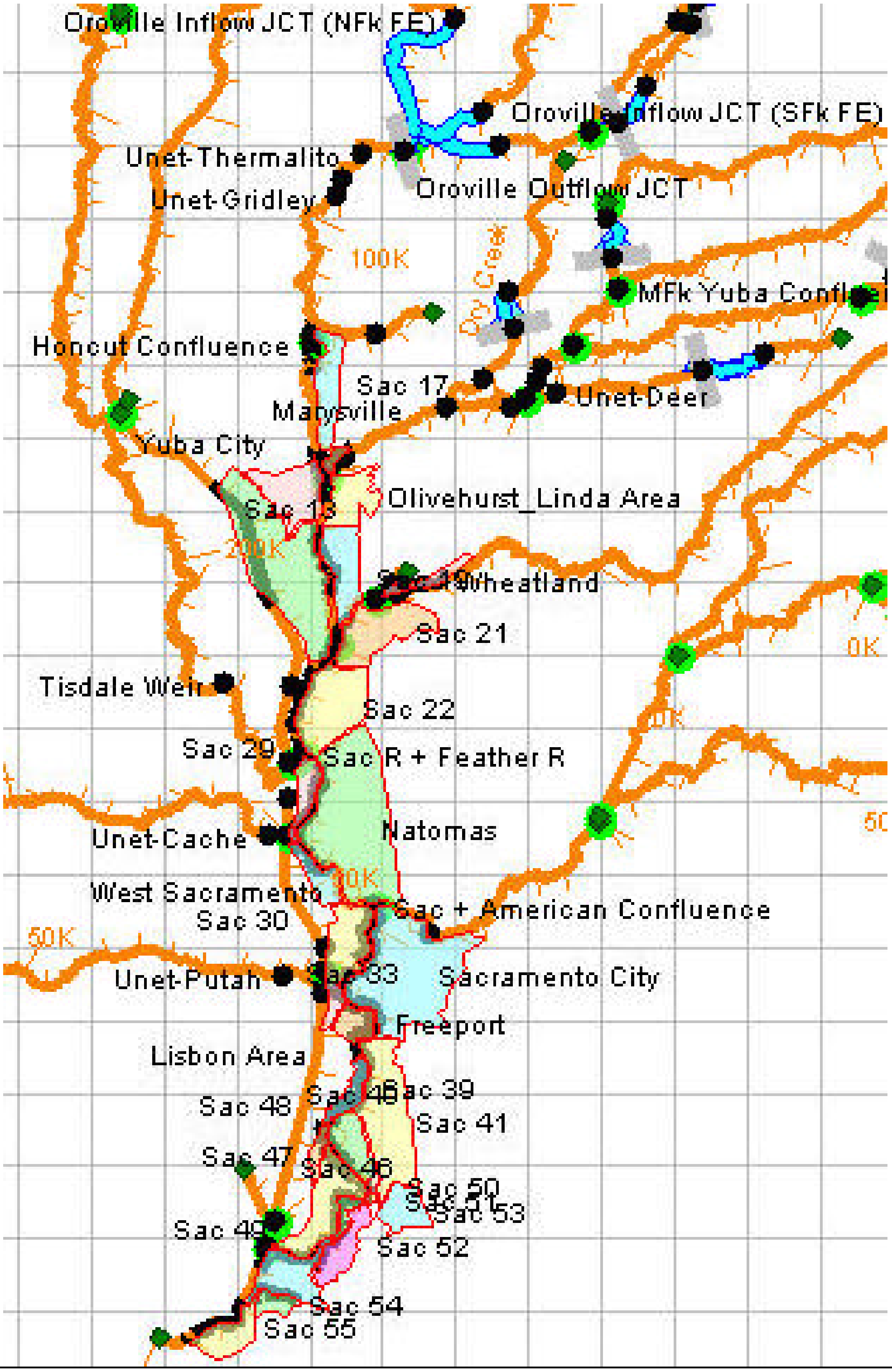
b. Junction in HEC-ResSim Flood Operations simulation model

c. DSS output file path parts from Unet model simulation of Sacramento Basin

d. DSS file = "BSIxxxyy.dss" where *xxx* is a 3-character number (010, 025, 050, 100, 200, or 500) representing the reutrn period of the flood event and *yy* is a 2-character abbreviation representing the storm centering (OV, YU, SC)

e. C part = "Flow" or "Stage"; D part = "01Jan1900"; E part = "1Hour", and F part = "BSEIxxxyyyy" where *xxx* is as in note a, and *yyyy* is a 3 or 4 character abbreviation represetnign the storm centering (OROV, YUBA, SAC)

Figure F-1. Delineation of Impact Areas in HEC-FIA Watershed



Appendix G. Creating Base Case Control Runs

This appendix describes how base case control runs were created and entered in the flood operations and water supply allocation modules. Four types of control runs were made. These involved: (i) inflow hydrology, (ii) routing time hydrology, (iii) impact area set, and (iv) demand level.

G.1 Inflow Hydrology Runs

Separate control runs for synthetic storms centered in the Feather and Yuba basins and at Shanghai bend were created and simulated in the HEC-ResSim flood operations model. Inflow data for each centering was specified in the DSS files “Orov5B.dss”, “Orov5B2.dss”, “Yuba5B.dss”, “Yuba5B2.dss” (Hickey et al. 2002), “Shang5A.dss” and “Shang5A2.dss” (Whitin 2003). Inflow time-series were linked to the flood operations model (Figure G-1 shows an example for the Feather center, 500-year event). Links were made for each flow scenario (200-, 100-, 50-, 25-, 10-, and 2-year flow events). Flow scenarios were grouped in a simulation, simulated, and results were then linked to the FIA model as with the Sacramento basin storm center.

G.2 Routing Time

Routing time control runs were created and evaluated in the HEC-FIA module by linking UNET model results [Tibbits, 2002 #78]. UNET model results represented time-series of base case flood operations routed through the Sacramento basin. UNET time-series were linked to the impact area set (Figure G-2 shows an example for the 500-year event, Sacramento storm center). Paths represented UNET output at appropriate reference flow location. Separate links were made for each flow scenario (200-, 100-, 50-, 25-, and 10-year events; the 2-year event was not simulated in the UNET model). Flow scenarios were grouped in a simulation, computed, and damage results were weighted. This process was performd for storm events centered in the Sacramento, Feather, and Yuba basins.

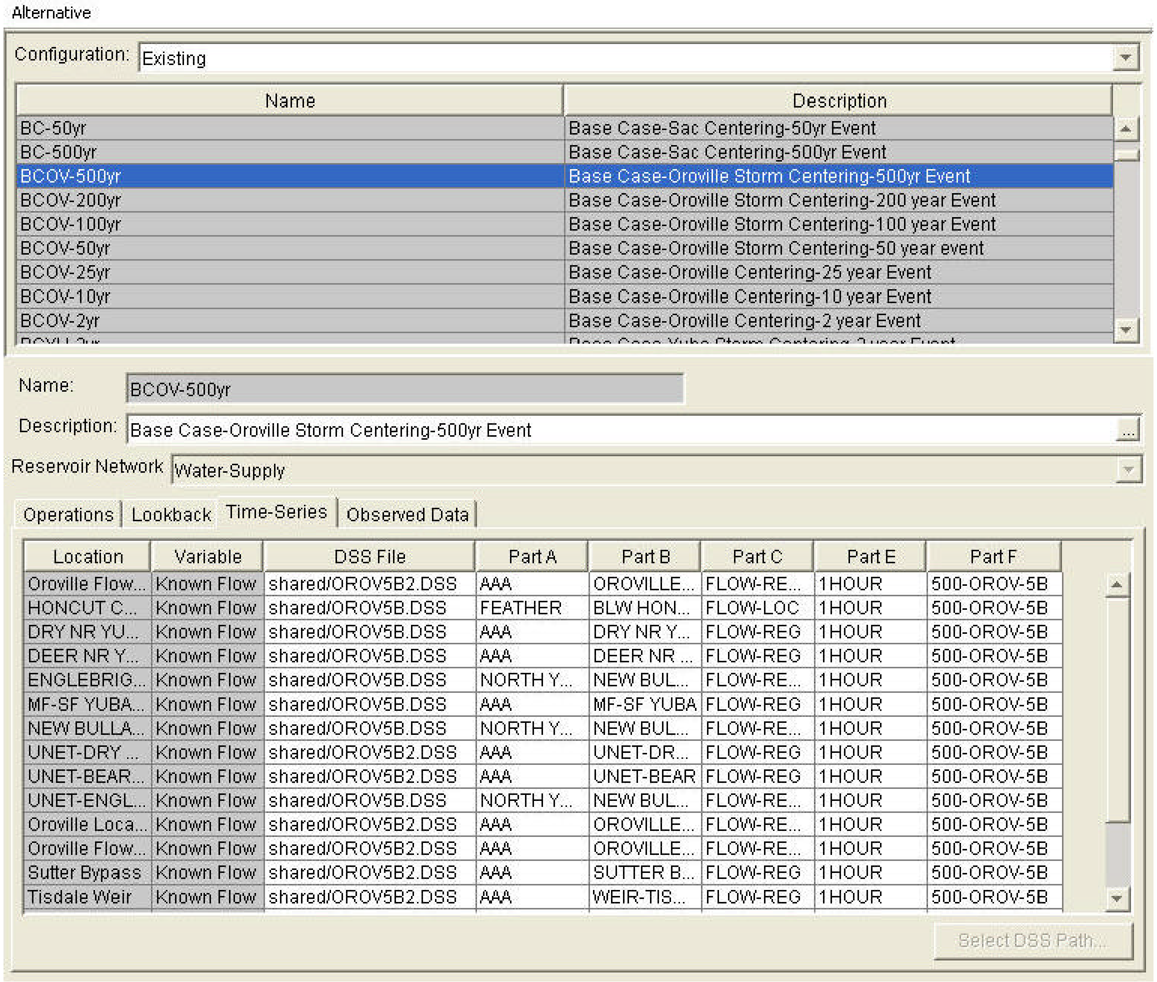
G.3 Impact Area Set

Impact area set control runs were also created in the HEC-FIA module. A second impact area set was defined (Appendix F). Time-series of output from the flood operations simulation model (Appendix A) were linked to the impact area set (Figure G-3 shows an example for the base case project, Sacramento storm centering, 500-year event scenario linked to the impact area set defined for the FIA study). This linking was repeated for each frequency-based flow scenario. Flow scenarios were grouped in a simulation and then evaluated.

