OROVILLE DAM AND RESERVOIR

Feather River, California

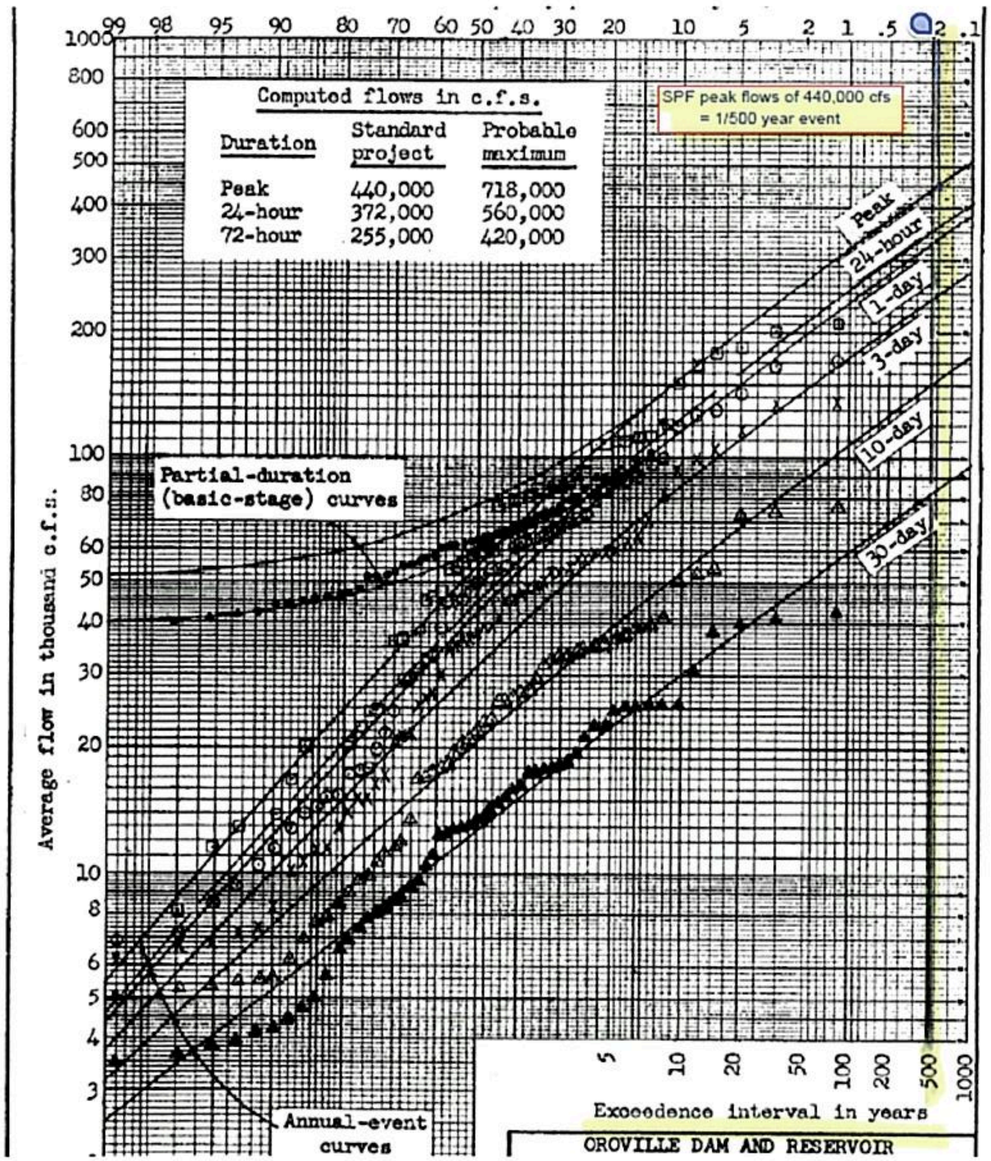
REPORT ON RESERVOIR REGULATION FOR FLOOD CONTROL

By agreement between the State of California and the Corps of Engineers, selection of the maximum flood control space requirement for Oroville Reservoir was based primarily on protection of urban and agricultural areas along Feather River below the reservoir against winter floods (rain or rain augmented by snowmelt) up to the magnitude of the standard project flood, with permissible releases limited to a maximum of 150,000 c.f.s.

AUGUST 1970

DEPARTMENT OF THE ARMY

SACRAMENTO DISTRICT, CORPS OF ENGINEERS
SACRAMENTO, CALIFORNIA



- The 1970 SPF was a 1/500 year event.
- The agreed upon flood protection should remain at a 1/500 year level.

G.6 Simulation of FIRO Alternatives

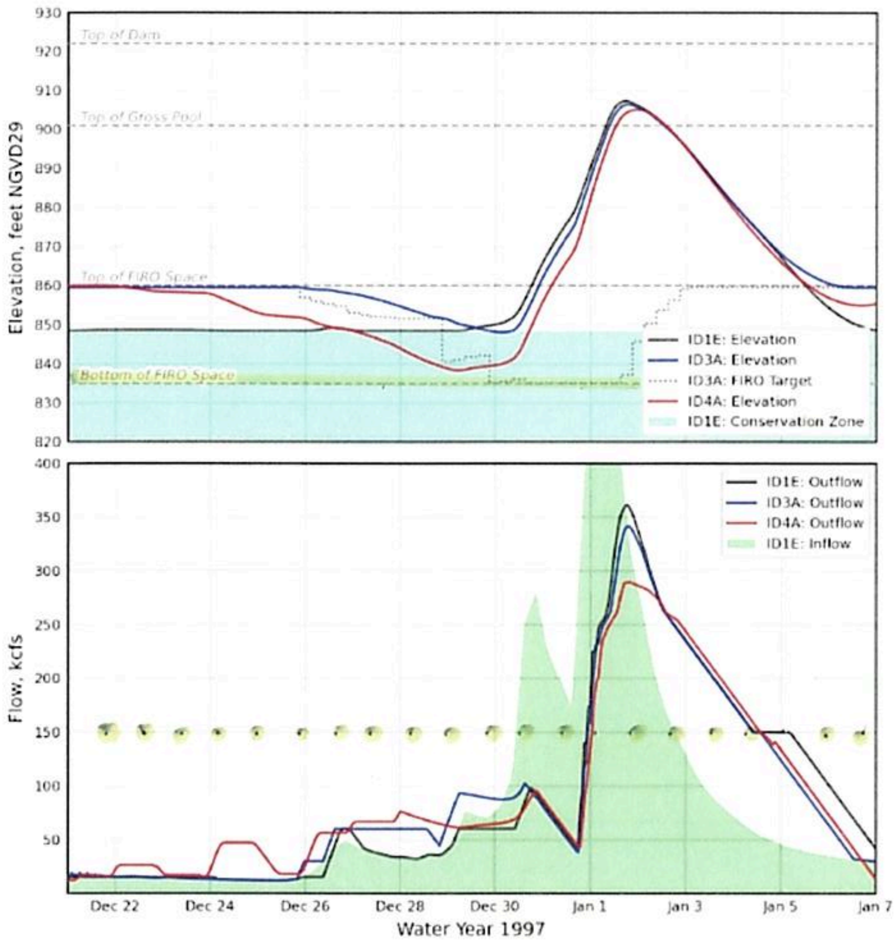
Simulation of alternatives was completed at an hourly time step using scaled hydrology for the 1986 and 1997 flood events developed by the CNRFC. These scaled events were developed by scaling precipitation by different factors as summarized in Table G-3. Also included with this table are associated return periods (developed by MBK Engineers), however these return periods were based on hydrology from the Central Valley Hydrology Study (CVHS) (US Army Corps of Engineers Sacramento District, 2015), which scaled observed hydrology by the same factors. It should be noted that the resultant hydrology developed by the CNRFC is not necessarily equivalent to the CVHS hydrology, and the CNRFC hydrology typically exceeds the CVHS hydrology for the same scale factor.

