STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
OROVILLE EMERGENCY RECOVERY – SPILLWAYS

Lake Oroville 2017/2018 Flood Control Season Operations Plan

October 16, 2017

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Appendices

1) Introduction

On February 7, 2017, during flood control operations, Lake Oroville's flood control outlet (FCO) spillway was damaged. Beginning on May 25, 2017, DWR initiated authorized construction to repair the FCO spillway concentrating on the repair and partial reconstruction of the main FCO spillway by November 1, 2017. DWR will be reconstructing the entire FCO spillway over a two year period.

During the 2017/2018 flood control season, the FCO spillway will be able to safely pass flows, however, because of the partial reconstruction; the maximum planned operational release will be less during this period than the original design. Therefore, the Lake Oroville 2017/2018 Flood Control Season Operations Plan (Plan) has been developed to address the interim FCO spillway flow limitations. This Plan incorporates the flow limitation and serves as a bridge until the final FCO spillway is reconstructed to safely pass the design capacity by the end of 2018.

This Plan outlines the operational strategies that limit the interim preferred FCO spillway design release to 100,000 cubic feet per second (cfs). This Plan ensures dam safety, provides downstream flood protection, and meets the existing US Army Corps of Engineers (USACE) flood control requirements set forth in the 1970 water control manual (WCM) for Lake Oroville. DWR is targeting lower lake elevations than required by the existing WCM, however, if conditions require, could operate to the WCM. Because of the conservative operations strategy outlined in the Plan, DWR will not be submitting a formal request to the USACE for a formal deviation to the existing WCM for the 2017/2018 flood control season.

The Plan operations are split between a general operations strategy that would guide operations through approximately 99.5% of anticipated hydrology and an emergency contingency planning process that would guide operations for more rare hydrologic events. This Plan outlines operations from November 1, 2017 through April 30, 2018. No later than April 15, 2018, DWR will prepare and submit to FERC and DSOD a Final FCO Gate Closure Plan that incorporates actual and forecast snowpack information and technical analyses that will support the final FCO gate closure with the intent to maximize the 2018 construction season.

2) Plan Objectives

DWR is committed to public safety and this Plan was developed in accordance with the following primary objectives:

- Provide equal or greater flood protection for the downstream entities.
- Safely pass the standard project flood (SPF) from the 1970 USACE WCM developed for Oroville Dam and Reservoir.
- Does not increase dam safety risk during the SPF, which is achieved by establishing the two following objectives:

    - Avoid activation of the emergency spillway (elevation 901 feet).
    - Avoid gated FCO releases greater than the interim 2017/2018 preferred design outflow objective of 100,000 cfs.
- Operate Lake Oroville to accommodate an early start to the 2018 construction season.

3) Hydrological Engineering Analysis for Flood Control

Using a risk-based decision process, David Ford Consulting Engineers (Ford Engineers) performed the hydrological engineering analysis to support the Plan and provided technical webinars outlining the technical methods used for the analysis. The webinars were provided on September 18, 2017 for the USACE and on September 20, 2017, for the Division of Safety of Dams (DSOD) and the Federal Energy Regulatory Commission (FERC). Included in Appendix A is the engineering analysis memo entitled, *Lake Oroville November 2017 through May 2018 Operation Plan* and the webinar slides entitled O*roville Operations Simulation Methods*, both prepared by Ford Engineers.

As described in the USACE 1970 WCM, DWR is required to maintain 375 to 750 thousand acre-feet (TAF) (875.3 to 848.5 feet elevation) of available flood storage space, dependent on the Feather River Watershed basin wetness, between October 15 and March 31 of each year. The current USACE water control diagram (Appendix B) was developed with certain flood pool assumptions (storage, elevation, and basin wetness) and maximum outflow of 150,000 cfs to provide protection to downstream communities from the standard project flood (SPF). The SPF is an event that is hypothetically possible although never experienced historically. The WCM recognizes that greater releases may be required during even larger hypothetical events as prescribed by the emergency spillway release diagram for dam safety purposes.