G.4 Demand Levels

Demand level control runs were created directly in the HEC-5 water supply allocation model code. First, the time-series of unit water demands were multiplied by the factors (0.5, 2, 3, 4, and 5). Next, minimum in-stream flow requirements were added and the series were saved as separate DSS paths. Then, separate "events" were added at the end of the HEC-5 model code (see file "PorLBCC1.dat" in Appendix E). The appropriate demand level time series were linked to ZR=MR601 and ZR=MR599 records in each event. The HEC-5 code was run, and each demand level "event" was simulated.

Figure G-1. Linking inflow data for the Feather River Storm Center to the Flood Operations Simulation Model (Base Case project; 500-year event)



Configuration: Existing

Name	Description
BC-50yr	Base Case-Sac Centering-50yr Event
BC-500yr	Base Case-Sac Centering-500yr Event
BCOV-500yr	Base Case-Oroville Storm Centering-500yr Event
BCOV-200yr	Base Case-Oroville Storm Centering-200 year Event
BCOV-100yr	Base Case-Oroville Storm Centering-100 year Event
BCOV-50yr	Base Case-Oroville Storm Centering-50 year event
BCOV-25yr	Base Case-Oroville Centering-25 year Event
BCOV-10yr	Base Case-Oroville Centering-10 year Event
BCOV-2yr	Base Case-Oroville Centering-2 year Event

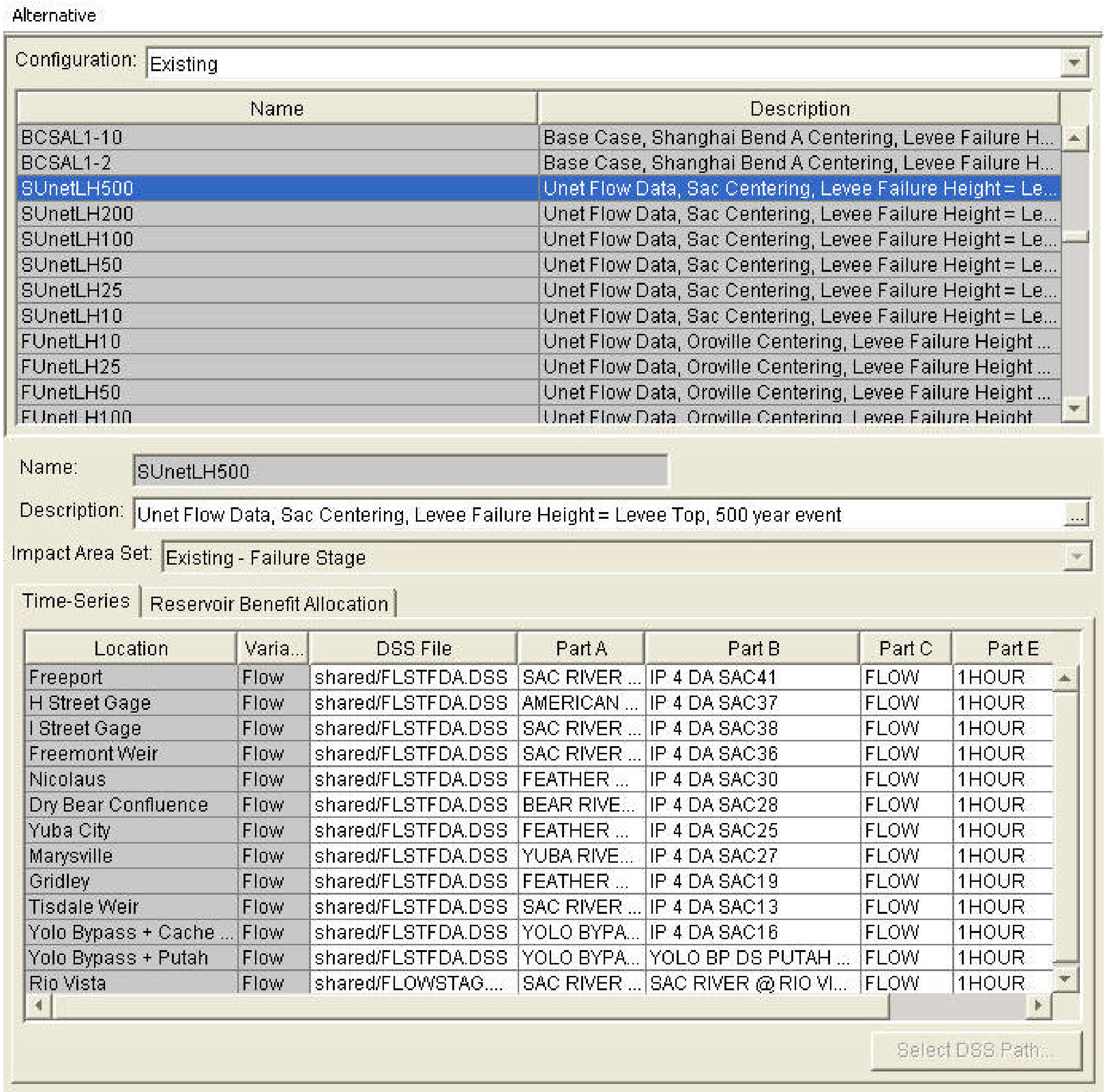
Name: BCOV-500yr

Description: Base Case-Oroville Storm Centering-500yr Event

Reservoir Network Water-Supply

Location	Variable	DSS File	Part A	Part B	Part C	Part E	Part F
Oroville Flow...	Known Flow	shared/OROV5B2.DSS	AAA	OROVILLE...	FLOW-RE...	1HOUR	500-OROV-5B
HONCUT C...	Known Flow	shared/OROV5B.DSS	FEATHER	BLW HON...	FLOW-LOC	1HOUR	500-OROV-5B
DRY NR YU...	Known Flow	shared/OROV5B.DSS	AAA	DRY NR Y...	FLOW-REG	1HOUR	500-OROV-5B
DEER NR Y...	Known Flow	shared/OROV5B.DSS	AAA	DEER NR ...	FLOW-REG	1HOUR	500-OROV-5B
ENGLEBRIG...	Known Flow	shared/OROV5B.DSS	NORTH Y...	NEW BUL...	FLOW-RE...	1HOUR	500-OROV-5B
MF-SF YUBA...	Known Flow	shared/OROV5B.DSS	AAA	MF-SF YUBA	FLOW-REG	1HOUR	500-OROV-5B
NEW BULLA...	Known Flow	shared/OROV5B.DSS	NORTH Y...	NEW BUL...	FLOW-RE...	1HOUR	500-OROV-5B
UNET-DRY ...	Known Flow	shared/OROV5B2.DSS	AAA	UNET-DR...	FLOW-REG	1HOUR	500-OROV-5B
UNET-BEAR...	Known Flow	shared/OROV5B2.DSS	AAA	UNET-BEAR	FLOW-REG	1HOUR	500-OROV-5B
UNET-ENGL...	Known Flow	shared/OROV5B.DSS	NORTH Y...	NEW BUL...	FLOW-RE...	1HOUR	500-OROV-5B
Oroville Loca...	Known Flow	shared/OROV5B2.DSS	AAA	OROVILLE...	FLOW-RE...	1HOUR	500-OROV-5B
Oroville Flow...	Known Flow	shared/OROV5B2.DSS	AAA	OROVILLE...	FLOW-RE...	1HOUR	500-OROV-5B
Sutter Bypass	Known Flow	shared/OROV5B2.DSS	AAA	SUTTER B...	FLOW-REG	1HOUR	500-OROV-5B
Tisdale Weir	Known Flow	shared/OROV5B2.DSS	AAA	WEIR-TIS...	FLOW-REG	1HOUR	500-OROV-5B

Figure G-2. Linking UNET model routing time data to the FDA Impact Area set in HEC-FIA
(Base Case project; Sacramento Storm Center; 500-year event)



Alternative

Configuration: Existing

Name	Description
BCSAL1-10	Base Case, Shanghai Bend A Centering, Levee Failure H...
BCSAL1-2	Base Case, Shanghai Bend A Centering, Levee Failure H...
SUnetLH500	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
SUnetLH200	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
SUnetLH100	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
SUnetLH50	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
SUnetLH25	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
SUnetLH10	Unet Flow Data, Sac Centering, Levee Failure Height = Le...
FUnetLH10	Unet Flow Data, Oroville Centering, Levee Failure Height ...
FUnetLH25	Unet Flow Data, Oroville Centering, Levee Failure Height ...
FUnetLH50	Unet Flow Data, Oroville Centering, Levee Failure Height ...
FUnetLH100	Unet Flow Data, Oroville Centering, Levee Failure Height