Table G-3. *CNRFC Scaled Events.*

Year	Scale Factor (%)	Return Period (year)
1986	100	75
1986	110	112
1986	120	164
1986	130	238
1986	140	346
1986	150	499
1997	90	106
1997	100	166
1997	110	268
1997	120	420
1997	130	653

1997 120% Scaling Oroville

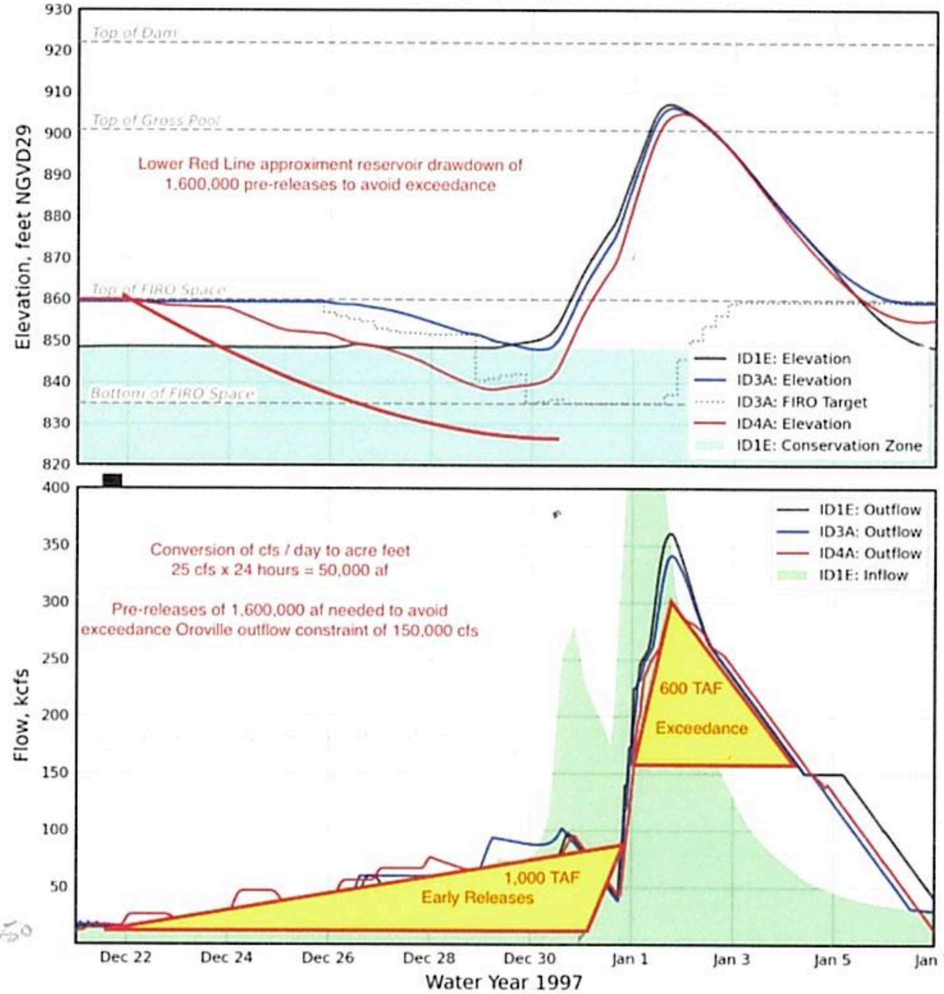
1/420 yr.



SPF equivalent 440K cfs peak inflows

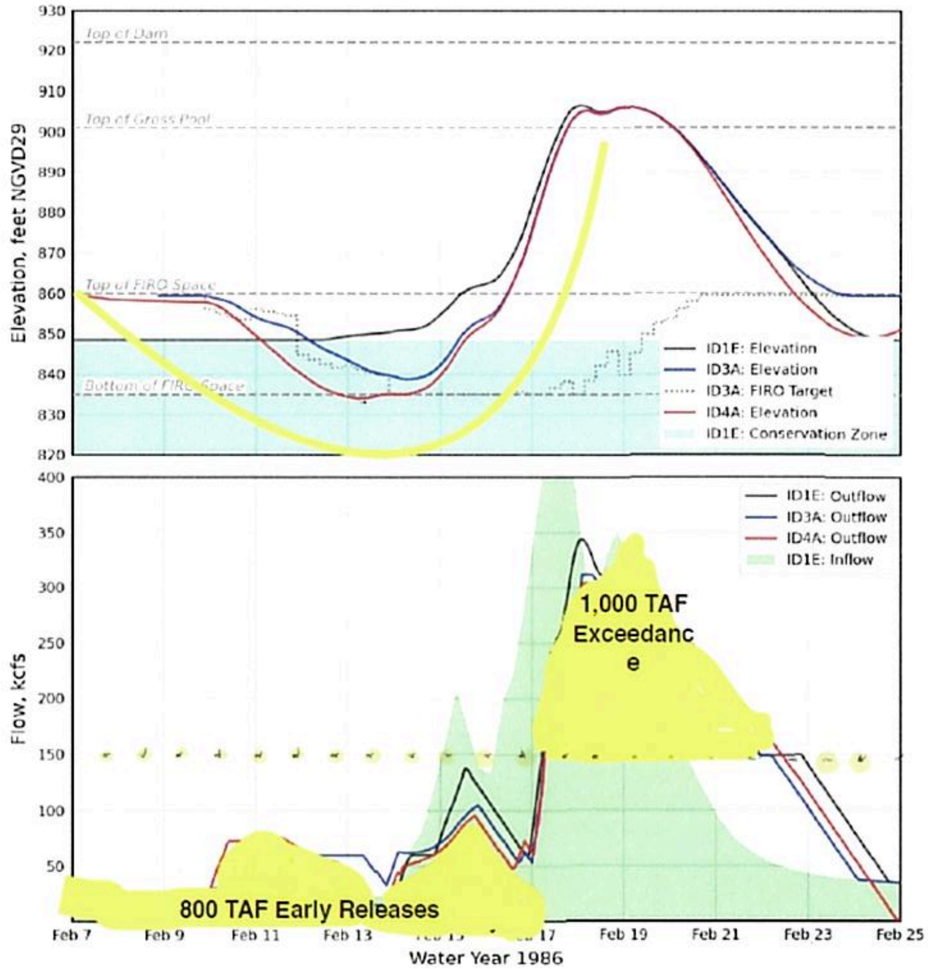
- Surcharges Auxiliary Spillway by 5-7 ft.
- The 2017 event surcharged 20 inches
- Outflows 300-350K cfs
- Targeted outflow limit of 150K cfs