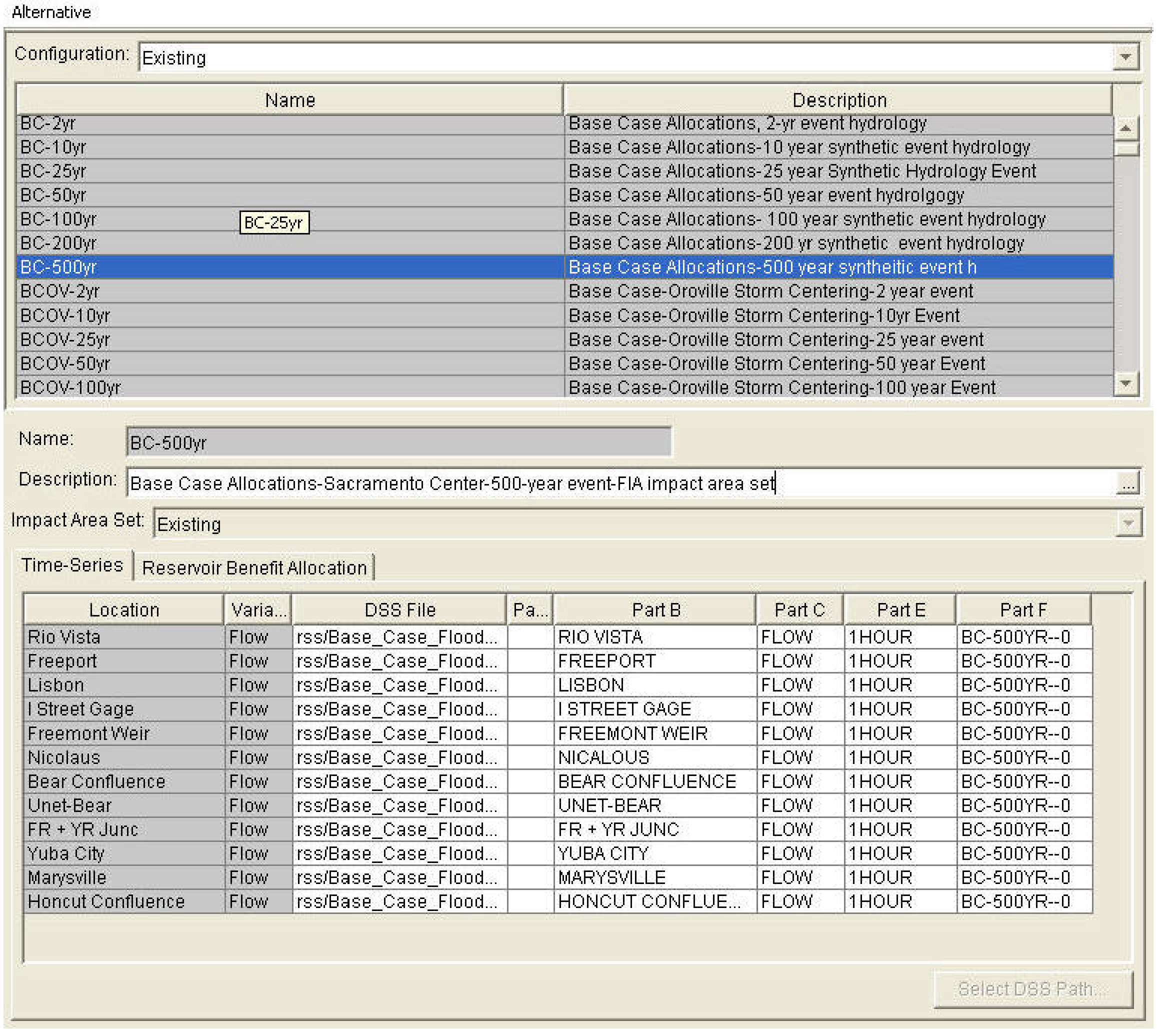
Name: SUnetLH500

Description: Unet Flow Data, Sac Centering, Levee Failure Height = Levee Top, 500 year event

Impact Area Set: Existing - Failure Stage

Location	Varia...	DSS File	Part A	Part B	Part C	Part E
Freeport	Flow	shared/FLSTFDA.DSS	SAC RIVER ...	IP 4 DA SAC41	FLOW	1HOUR
H Street Gage	Flow	shared/FLSTFDA.DSS	AMERICAN ...	IP 4 DA SAC37	FLOW	1HOUR
I Street Gage	Flow	shared/FLSTFDA.DSS	SAC RIVER ...	IP 4 DA SAC38	FLOW	1HOUR
Freemont Weir	Flow	shared/FLSTFDA.DSS	SAC RIVER ...	IP 4 DA SAC36	FLOW	1HOUR
Nicolaus	Flow	shared/FLSTFDA.DSS	FEATHER ...	IP 4 DA SAC30	FLOW	1HOUR
Dry Bear Confluence	Flow	shared/FLSTFDA.DSS	BEAR RIVE...	IP 4 DA SAC28	FLOW	1HOUR
Yuba City	Flow	shared/FLSTFDA.DSS	FEATHER ...	IP 4 DA SAC25	FLOW	1HOUR
Marysville	Flow	shared/FLSTFDA.DSS	YUBA RIVE...	IP 4 DA SAC27	FLOW	1HOUR
Gridley	Flow	shared/FLSTFDA.DSS	FEATHER ...	IP 4 DA SAC19	FLOW	1HOUR
Tisdale Weir	Flow	shared/FLSTFDA.DSS	SAC RIVER ...	IP 4 DA SAC13	FLOW	1HOUR
Yolo Bypass + Cache ...	Flow	shared/FLSTFDA.DSS	YOLO BYPA...	IP 4 DA SAC16	FLOW	1HOUR
Yolo Bypass + Putah	Flow	shared/FLSTFDA.DSS	YOLO BYPA...	YOLO BP DS PUTAH ...	FLOW	1HOUR
Rio Vista	Flow	shared/FLOWSTAG....	SAC RIVER ...	SAC RIVER @ RIO VI...	FLOW	1HOUR

Figure G-3. Linking Flood Operations simulation output to the FIA Study Impact Area set in HEC-FIA (Base Case project; Sacramento Storm Center; 500-year event)



Alternative

Configuration: Existing

Name	Description
BC-2yr	Base Case Allocations, 2-yr event hydrology
BC-10yr	Base Case Allocations-10 year synthetic event hydrology
BC-25yr	Base Case Allocations-25 year Synthetic Hydrology Event
BC-50yr	Base Case Allocations-50 year event hydrolgogy
BC-100yr	Base Case Allocations- 100 year synthetic event hydrology
BC-200yr	Base Case Allocations-200 yr synthetic event hydrology
BC-500yr	Base Case Allocations-500 year syntheitic event h
BCOV-2yr	Base Case-Oroville Storm Centering-2 year event
BCOV-10yr	Base Case-Oroville Storm Centering-10yr Event
BCOV-25yr	Base Case-Oroville Storm Centering-25 year event
BCOV-50yr	Base Case-Oroville Storm Centering-50 year Event
BCOV-100yr	Base Case-Oroville Storm Centering-100 year Event

Name: BC-500yr

Description: Base Case Allocations-Sacramento Center-500-year event-FIA impact area set

Impact Area Set: Existing

Location	Varia...	DSS File	Pa...	Part B	Part C	Part E	Part F
Rio Vista	Flow	rss/Base_Case_Flood...		RIO VISTA	FLOW	1HOUR	BC-500YR--0
Freeport	Flow	rss/Base_Case_Flood...		FREEPORT	FLOW	1HOUR	BC-500YR--0
Lisbon	Flow	rss/Base_Case_Flood...		LISBON	FLOW	1HOUR	BC-500YR--0
I Street Gage	Flow	rss/Base_Case_Flood...		I STREET GAGE	FLOW	1HOUR	BC-500YR--0
Freemont Weir	Flow	rss/Base_Case_Flood...		FREEMONT WEIR	FLOW	1HOUR	BC-500YR--0
Nicolaus	Flow	rss/Base_Case_Flood...		NICALOUS	FLOW	1HOUR	BC-500YR--0
Bear Confluence	Flow	rss/Base_Case_Flood...		BEAR CONFLUENCE	FLOW	1HOUR	BC-500YR--0
Unet-Bear	Flow	rss/Base_Case_Flood...		UNET-BEAR	FLOW	1HOUR	BC-500YR--0
FR + YR Junc	Flow	rss/Base_Case_Flood...		FR + YR JUNC	FLOW	1HOUR	BC-500YR--0
Yuba City	Flow	rss/Base_Case_Flood...		YUBA CITY	FLOW	1HOUR	BC-500YR--0
Marysville	Flow	rss/Base_Case_Flood...		MARYSVILLE	FLOW	1HOUR	BC-500YR--0
Honcut Confluence	Flow	rss/Base_Case_Flood...		HONCUT CONFLUE...	FLOW	1HOUR	BC-500YR--0

Appendix H. Creating Project Alternatives

This appendix describes how storage reallocation and reservoir re-operation project alternatives were created and entered in the flood operations and water supply allocation modules.

H.1 Storage Reallocation project alternatives

In the HEC-ResSim flood operations model, storage reallocation project alternatives were created as separate operations sets. Figure H-1 shows an example for Oroville for the case where the Guide Curve was lowered 200 TAF. Wintertime elevations corresponding to the 200 TAF volume decrease were entered as the new "Top of Conservation" zone elevation in the operations set (Figure H-1A). The operations sets were linked to seven synthetic inflow scenarios (2- through 500-year events) and the starting storage for each scenario set as the new guide curve height. Figures H-1B and C provide examples for the 500-year event. Each scenario was simulated and results were then linked to the HEC-FIA tool.

Figure H-2 shows the setup for a reallocation alternative at New Bullard's Bar reservoir (lower guide curve 100 TAF). Likewise, wintertime elevations corresponding to a 100 TAF volume decrease were entered as the new "Top of Conservation" zone elevation. In addition, the operation rule "Elev. Based CC" was changed. The original rule related the release objective to flood pool encroachment level (Operation #16 in Chapter 3, section 3.2). Elevations were changed to reflect new encroachment elevations with the altered size of the flood pool under reallocation. The operations set was linked to seven synthetic inflow scenarios (2- through 500-year events), starting storage was linked and changed to the new wintertime guide curve level, and each scenario was simulated. Simulation results were then linked to the FIA model.

In the HEC-5 water supply model, storage reallocation alternatives were created as separate input data files. Wintertime storage levels on the RL 3 record for each reservoir were changed. See documentation in the data files (i.e., "PorLBC5.dat" for the alternative that lowered Oroville guide curve 200 TAF).

H.2 Re-operation alternatives

Re-operation alternatives were also created as separate operations set in the HEC-ResSim flood operations model. These re-operations are explained as follows.

New Bullard's Bar operates only for Marysville. The rule "Max Flow-Marysville, func of flow at YC" defined in the New Bullard's Bar base case operation set was removed (Operation # 17 in Chapter 3, section 3.2). This operation dynamically related the flow objective at Marysville to flow in the Feather River at Yuba City. The relationship summed to preserve a channel capacity flow objective of 300,000 cfs at the Feather – Yuba confluence. However in this alternative, the relationship was removed. Instead, flow objective at Marysville was statically set to 180,000 cfs ("Max Flow-Marysville DC" rule in Figure H-3).

Raise New Bullard's Bar release objective to 75,000 cfs. In the Base Case, the release objective was 50,000 cfs (Operation #16 in Chapter 3, section 3.2) and was operationally modeled using an increasing release limit rule as a function of flood pool encroachment level. By 35% encroachment, release limit was the full value (50,000 cfs in the base case). In this alternative, a new operation rule was substituted and release limits were scaled up to the full value of 75,000 cfs ("Elev. b CC – 75k cfs – RF" in Figure H-4).

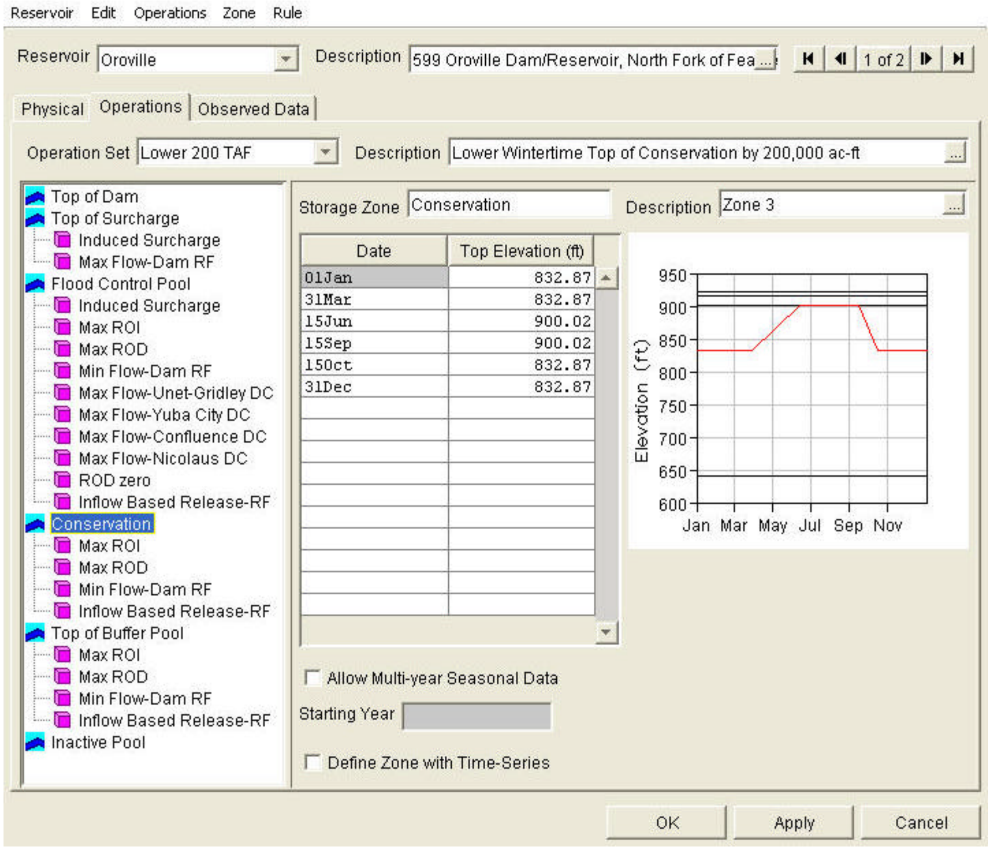
This alternative combined the changes of alternatives #17 and #18 (Figure H-5).

Lower the flow objective at the Feather and Yuba confluence to 270,000 cfs. Also, allow New Bullard's Bar to operate solely for Marysville (as in Alternative #17). In the Base Case, the confluence flow objective was 300,000 cfs (Operation #6 in Chapter 3 section 3.2). This alternative was implemented by scripting a new operating rule for Oroville Reservoir ("Max Flow-Confluence 270 DC" in Figure H-6A). The operations set scripted for Alternative #17 at New Bullard's Bar was also used (Figure H-6B).

Reservoir re-operation alternatives were not simulated in the water supply allocation model. The re-operations considered only considered re-operations for flood protection purposes on hourly or daily time intervals. These re-operations did not influence how water was released or stored over the period of record

Figure H-1. Setup for Reallocation Alternative to Lower Oroville Guide Curve by 200 TAF

A. Operations Set



Reservoir: Oroville

Description: 599 Oroville Dam/Reservoir, North Fork of Fea...

Operation Set: Lower 200 TAF

Description: Lower Wintertime Top of Conservation by 200,000 ac-ft

Storage Zone: Conservation

Description: Zone 3

Date	Top Elevation (ft)
01Jan	832.87
31Mar	832.87
15Jun	900.02
15Sep	900.02
15Oct	832.87
31Dec	832.87

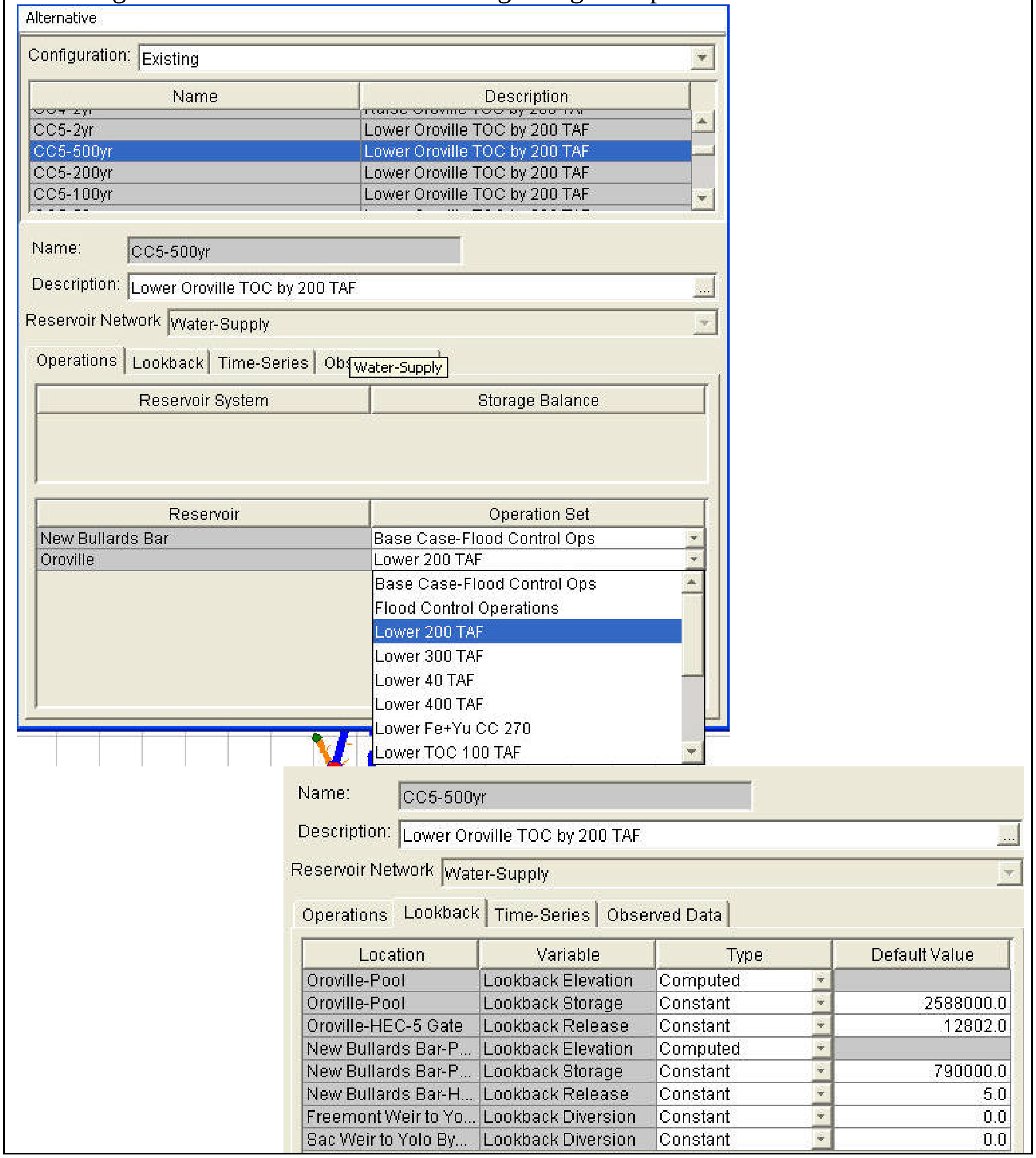
☐ Allow Multi-year Seasonal Data

Starting Year

☐ Define Zone with Time-Series

Figure H-1 (continued)