1997 120% Scaling
Oroville

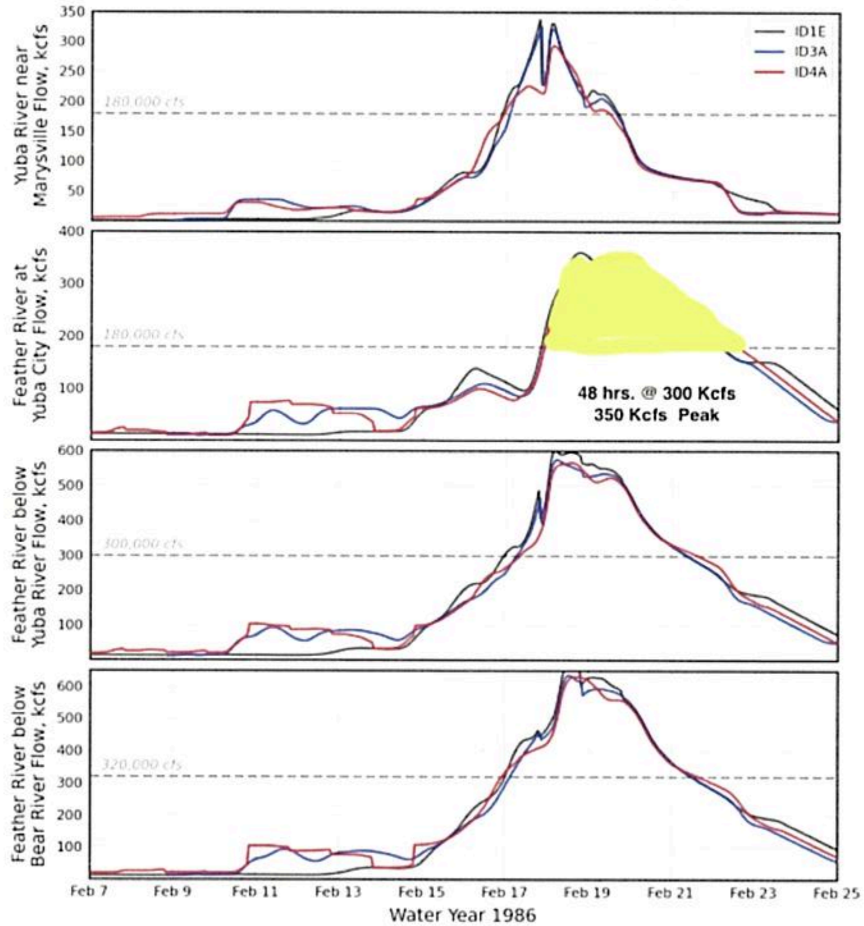


1986 140% Scaling
Oroville

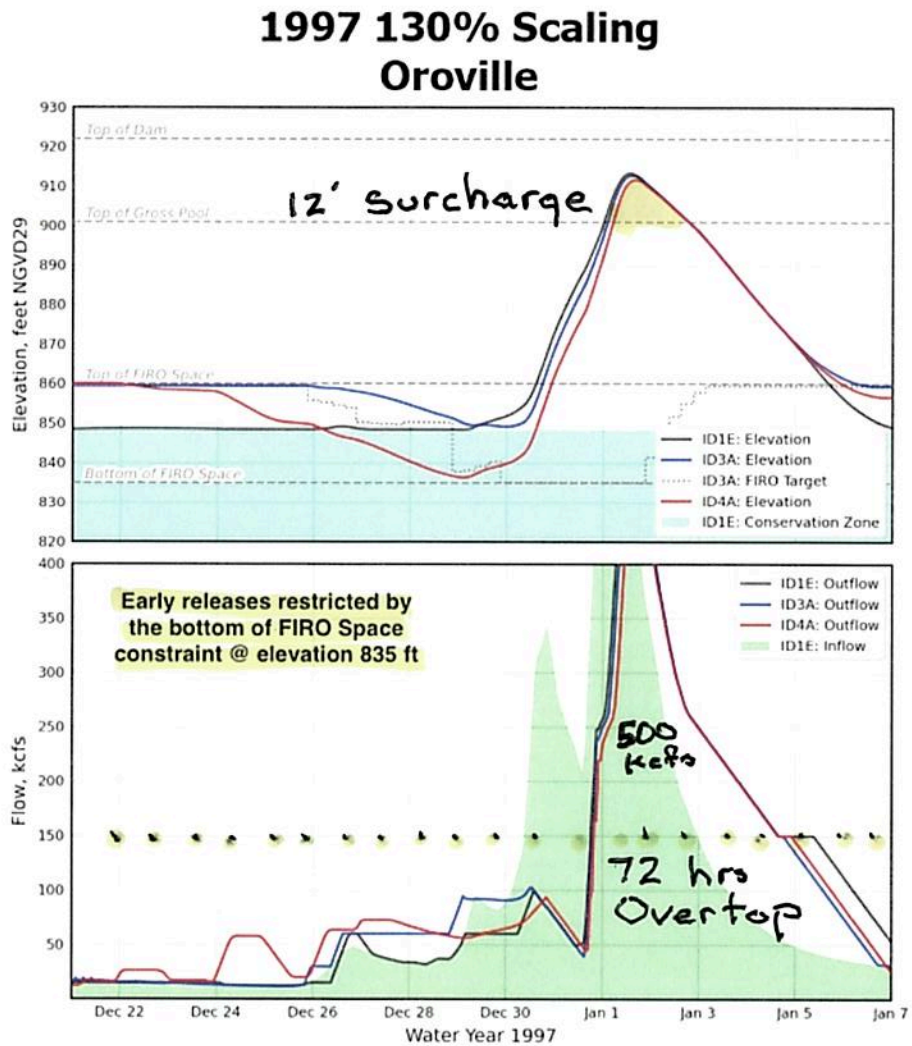
1/346 yr



1986 140% Scaling
Downstream Control Points



CVHS Flood Event 1/350 yr

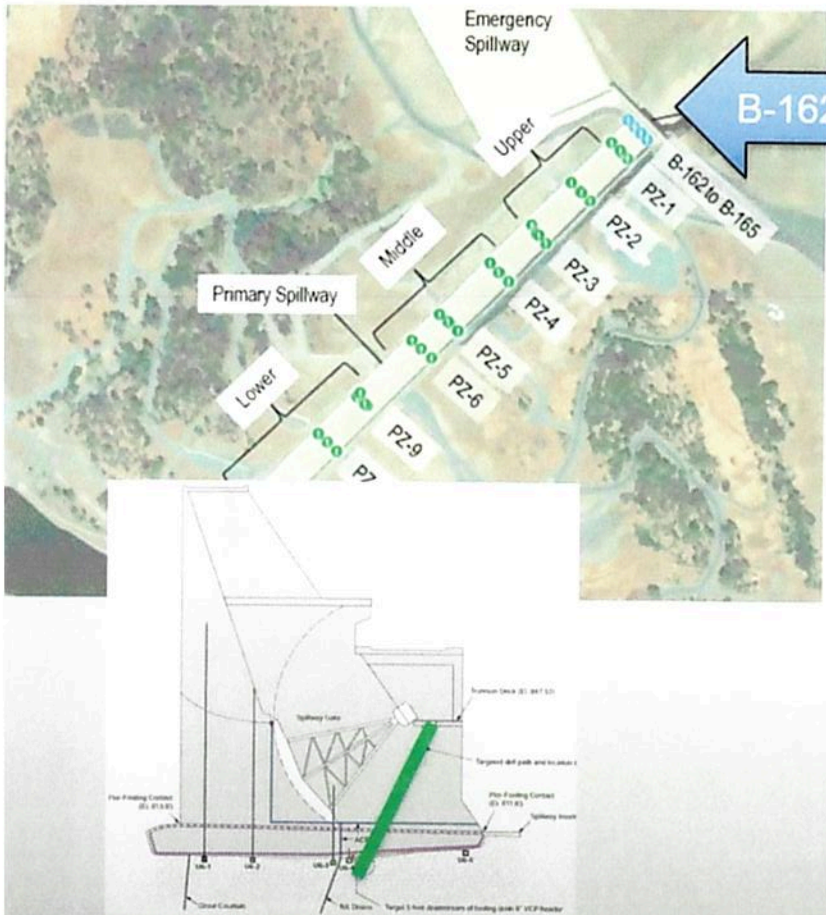


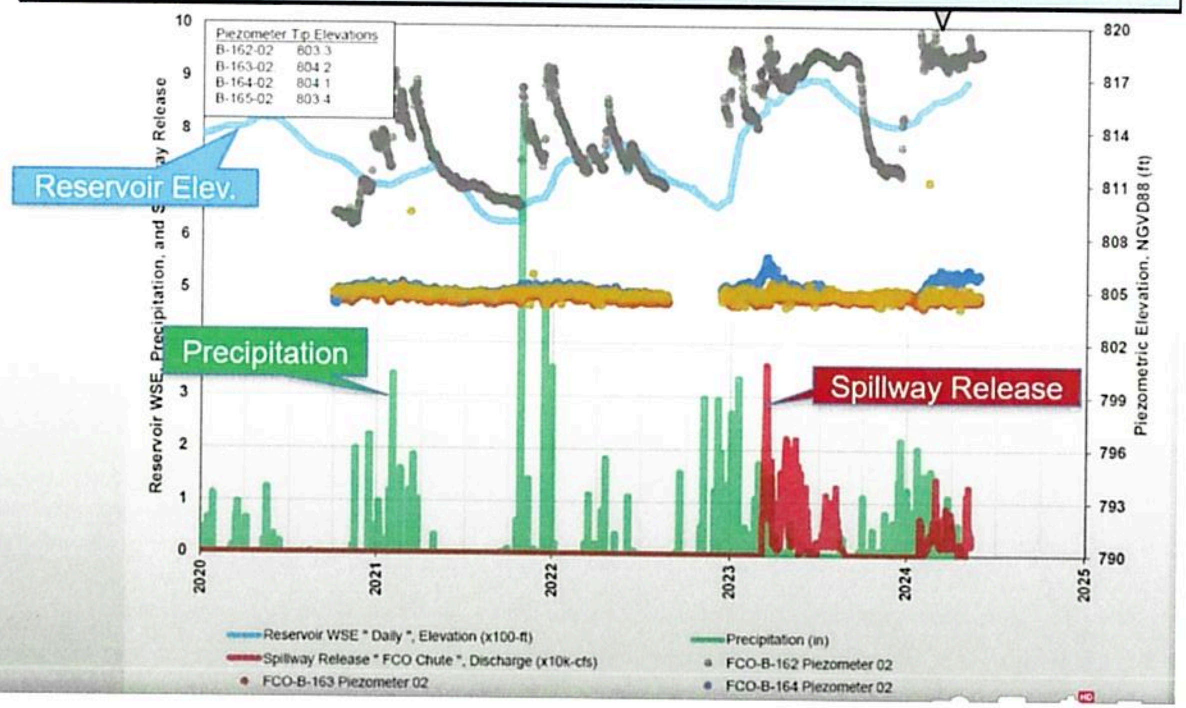
City of Oroville Inundation Map

- Standard Project Flood equivalent 440K cfs inflows
- 300K cfs outflows at Oroville

2024 Spillway Performance

- Recovery of the conservation pool after a large event isAr not a concern.
- Are there infrastructure concerns when operating the FIRO space at elevation 813, bottom of the FCO-Gates?





CALIFORNIA DEPARTMENT OF
WATER RESOURCES

Level of Flood Protection

Let the 1/500 year flood protection agreement in the 1970 Water Control Manual dictate the bottom of the FIRO Space, versus allowing a predetermined FIRO Space of elevation 835 ft dictate the level of flood protection achieved.

Make every effort possible to uphold 1/500 yr level of flood protection agreement in Oroville's 1970 Water Control Manual, currently the equivalent of 1/500 yr protection would be safely passing the 1997 storm x 123% and 1986 storm x 150%

Why was elevation 835' made a hard constraint for the bottom of the FIRO Space throughout the FIRO FVA Appendix hydrographs:

Question1a) recovery of the conservation pool?
1b) concerns regarding the unlined FCO-Gate Intake Channel
1c) piezometers reading when the gates are operating between elevation 815' - 830'?

Oroville's FIRO Space requirement

Remove the hard constraint of 835' bottom of the FIRO Space from the ResSim "Rule Stack" and create new hydrographs of reservoir and downstream outcome for the 1997 x 120% event.

Question 2) Did the reservoir still surcharge the auxiliary spillway by 4-7 feet?

Question 3) Were reservoir outflows still 300,000cfs, twice their constraint level?