B. Linking Time-Series and Lookback starting storage to Operations Set



Configuration: Existing

Name	Description
CC5-2yr	Lower Oroville TOC by 200 TAF
CC5-500yr	Lower Oroville TOC by 200 TAF
CC5-200yr	Lower Oroville TOC by 200 TAF
CC5-100yr	Lower Oroville TOC by 200 TAF

Name: CC5-500yr

Description: Lower Oroville TOC by 200 TAF

Reservoir Network: Water-Supply

Reservoir System	Storage Balance

Reservoir	Operation Set
New Bullards Bar	Base Case-Flood Control Ops
Oroville	Lower 200 TAF

Name: CC5-500yr

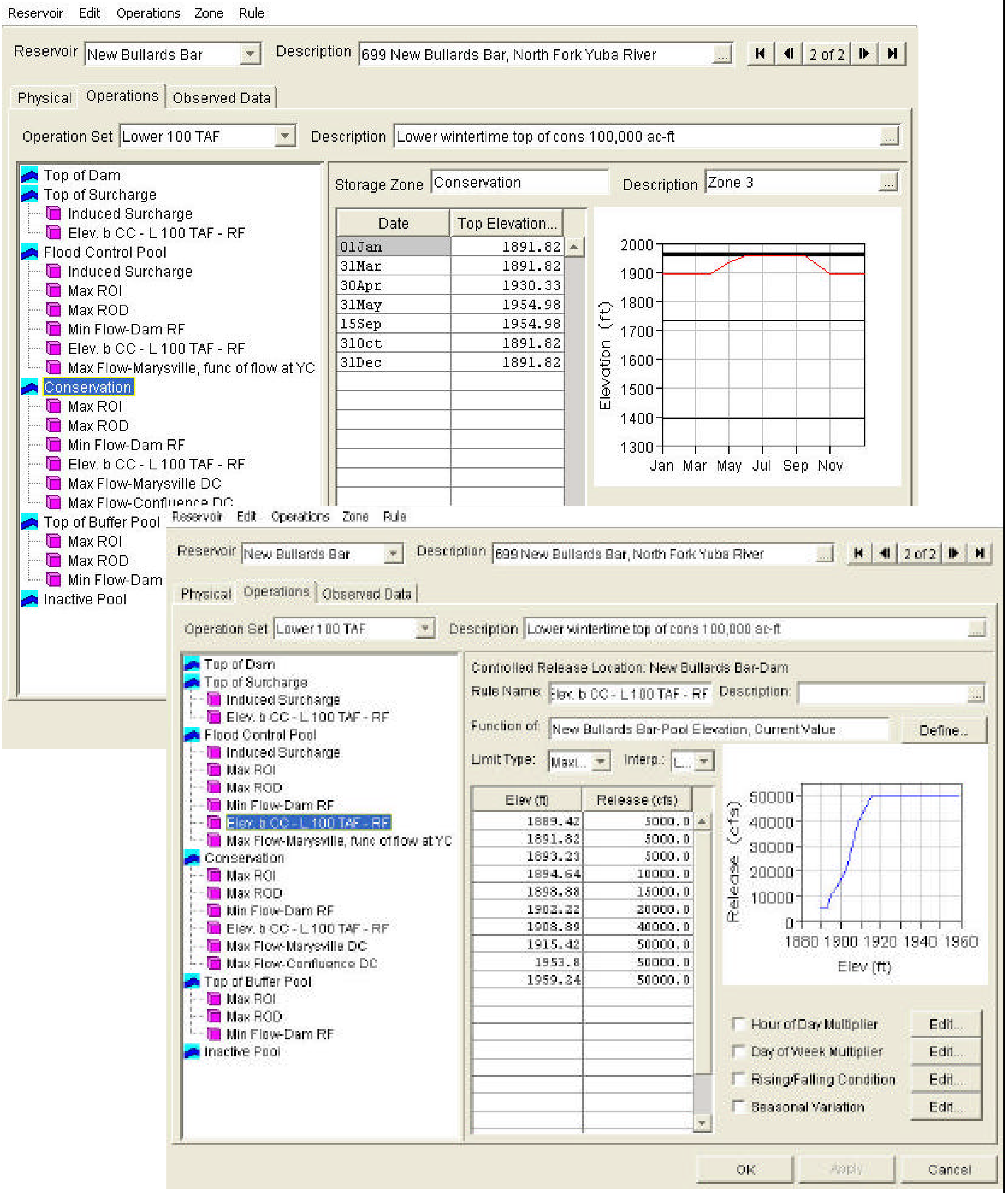
Description: Lower Oroville TOC by 200 TAF

Reservoir Network: Water-Supply

Location	Variable	Type	Default Value
Oroville-Pool	Lookback Elevation	Computed	
Oroville-Pool	Lookback Storage	Constant	2588000.0
Oroville-HEC-5 Gate	Lookback Release	Constant	12802.0
New Bullards Bar-P...	Lookback Elevation	Computed	
New Bullards Bar-P...	Lookback Storage	Constant	790000.0
New Bullards Bar-H...	Lookback Release	Constant	5.0
Freemont Weir to Yo...	Lookback Diversion	Constant	0.0
Sac Weir to Yolo By...	Lookback Diversion	Constant	0.0

Figure H-2. Setup for Reallocation Alternative to Lower New Bullard's Bar Guide Curve by 100 TAF

A. Operations Set and Encroachment Rule



Reservoir: New Bullards Bar

Description: 699 New Bullards Bar, North Fork Yuba River

Operation Set: Lower 100 TAF

Description: Lower wintertime top of cons 100,000 ac-ft

Storage Zone: Conservation

Description: Zone 3

Date	Top Elevation...
01Jan	1891.82
31Mar	1891.82
30Apr	1930.33
31May	1954.98
15Sep	1954.98
31Oct	1891.82
31Dec	1891.82

Controlled Release Location: New Bullards Bar-Dam

Rule Name: Elev. b CC - L 100 TAF - RF

Description:

Function of: New Bullards Bar-Pool Elevation, Current Value

Limit Type: Maxi...

Interp.: L...

Elev (ft)	Release (cfs)
1889.42	5000.0
1891.82	5000.0
1893.23	5000.0
1894.64	10000.0
1898.88	15000.0
1902.22	20000.0
1908.89	40000.0
1915.42	50000.0
1953.8	50000.0
1959.24	50000.0

☐ Hour of Day Multiplier

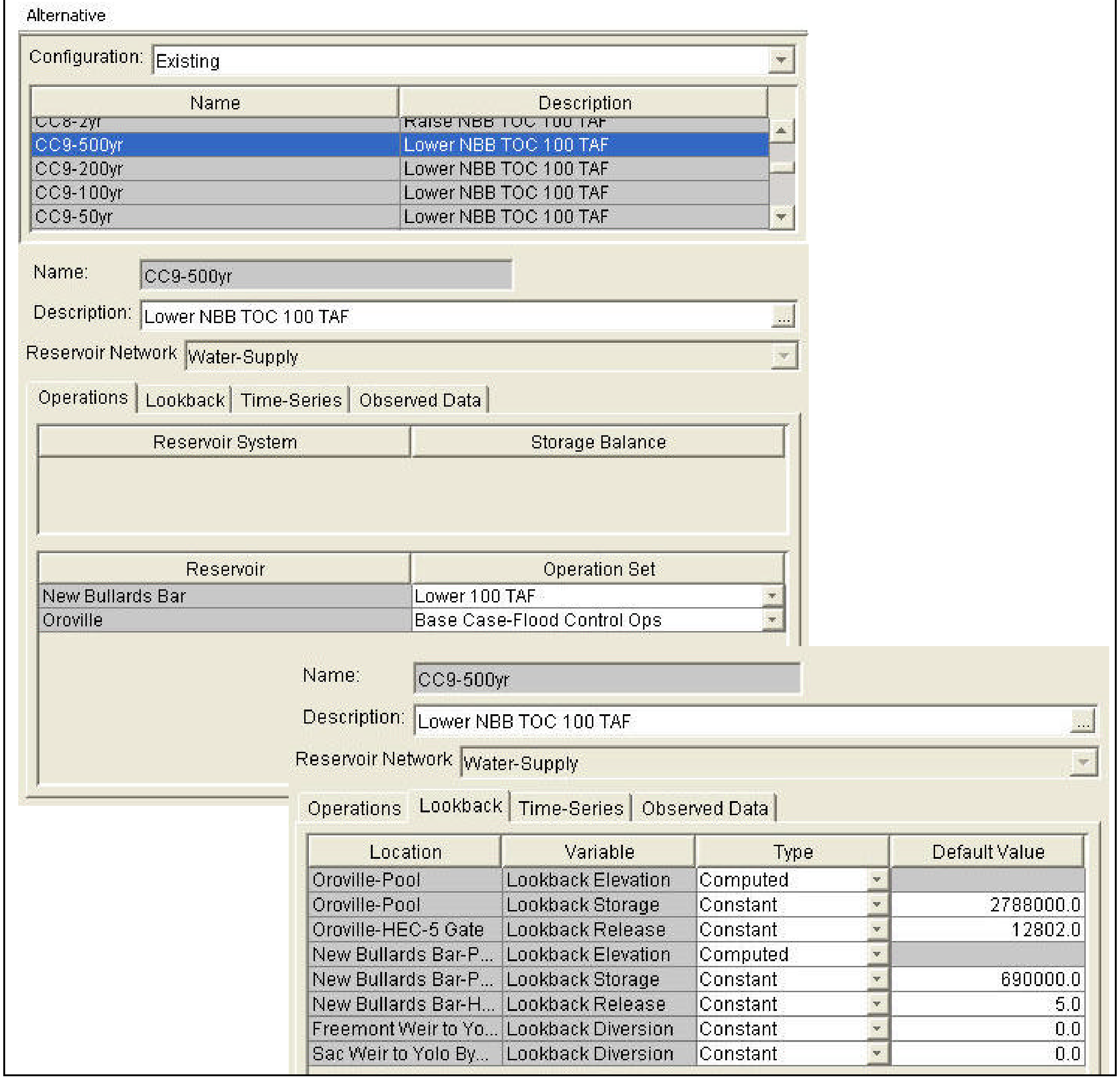
☐ Day of Week Multiplier

☐ Rising/Falling Condition

☐ Seasonal Variation

Figure H-2 (continued)