Question 4) What elevation was the bottom of the reservoir drawdown?

Question 5) Does Oroville's infrastructure have the ability to operate at this new elevation (Yes/No) ?

Question 6) If No, what infrastructure improvements projects would enable safe passage of the SPF?

Table 4-1. *Relative performance of FIRO alternatives (ID3A and ID4A) compared to baseline operations (ID1E). Color coding indicates lower (light green) and higher (medium green) effectiveness in meeting performance metrics, as indicated by the highest scale factor that achieved the objective. The "E" following the baseline alternative designates no ARC Spillway at NBB, while the "A" following FIRO alternatives indicates the evaluation assumed operation of the ARC Spillway.*

	1986			1997		
Objective	**ID1E**	**ID3A**	**ID4A**	**ID1E**	**ID3A**	**ID4A**
ORO Gross Pool (901 feet)	116	118	118	106	108	110
ORO Max. Release (150 kcfs)	116	118	118	106	108	110
Feather at Yuba City (180 kcfs)	116	120	120	108	110	110
NBB Gross Pool (1,956 feet)	114	118	120	102	110	130
NBB Max. Release (50 kcfs)	114	118	120	102	108	108
Yuba at Marysville (180 kcfs)	116	118	120	104	104	106
Feather below Yuba (300 kcfs)	114	118	118	106	106	108
Feather below Bear (320 kcfs)	104	106	106	106	106	108

Table values indicate the maximum scale factor through which the objective is achieved.

Performance of FIRO alternatives ID3 AND ID4

- 1986 and 1997 storm scaled by 106% is largest to achieve all 8 objectives
- 1986 x 106% estimated as a 1/90 year storm event
- 1997 x 106% estimated as a 1/200 year storm event

Climate - altered stream flows

Figure 4.10 The Inverse of AEP or Annual Return Period for Peak Total Sacramento River Flow Rate At-latitude of the City of Sacramento for Selected CVHS Flood Events

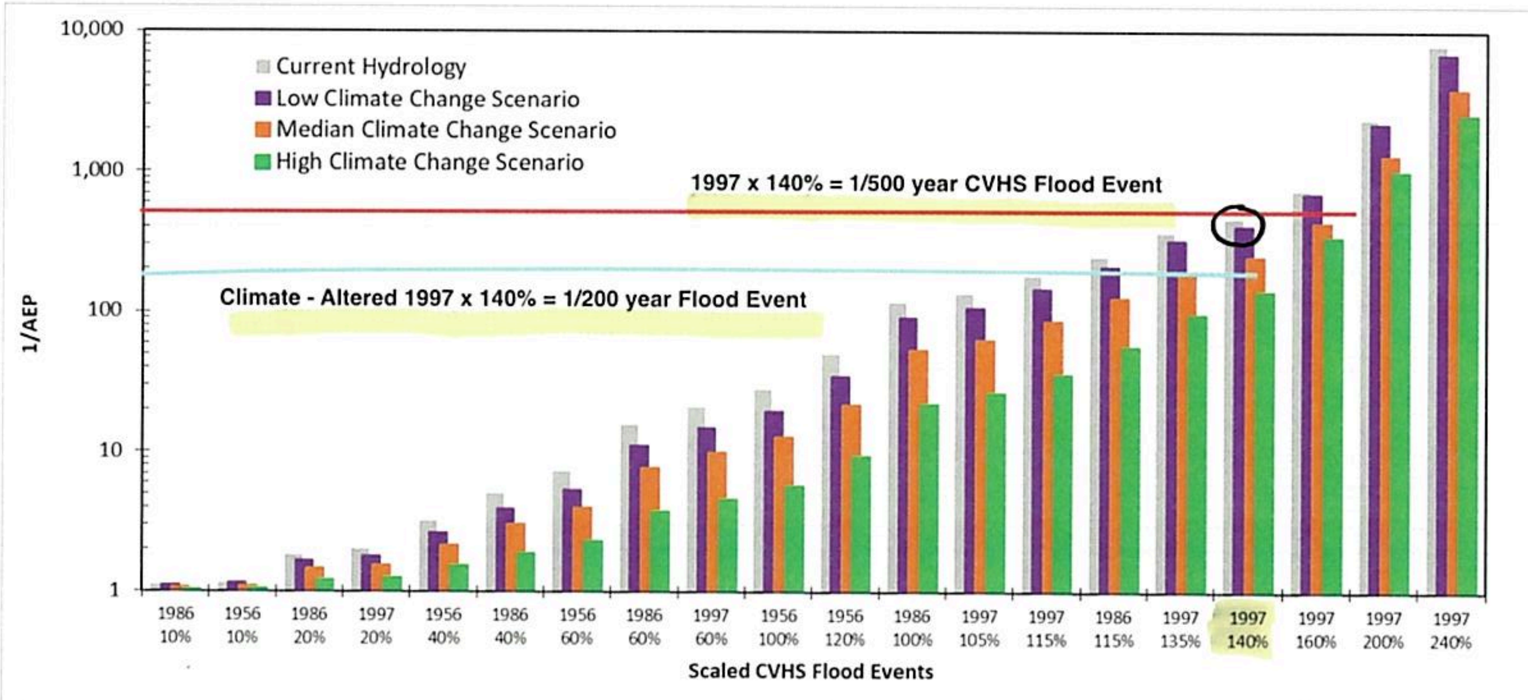
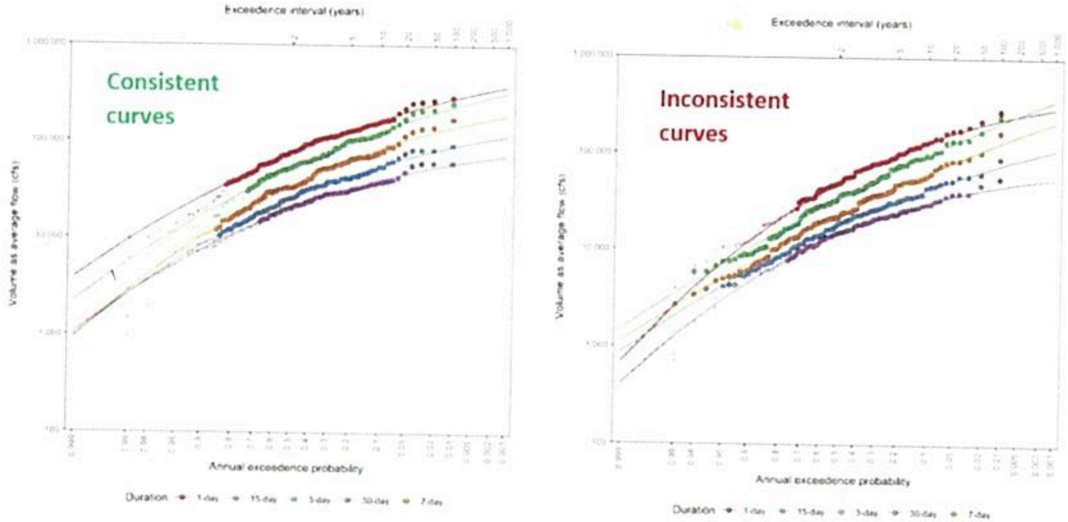