B. Linking Time-Series and Lookback starting storage to Operations Set



Alternative

Configuration: Existing

Name	Description
CC8-2yr	Raise NBB TOC 100 TAF
CC9-500yr	Lower NBB TOC 100 TAF
CC9-200yr	Lower NBB TOC 100 TAF
CC9-100yr	Lower NBB TOC 100 TAF
CC9-50yr	Lower NBB TOC 100 TAF

Name: CC9-500yr

Description: Lower NBB TOC 100 TAF

Reservoir Network: Water-Supply

Operations | Lookback | Time-Series | Observed Data

Reservoir System	Storage Balance

Reservoir	Operation Set
New Bullards Bar	Lower 100 TAF
Oroville	Base Case-Flood Control Ops

Name: CC9-500yr

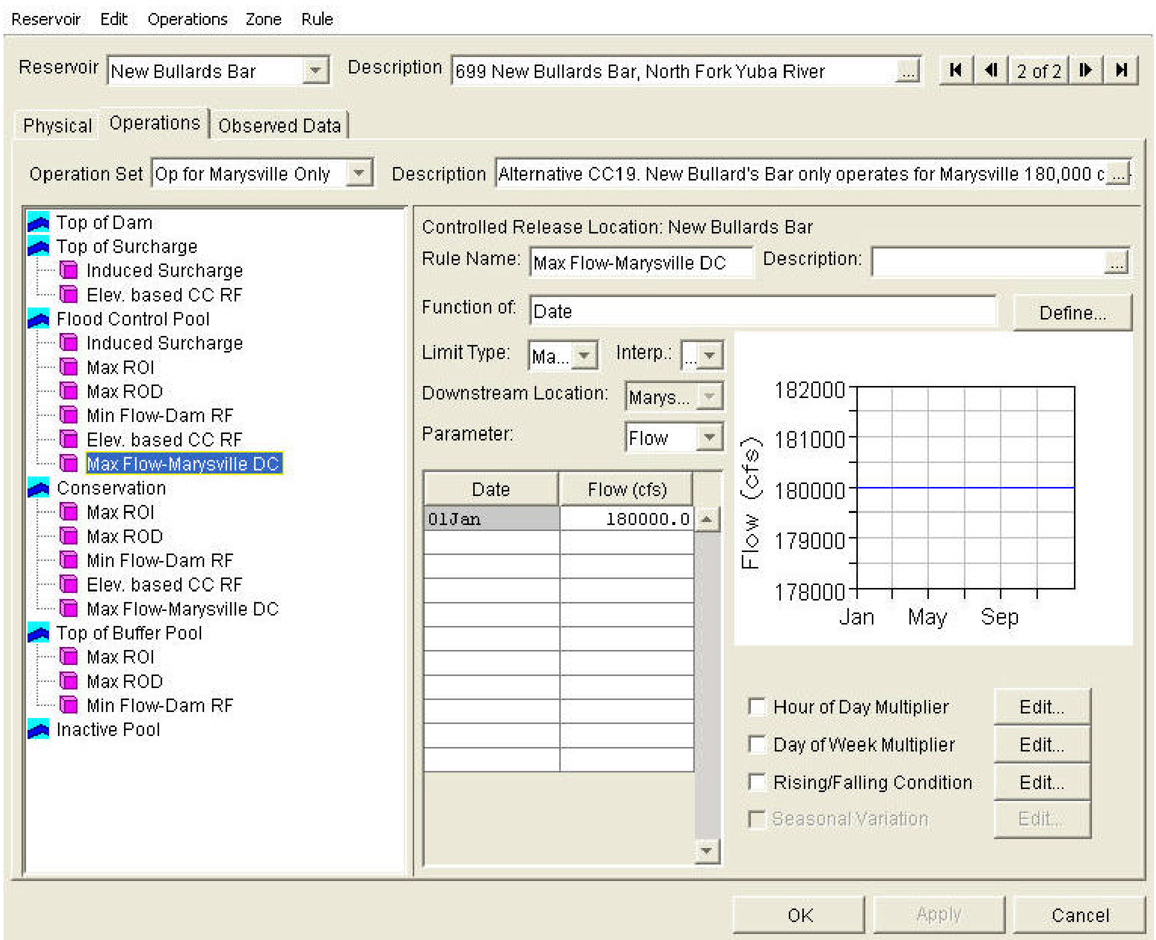
Description: Lower NBB TOC 100 TAF

Reservoir Network: Water-Supply

Operations | Lookback | Time-Series | Observed Data

Location	Variable	Type	Default Value
Oroville-Pool	Lookback Elevation	Computed	
Oroville-Pool	Lookback Storage	Constant	2788000.0
Oroville-HEC-5 Gate	Lookback Release	Constant	12802.0
New Bullards Bar-P...	Lookback Elevation	Computed	
New Bullards Bar-P...	Lookback Storage	Constant	690000.0
New Bullards Bar-H...	Lookback Release	Constant	5.0
Freemont Weir to Yo...	Lookback Diversion	Constant	0.0
Sac Weir to Yolo By...	Lookback Diversion	Constant	0.0

Figure H-3. Setup for Re-Operation Alternative #17.
(New Bullard's Bar operates for flow objective of 180,000 cfs at Marysville)



Reservoir: New Bullards Bar
Description: 699 New Bullards Bar, North Fork Yuba River
2 of 2

Operation Set: Op for Marysville Only
Description: Alternative CC19. New Bullard's Bar only operates for Marysville 180,000 c

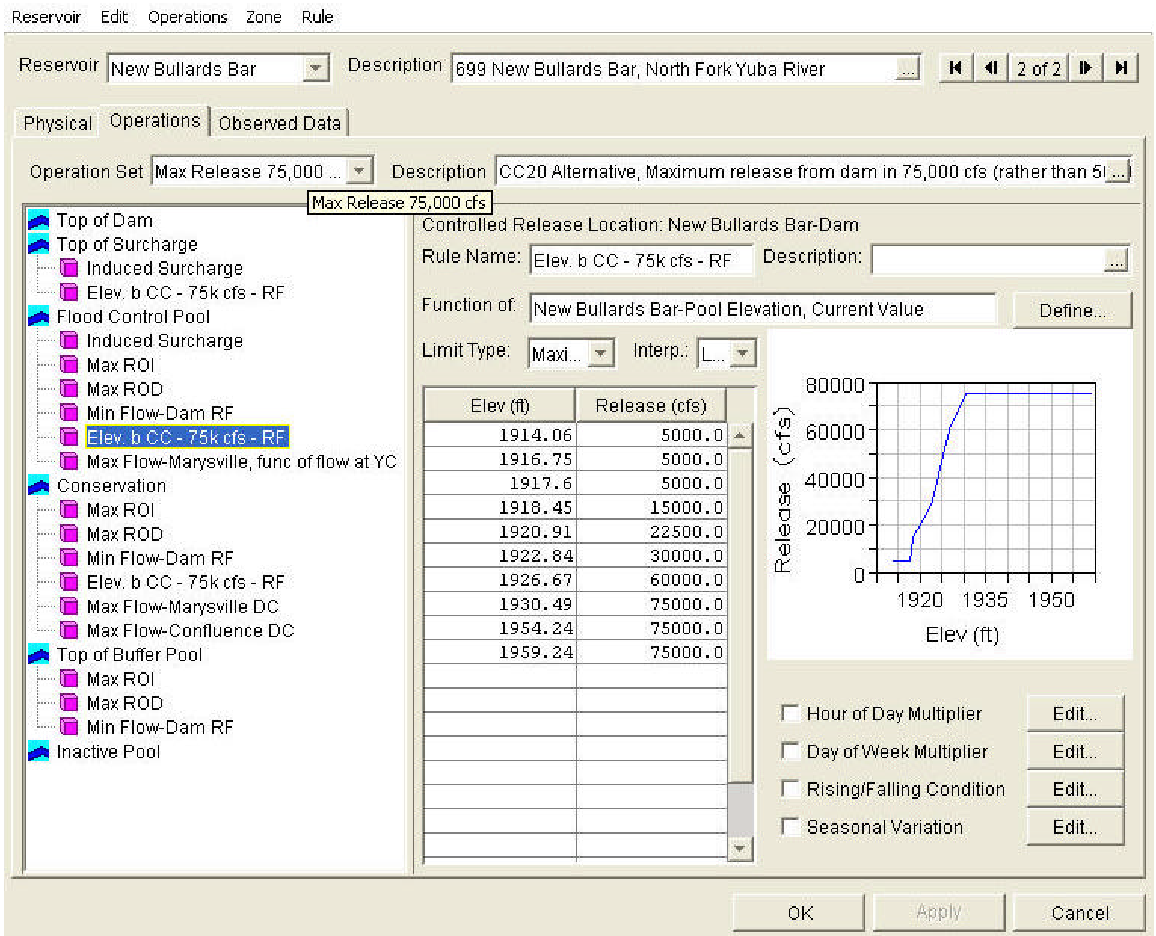
- Top of Dam
- Top of Surcharge
  - Induced Surcharge
  - Elev. based CC RF
- Flood Control Pool
  - Induced Surcharge
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. based CC RF
  - Max Flow-Marysville DC
- Conservation
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. based CC RF
  - Max Flow-Marysville DC
- Top of Buffer Pool
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
- Inactive Pool

Controlled Release Location: New Bullards Bar
Rule Name: Max Flow-Marysville DC
Description:
Function of: Date
Limit Type: Ma...
Interp.: ...
Downstream Location: Marys...
Parameter: Flow

Date	Flow (cfs)
01Jan	180000.0

☐ Hour of Day Multiplier
☐ Day of Week Multiplier
☐ Rising/Falling Condition
☐ Seasonal Variation

Figure H-4. Setup for Re-Operation Alternative #18
(raise objective release criteria at New Bullard's Bar to 75,000 cfs)



Reservoir: New Bullards Bar

Description: 699 New Bullards Bar, North Fork Yuba River

Operation Set: Max Release 75,000 ...