Figure 4.7 Example curve fitting, consistent curves where the durations do not cross for rare events, and inconsistent curves where the 1-day curve cross the 3-day curve near the p=0.005 (200-year) AEP



In general, the medium climate change ratios for the San Joaquin River Basin were observed to be greater than those in the Sacramento River Basin. For example, the San Joaquin River Basin 3-day p=0.01 (100-year) ratios range from 1.07 to 1.86, whereas the Sacramento River Basin 3-day p=0.01 (100-year) ratios range from 0.99 to 1.35. Detailed results of the climate change ratios are included in Attachments A through C of Appendix B, "Climate Change Volume-Frequency Analysis." Plots of regulated stage-frequency curves, the ultimate application of the climate change ratios, at each index point are included in Appendix D, "Risk Analysis Summary by Index Point."

Figure 3.3 Sacramento River Basin Index Points and Impact Areas

Yuba City Index SAC 25
Check-climate ratios in Appendix D

Key Components of a PMF Calculation With Snowmelt

Key components of a PMF calculation with snowmelt

A PMF calculation with snowmelt is not a simple lookup from a table; it requires a detailed study using specific meteorological data and hydrologic modeling.

1. **Probable Maximum Precipitation (PMP):** PMP is the starting point for a PMF. For a rain-on-snow event, this is not a value from Atlas 14 but a specialized estimate. The process involves:
   - **Moisture maximization:** Determining the maximum possible atmospheric moisture content for the area.
   - **Storm transposition:** Maximizing a historic storm by placing it over the basin in the most critical position.
2. **Snowpack analysis:** The PMF assumes the worst-case scenario. For a rain-on-snow event, this means assuming the maximum possible pre-existing snowpack. This might be a 100-year return level snow water equivalent (SWE) or the Probable Maximum Snowpack (PMSP).
3. **Critical combination:** The PMF analysis determines the worst-case timing and intensity of the PMP event occurring over the maximum snowpack. The calculations include:
   - **Pre-existing conditions:** The ground is often assumed to be frozen or saturated to maximize runoff.
   - **Energy budget:** Modeling the effects of solar radiation, wind, and air temperature on the snowpack.
   - **Melt factor:** The heat transfer from rain and warm, humid air is a dominant factor in generating rapid snowmelt.

The current probable maximum flood did not follow these key components.

The next PMF will likely be much larger.

Example of historical snow water content compared to 2018 PMF

BUCKS LAKE (BKL)

Date	Depth	W.C.	Density
03/15/2023	--	70.9	0%
03/16/2023	--	68.9	0%
03/17/2023	--	68.5	0%
03/18/2023	--	68.6	0%
03/19/2023	--	68.9	0%
03/20/2023	--	69.8	0%
03/21/2023	--	70.4	0%
03/22/2023	--	70.8	0%
03/23/2023	--	71.4	0%
03/24/2023	--	72.1	0%
03/25/2023	--	72.7	0%
03/26/2023	--	73.2	0%
03/27/2023	--	73.7	0%
03/28/2023	--	74.2	0%
03/29/2023	--	76.1	0%
03/30/2023	--	77.5	0%
03/31/2023	--	78.2	0%
04/01/2023	--	78.5	0%
04/02/2023	--	78.7	0%
04/03/2023	--	78.7	0%
04/04/2023	--	78.7	0%
04/05/2023	--	78.7	0%
04/06/2023	--	78.7	0%
04/07/2023	--	78.8	0%
04/08/2023	--	79.0	0%
04/09/2023	--	78.8	0%
04/10/2023	--	78.7	0%
04/11/2023	--	78.6	0%
04/12/2023	--	78.4	0%
04/13/2023	--	77.8	0%
04/14/2023	--	77.2	0%

Oroville Dam 2018 Probable Maximum Flood snow pack depths varied from zero at 4,000-foot elevation to about 60 inches at 8,000-foot elevation. The snow melt over the entire watershed contributed an additional 4.5 inches of total water above the PMP of 28.9 inches.

March of 2023 Bucks Lake snow gage at elevation 5,820 hand "water content" of 78 inches, and as an historical amount should be used in calculating the next PMF.

Key component of a PMF calculation with snowmelt:

Determine the maximum possible atmospheric moisture content and placing it over the basin's most critcal position.

Snowpack analysis- the PMF assumes the worst-case scenario. For a rain-on-snow event, this means assuming the maximum possible pre-existing snowpack.

New PMF Study most likely require CNA Plan

COMPREHENSIVE NEEDS ASSESSMENT ALTERNATIVE PLANS AND SCORING

Table 6. CNA Alternative Plans and Scoring

		PLAN 1 Maximum Risk Reduction	PLAN 2 Extend Reliable Life of Facility	PLAN 3 Minimize Dam Safety Risks - A	PLAN 4 Minimize Dam Safety Risks - B	PLAN 5 Balanced Risk Modified	PLAN 6 Enhanced Operational Capabilities	PLAN 7 Deterministic Dam Safety Guidelines, Accept. Dam.	PLAN 8 Tolerable Risk Reduction +	PLAN 9 Tolerable Risk Reduction	PLAN 10 Focus on Flood Management
T1-A	Minimally improved pilot channel					X		X	X		
T1-C	New Full length RCC chute				X						
T1-E	New FCO gated reinforced concrete chute	X	X	X			X				X
T1-P	Hyatt Powerplant discharge portal bulkheads	X	X	X	X	X	X		X	X	X
T1-Z	Secant Pile Wall buttress					X		X	X		
T1-AW	Partial extension of RCC apron w/ minimally imp. Ch.							X			
T3-A	FCO Upstream bulkhead gates*	X	X	X	X	X	X	X	X	X	X
T3-CO	FCO Structural upgrades/retrofit*	X	X	X	X	X	X	X	X	X	X
T3-BH 2	FCO Radial Gate backup power, local starter, etc.*	X	X	X	X	X	X	X	X	X	X
T3-W	FCO Debris control structures/devices	X	X	X	X	X					X
T4-N	Rock bolts in Hyatt Powerplant	X	X								
T4-W	Palermo Intake landslide stabilization	X	X								
T4-O	Barrier around ACC and switchyard, landslide stabl.	X	X								
T4-U	Palermo Canal Lining	X	X	X	X	X					
T4-C	New High-Level Outlet @ El 775 ft	X									
T4-E	New Low-Level Outlet @ El 435 ft		X	X	X	X	X	X			
T4-G	New Low-Level Outlet @ El 343 ft	X									
T5-02	Modify portion of dam that wraps around Mon. 31*	X	X	X	X	X	X	X	X	X	X
T5-03	Modify the upper 40 ft of Main Dam	X	X	X							
T5-05	Raise Main Dam by 3 ft	X	X	X							
T5-B2	Raise Bidwell Bar Saddle Dam (BBCSD) by 3 ft	X	X	X							
T5-P2	Raise Parish Camp Saddle Dam (PCSD) by 3 ft	X	X	X	X	X	X	X	X	X	X
	* Measure in every Plan										
	A. RISK REDUCTION SCORE	4.4	4.7	4.5	3.45	3.4	3.75	3.1	2.75	2.1	4.1
	B. PARA / MEETING OBJECTIVES SCORE	4.85	4.65	4.35	4	3.65	3.85	2.95	2.2	1.95	3.4
	C. GOOD ENGINEERING/BEST PRACTICES SCORE	2.25	3.05	3.25	3.7	4.4	3.95	3.25	2.75	2.05	3.2
	Total Weighted Score	72.6	80.6	79.4	73.2	77	77	62.6	52.8	41	72

Increase Spillway Release Capacity

- Plans 4, 7 Extend Auxiliary RCC
- Plans 1, 2, 3, 6, 10 Add FCO – Gates
- Plans 1, 2, 3, 4, 5, 6, 7 Low Level Outlet

Any plan will improve 1/500 yr Flood Protection

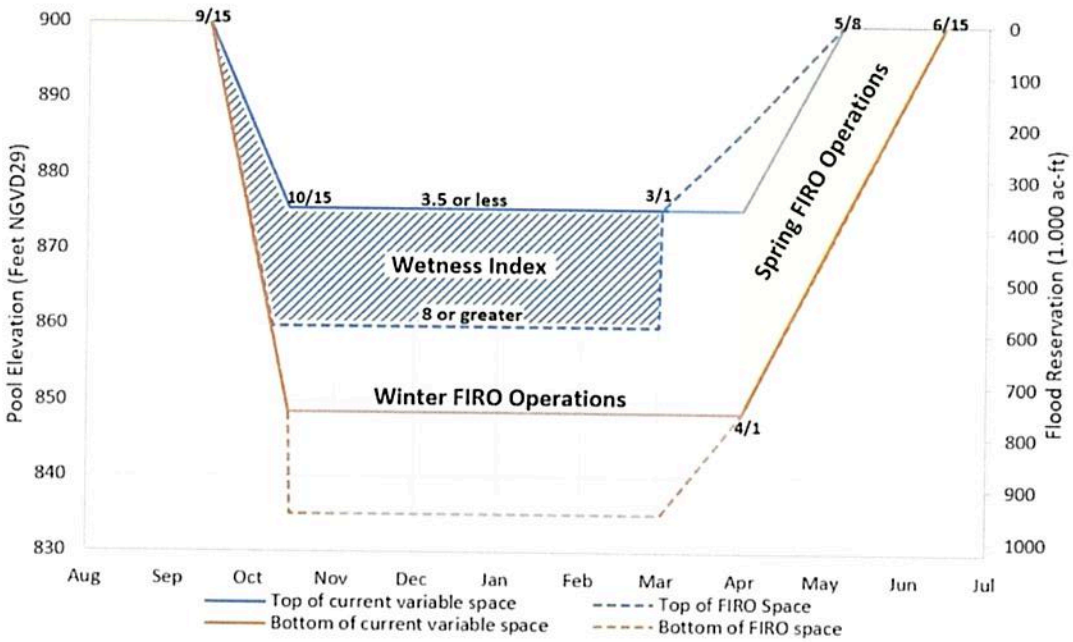


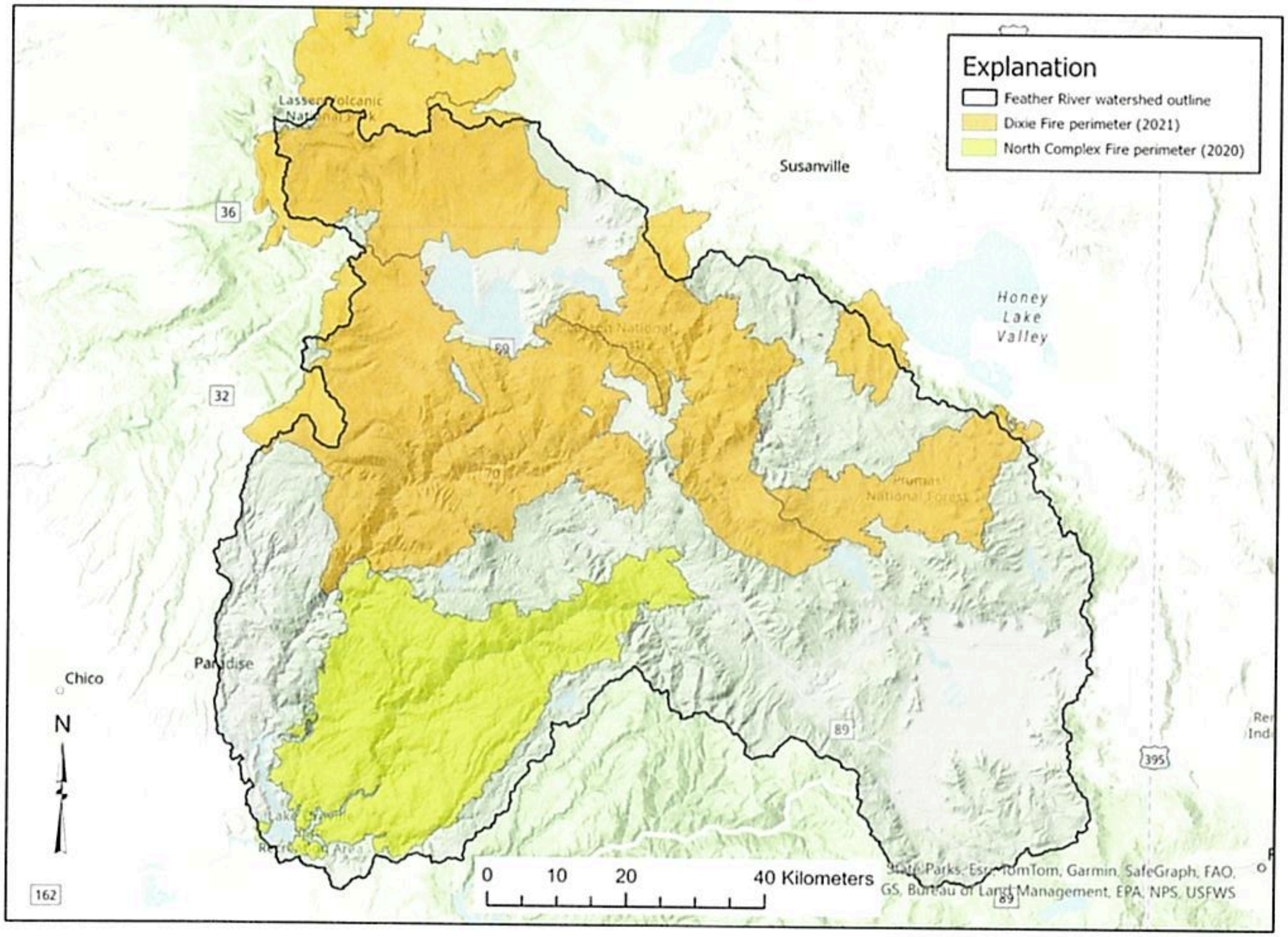
Figure 3-3. *FIRO Space for ORO Reservoir.*

USACE Original Flood Pool 750K af

- FIRO Space 600-950K af
- Addition of Wetness Index can decrease Flood Pool to 350K af by assuming the watershed will absorb the first 250K af of precipitation
- Wetness Index does not account for the snowpacks water equivalency sitting on top of the soil

Map of wildfires in Feather River watershed

By California Water Science Center   February 2023 (approx.)