Max Release 75,000 cfs

Description: CC20 Alternative, Maximum release from dam in 75,000 cfs (rather than 5

- Top of Dam
- Top of Surcharge
  - Induced Surcharge
  - Elev. b CC - 75k cfs - RF
- Flood Control Pool
  - Induced Surcharge
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. b CC - 75k cfs - RF
  - Max Flow-Marysville, func of flow at YC
- Conservation
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. b CC - 75k cfs - RF
  - Max Flow-Marysville DC
  - Max Flow-Confluence DC
- Top of Buffer Pool
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
- Inactive Pool

Controlled Release Location: New Bullards Bar-Dam

Rule Name: Elev. b CC - 75k cfs - RF

Description:

Function of: New Bullards Bar-Pool Elevation, Current Value

Limit Type: Maxi...

Interp.: L...

Elev (ft)	Release (cfs)
1914.06	5000.0
1916.75	5000.0
1917.6	5000.0
1918.45	15000.0
1920.91	22500.0
1922.84	30000.0
1926.67	60000.0
1930.49	75000.0
1954.24	75000.0
1959.24	75000.0

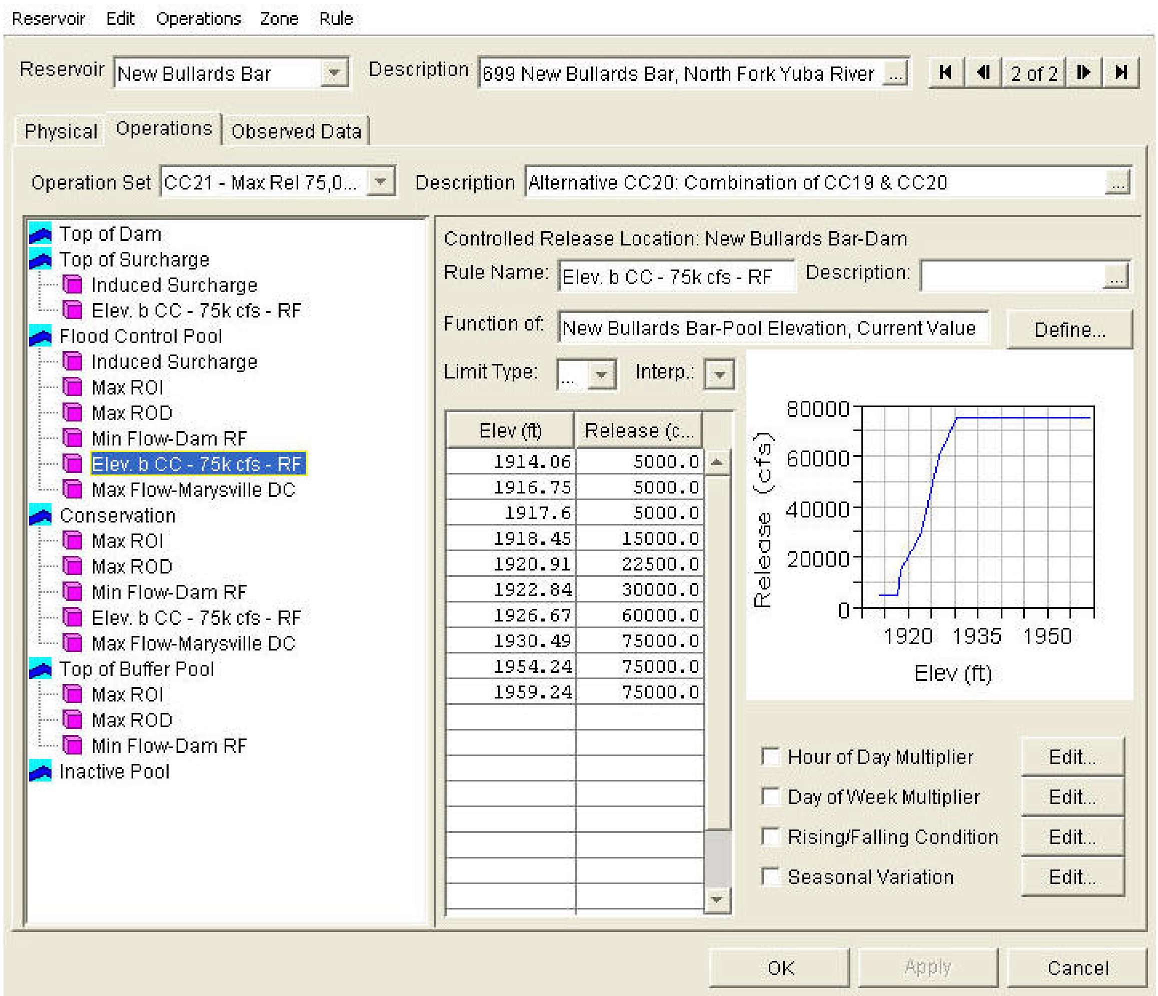
☐ Hour of Day Multiplier

☐ Day of Week Multiplier

☐ Rising/Falling Condition

☐ Seasonal Variation

Figure H-5. Setup for Re-Operation Alternative #19 (Raises objective release criteria at New Bullard's Bar to 75,000 cfs and New Bullard's Bar operates for flow objective of 180,000 cfs at Marysville)



Reservoir: New Bullards Bar

Description: 699 New Bullards Bar, North Fork Yuba River

Operation Set: CC21 - Max Rel 75,0...

Description: Alternative CC20: Combination of CC19 & CC20

- Top of Dam
- Top of Surcharge
  - Induced Surcharge
  - Elev. b CC - 75k cfs - RF
- Flood Control Pool
  - Induced Surcharge
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. b CC - 75k cfs - RF
  - Max Flow-Marysville DC
- Conservation
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Elev. b CC - 75k cfs - RF
  - Max Flow-Marysville DC
- Top of Buffer Pool
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
- Inactive Pool

Controlled Release Location: New Bullards Bar-Dam

Rule Name: Elev. b CC - 75k cfs - RF

Description:

Function of: New Bullards Bar-Pool Elevation, Current Value

Limit Type: ...

Interp.:

Elev (ft)	Release (c...
1914.06	5000.0
1916.75	5000.0
1917.6	5000.0
1918.45	15000.0
1920.91	22500.0
1922.84	30000.0
1926.67	60000.0
1930.49	75000.0
1954.24	75000.0
1959.24	75000.0