Any use of a soil wetness index should factor in the reduced soil absorbtion of the fire-scarred watershed.

SNOWMELT DURING 2017 OROVILLE DAM SPILLWAYS INCIDENT

Center for Western Weather and Water Extremes, Brian Henn

Extreme Runoff Generation From Atmospheric River Driven Snowmelt During the 2017 Oroville Dam Spillways Incident

Brian Henn[1,2], **Keith N. Musselman**[3], **Leanne Lestak**[3], **F. Martin Ralph**[1], and **Noah P. Molotch**[3,4]

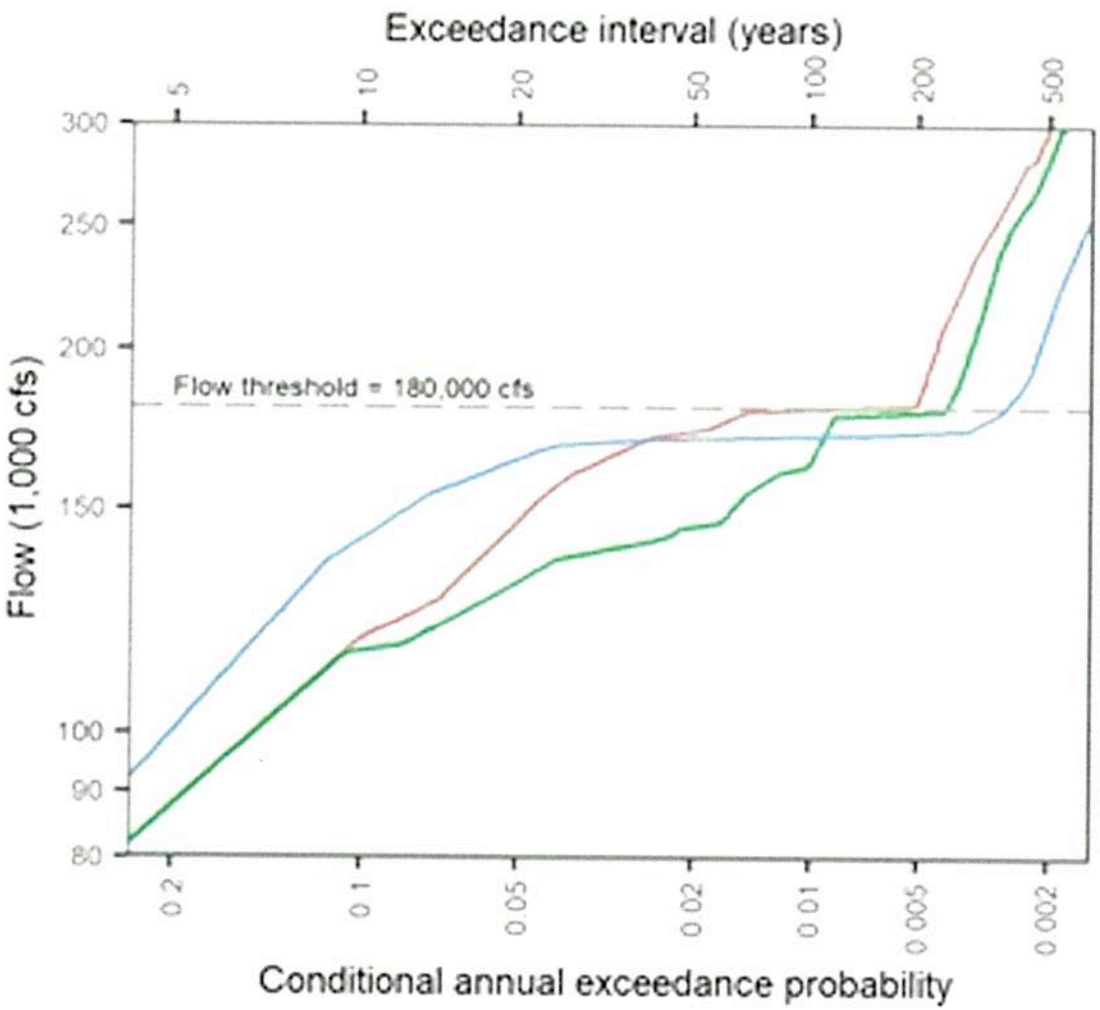
[1]Center for Western Weather and Water Extremes, University of California San Diego, La Jolla, CA, USA, [2]Vulcan Climate Modeling, Vulcan, Inc., Seattle, WA, USA, [3]Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO, USA, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Abstract In February 2017, a 5-day sequence of atmospheric river storms in California, USA, resulted in extreme inflows to Lake Oroville, the state's second-largest reservoir. Damage to the reservoir's spillway infrastructure necessitated evacuation of 188,000 people; subsequent infrastructure repairs cost $1 billion. We assess the atmospheric conditions, snowmelt, and runoff against major historical events. The event generated exceptional runoff volumes (second largest in a 30-yr record) partially at odds with the event precipitation totals (ninth largest). We explain the discrepancy with observed record melt of deep antecedent snowpack, heavy rainfall extending to unusually high elevations, and high water vapor transport during the atmospheric river storms. An analysis of distributed snow water equivalent indicates that snowmelt increased water available for runoff watershed-wide by 37% (25–52% at 90% confidence). The results highlight potential threats to public safety and infrastructure associated with a warmer and more variable climate.

Plain Language Summary In February 2017, extreme runoff into California's second-largest reservoir, Lake Oroville, and cracks in the reservoir's spillways resulted in evacuations of thousands of people and major repair costs. We analyzed to what extent the atmospheric river storms that caused the extreme runoff were unusual in terms of precipitation, snowmelt, temperature, and moisture in the air. We found that the precipitation amounts were less unusual than the runoff amounts, suggesting that other factors were involved. We also found that snowmelt in the Sierra Nevada mountains above the reservoir was the heaviest on record at many locations, driven by unusually warm temperatures and deep preexisting snowpack before the storms began. Thus, the warm temperatures and record melt likely increased the water available for runoff by about a third during the spillways incident. Our findings are consistent with other studies that suggest that unusually warm temperatures during winter atmospheric river storms in the Western United States are associated with flood risk due to substantial rainfall and snowmelt. Other studies show that climate change is expected to increase the type of flood risk in the 2017 incident.