☐ Hour of Day Multiplier

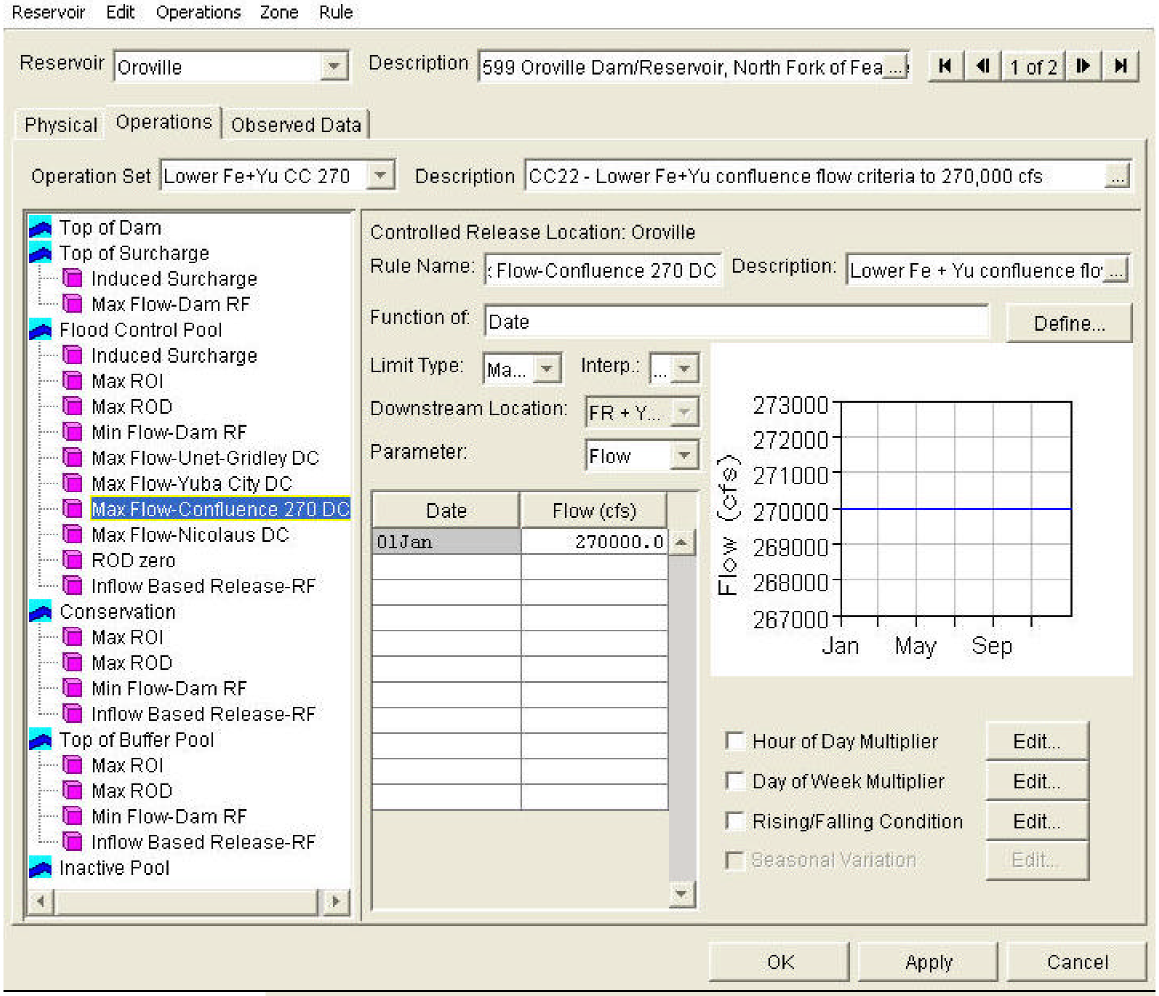
☐ Day of Week Multiplier

☐ Rising/Falling Condition

☐ Seasonal Variation

Figure H-6. Setup for Re-Operation Alternative #20 (lower Feather-Yuba confluence flow objective to 270,000 cfs)

A. Oroville Operations Set



Reservoir: Oroville

Description: 599 Oroville Dam/Reservoir, North Fork of Fea...

Operation Set: Lower Fe+Yu CC 270

Description: CC22 - Lower Fe+Yu confluence flow criteria to 270,000 cfs

- Top of Dam
- Top of Surcharge
  - Induced Surcharge
  - Max Flow-Dam RF
- Flood Control Pool
  - Induced Surcharge
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Max Flow-Unet-Gridley DC
  - Max Flow-Yuba City DC
  - Max Flow-Confluence 270 DC
  - Max Flow-Nicolaus DC
  - ROD zero
  - Inflow Based Release-RF
- Conservation
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Inflow Based Release-RF
- Top of Buffer Pool
  - Max ROI
  - Max ROD
  - Min Flow-Dam RF
  - Inflow Based Release-RF
- Inactive Pool

Controlled Release Location: Oroville

Rule Name: Flow-Confluence 270 DC

Description: Lower Fe + Yu confluence flo

Function of: Date

Limit Type: Ma...

Interp.: ...

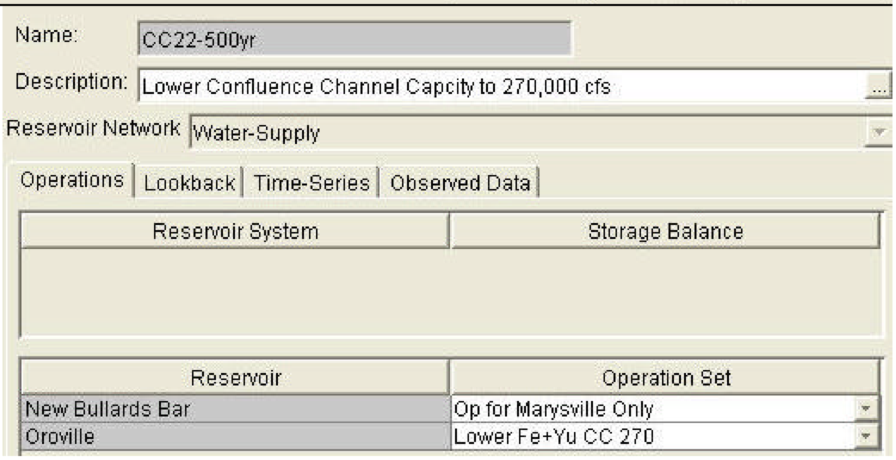
Downstream Location: FR + Y...

Parameter: Flow

Date	Flow (cfs)
01Jan	270000.0

☐ Hour of Day Multiplier
☐ Day of Week Multiplier
☐ Rising/Falling Condition
☐ Seasonal Variation

B. Linking operations sets



Name: CC22-500yr

Description: Lower Confluence Channel Capcity to 270,000 cfs

Reservoir Network: Water-Supply

Reservoir System	Storage Balance

Reservoir	Operation Set
New Bullards Bar	Op for Marysville Only
Oroville	Lower Fe+Yu CC 270

Appendix I. Additional Simulation Results

Table I-1. Expected Annual Damage

Project Alternative	Expected Annual Damage ($)		
	Total	In Feather - Yuba basin	In Lower Sacramento basin
(1)	(2)	(3)	(4)
(a) Storage reallocations at Oroville Reservoir			
2. Lower TOC 400 TAF in Oroville	$ 153,280,684	$ 9,999,025	$ 143,281,660
3. Lower TOC 300 TAF in Oroville	$ 153,736,120	$ 10,122,029	$ 143,614,092
4. Lower TOC 200 TAF in Oroville	$ 153,524,431	$ 9,893,781	$ 143,630,650
5. Lower TOC 138 TAF in Oroville (Conj Use Alts #1,3)	$ 153,608,929	$ 9,965,491	$ 143,643,438
6. Lower TOC 100 TAF in Oroville (Conj Use Alts #2,4)	$ 153,667,116	$ 10,016,674	$ 143,650,442
7. Lower TOC 40 TAF in Oroville	$ 156,690,805	$ 13,034,912	$ 143,655,894
1E. Base Case (0 TAF)	$ 156,991,356	$ 13,329,174	$ 143,662,182
8. Raise TOC 40 TAF in Oroville	$ 157,436,567	$ 13,633,238	$ 143,803,330
9. Raise TOC 200 TAF in Oroville	$ 157,666,832	$ 13,858,765	$ 143,808,067
10. Raise TOC 300 TAF in Oroville	$ 161,195,825	$ 17,360,494	$ 143,835,331
11. Raise TOC 400 TAF in Oroville	$ 164,814,848	$ 20,706,603	$ 144,108,246
(b) Storage Reallocations at New Bullard's Bar Reservoir			
12. Lower TOC 120 TAF at NBB (Conj Use Alts #1,3)	$ 156,946,077	$ 13,295,110	$ 143,650,967
13. Lower TOC 100 TAF at NBB	$ 156,949,396	$ 13,296,979	$ 143,652,417
14. Lower TOC 45 TAF at NBB	$ 156,951,574	$ 13,298,267	$ 143,653,307
1E. Base Case (0 TAF)	$ 156,991,356	$ 13,329,174	$ 143,662,182
15. Raise TOC 45 TAF at NBB	$ 157,200,870	$ 13,396,460	$ 143,804,411
16. Raise TOC100 TAF at NBB	$ 157,688,072	$ 13,880,975	$ 143,807,097
(c) Re-operations			
17. Base Case - NBB operates only for Marysville	$ 157,303,401	$ 13,649,536	$ 143,653,866
18. Base Case - NBB outlet capacity is 75,000 cfs	$ 157,332,699	$ 13,671,104	$ 143,661,595
19. Base Case - Combination of #19 & #20	$ 157,380,492	$ 13,724,957	$ 143,655,535
20. Base Case - Lower Confluence CC to 270,000 cfs	$ 156,371,058	$ 12,717,268	$ 143,653,791

Notes:

a. All project alternatives simulated using Sacramento Basin storm centering and FDA Study impact area set

Table I-2. Water Supply Indicators for Demand Level = 1

Project Alternative (1)	**Reliability**[a,b] **[%]** (5)	**Vulnerability**[a,b] **[ac-ft/month]** (6)	**Resiliency**[a,b] **[months]** (7)
(a) Storage reallocations at Oroville Reservoir			
2. Lower TOC 400 TAF in Oroville	100.0%	0	0
3. Lower TOC 300 TAF in Oroville	100.0%	0	0
4. Lower TOC 200 TAF in Oroville	100.0%	0	0
5. Lower TOC 138 TAF in Oroville (Conj Use Alts #1,3)	100.0%	0	0
6. Lower TOC 100 TAF in Oroville (Conj Use Alts #2,4)	100.0%	0	0
7. Lower TOC 40 TAF in Oroville	100.0%	0	0
1E. Base Case (0 TAF)	100.0%	0	0
8. Raise TOC 40 TAF in Oroville	100.0%	0	0
9. Raise TOC 200 TAF in Oroville	100.0%	0	0
10. Raise TOC 300 TAF in Oroville	100.0%	0	0
11. Raise TOC 400 TAF in Oroville	100.0%	0	0
(b) Storage Reallocations at New Bullard's Bar Reservoir			
12. Lower TOC 120 TAF at NBB (Conj Use Alts #1,3)	91.9%	27,318	4.2
13. Lower TOC 100 TAF at NBB	91.9%	27,318	4.2
14. Lower TOC 45 TAF at NBB	91.9%	27,318	4.2
1E. Base Case (0 TAF)	91.9%	27,318	4.2
15. Raise TOC 45 TAF at NBB	91.9%	27,318	4.2
16. Raise TOC100 TAF at NBB	91.9%	27,318	4.2

Notes:

a. to meet unit-level demand at FRSA from storage reallocations at Oroville reservoir

b. to meet unit-level demand at Marysville from storage reallocations at New Bullard's Bar reservoir