- An analysis of distributed snow water equivalency indicates that snow melt increased water available for run off - watershed wide by 37%
- Currently snow melt is not being considered in sizing of the variable FIRO flood pool
- Forecasted reservoir releases could be 37% higher on already reduced flood pool

Feather River at Yuba City



- FIRO FVA 4-3 Transfer of Benefits to Downstream Flows
- Avoid the indirect costs of downstream evacuations.
- Estimated at $50M-$75M during the 2017 spillway event

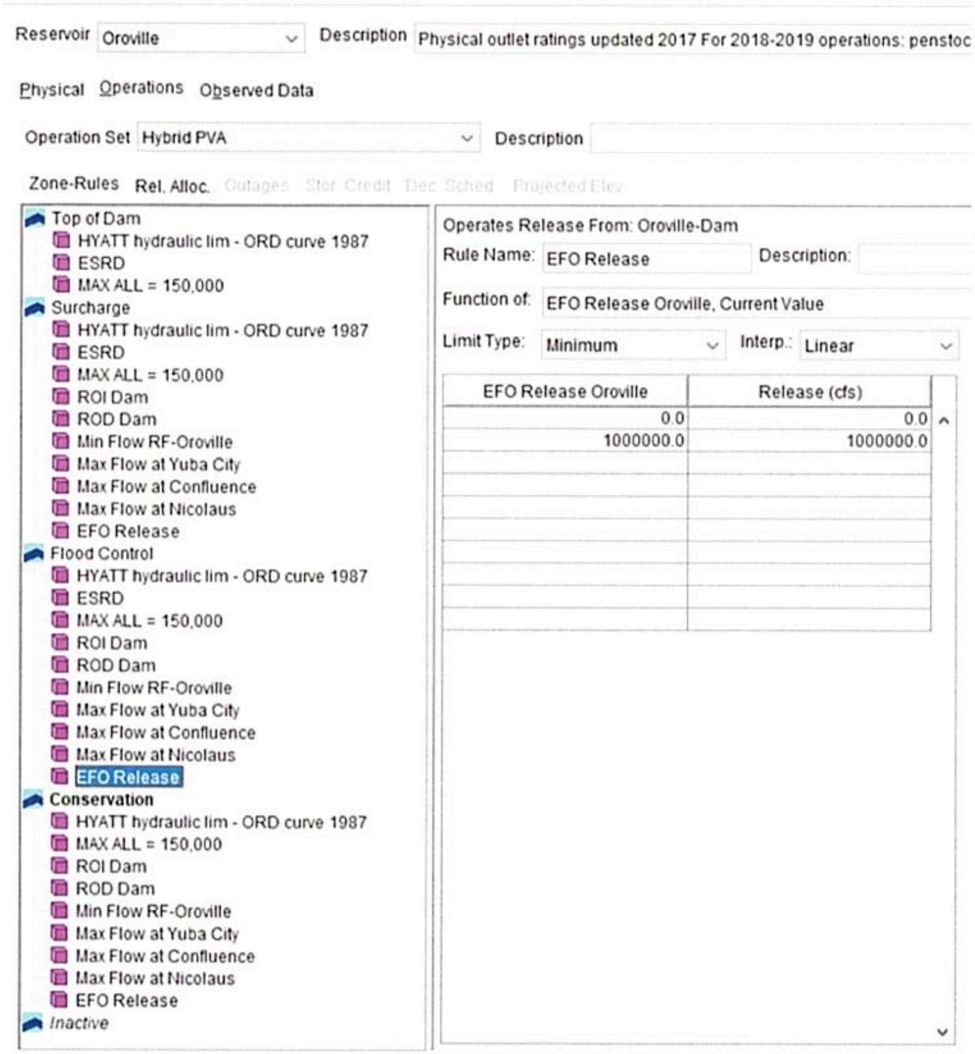


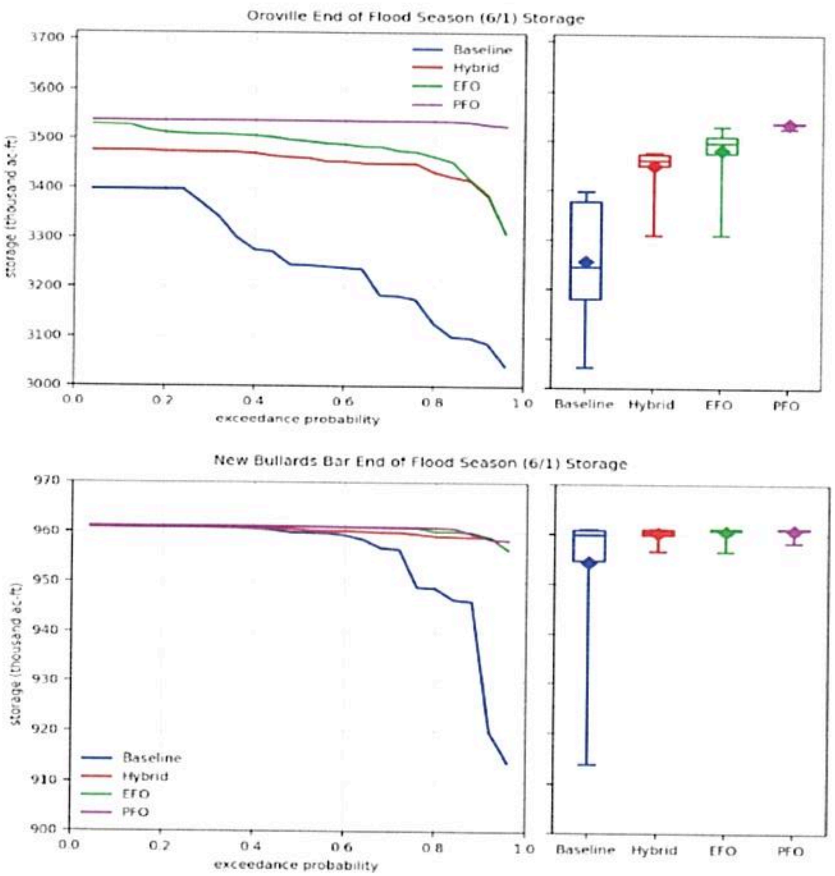
Figure G3-1. Oroville: Hybrid PVA Operation Set Screenshot

- Need to create a non-evacuation constraint as lower priority in the rule stack (160,000 cfs @ YC)
- Then estimate the cost of evacuation and then prioritize the rule accordingly.

YUBA-FEATHER FORECAST INFORMED RESERVOIR OPERATIONS (FIRO)

End of Season Storage Gains From WCP Alternatives

Figure L-8. Frequency of end of flood season storage for ORO (top) and NBB (bottom) as a function of WCP alternative.



Alternative Plan	Storage Benefit
Plan ID4 to Baseline	200,000 AF
Plan ID3 to Baseline	220,000 AF

Estimated value of stored water $1000/AF
200,000 AF x $1000 = $200M annual benefit
(Annual benefit over 5 years equals $1 billion)

Climate-altered Reservoir Inflows

Obtain climate-altered reservoir inflows, possibly from CVFPP 2022 Appendix D "Risk Analysis Summary by Index Point to better understand the deteriorating level of flood protection that will result from a "no-action: approach to Oroville's limited FIRO Space capacity.

Question 7) What level of flood protection would Oroville provide downstream communities in 2050, 2075?

Outdated Probable Maximum Flood (PMF)

The current 2018 PMF was rushed to the Board of Consultants during the rebuilding of the main spillway for construction design and failed to calculate key components. Should have developed PMP from Atlas 14 and have used the largest historical snowpack. Now the Billion dollar spillway design is already outdated and there minor infrastructure projects needed to pass the PMF and its associated freeboard.

The same PMF was given to the FERC Part 12 / L2RA Independent Consultants in 2018 during its very comprehensive investigation. In 2029 another FERC Part 12 / L2RA investigation will be conducted and the dam owners are planning to give those independent consultants the same outdated PMF. A New PMF will most likely be larger and require a propose CNA infrastructure plan

Question 8) Instead of waiting for new PERCIP Act guidance, can DWR partner with NOAA and help lead the dam industry in the development of PMF so as to have a new PMF hydrology available for the 2029 Part 12 / L2R?

Soil Wetness Index - With the current FIRO Space, Oroville already fails to safely pass major storms for lack of adequate early releases. To evacuate the 250,000 acre feet in the wetness index would require 2 ½ days of an additional 50,000cfs of early releases. Soil absorption and snowmelt forecasts have inherently low accuracy rates and including all three of these risk uncertainties into the sizing of the FIRO Space to benefit spring refill is not putting safety first within the WCM update.

Question 9) What other options are available to increase spring refill that doesn't require this level of risk uncertainty?

Recommendation - Create a ResSim rule stack that lowers downstream evacuation probabilities. FIRO FVA 4-3 Transfer of Benefit Assign the indirect cost of downstream stream evacuations, and prioritize the ResSim rule stack accordingly.