Ford Engineers determined what additional flood storage is required (beyond the existing WCM flood pool requirement) to pass the SPF with the reduced interim FCO spillway design flow objective of 100,000 cfs without exceeding the emergency spillway crest elevation of 901 feet. Based on the analysis, DWR will target a lake elevation of 800 feet. This elevation provides an additional 48.5 feet of vacant flood control storage – adding about 600 TAF for a total of 1.35 million acre-feet of total flood control storage from November through March. DWR refers to this additional space as the enhanced flood pool.

The following summarizes the calculated performance of the proposed Plan for the vast majority of expected conditions and is also outlined in greater detail in Appendix A:

- The Plan allows the reservoir to pass the SPF without exceeding the emergency spillway crest elevation of 901 feet and without releasing greater than 100,000 cfs from the FCO spillway.

- The Plan avoids increasing pool elevation values significantly on the reservoir pool elevation-frequency curves for events that require flood storage.
- The Plan avoids increasing outflow values significantly on the reservoir outflow-frequency curves for events that require flood storage.
- The Plan avoids increasing peak flow values significantly on the peak flow-frequency curves for locations downstream for events that require flood storage.

For rare hydrologic events (hypothetically possible but never observed historically), the results show the following:

200-yr design event or an event that has 0.5% chance of occurrence in the given month

The Plan allows the reservoir to pass the 200-year event without exceeding 901 feet. The maximum pool elevations for the 200-year event under the Plan are less than or equal to those yielded with 1970 WCM operation, with the exception of December, January, and February (months for which frequency statistics are based on annual maximums). For those months, maximum pool elevations are approximately 0.2 feet higher than the 1970 WCM, an insignificant increase. Maximum Plan outflow is 100,000 cfs or below for all months except December, January, and February, when it is 110,000 cfs. Hydraulic analysis of the partially constructed chute indicate the FCO spillway can safely pass flows up to 150,000 cfs, therefore DWR is prepared to manage inflows having a recurrence interval of 1 in 200.

Downstream Flood Protection

This Plan avoids increasing peak flows downstream. The peak regulated flows at given downstream locations (Yuba City, Feather-Yuba confluence, and Nicolaus) are less than the flows resulting from the 1970 WCM operation. The Plan provides for a level of protection (1 in 200-year) which is comparable to the 1970 WCM operation.

4) Operations Strategy

The operations strategy incorporates the Plan objectives while providing flexibility to adapt to changing conditions due to forecasted hydrology, Hyatt Powerplant (Hyatt) availability, and downstream flow requirements. Although the operations strategy focuses on wet hydrology, DWR also needs to be mindful of the potential for dry hydrology, therefore the lake elevations as proposed are as reasonably low as feasible to allow DWR to manage through a potential dry winter while not increasing a dam safety or public safety risk.

a) Enhanced Flood Pool Elevation Target

Table 1 summarizes the required elevations for passing the SPF as outlined in the 1970 WCM and those developed by Ford Engineers which incorporate

the project features that have changed in 2017. The elevation targets developed by Ford Engineers will be referred to as the Enhanced Flood Pool Elevation Targets. Of great significance is that these targets are below the sill of the FCO gate structure during the winter period.

Table 1: Elevations to Pass the Standard Project Flood

Beginning Month Elevations (feet)							
	November	December	January	February	March	April	May
1970 USACE Water Control Manual Wet Basin	848.50	848.5	848.5	848.5	848.5	848.5	870.1
Enhanced Flood Pool Elevation Targets[1]	800	800	800	800	800	830	830

1 – Elevation needed to pass the SPF with a maximum FCO spillway release of 100,000 cfs and without activating the emergency spillway (901 feet).

b) Elevation Triggers for Outflow Action

At elevations below the FCO spillway (elevation 813.6 feet), releases are made through Hyatt Powerplant (Hyatt), so it may not be possible to effectively manage to the Enhanced Flood Pool Elevation Targets during high inflow conditions and especially if this elevation is reached early in the wet season. Therefore, DWR has developed a more aggressive outflow strategy for elevations below the Enhanced Flood Pool Elevation Targets.

Table 2 and Figure 1 summarize elevations that will trigger more aggressive outflow operations prior to reaching the Enhanced Flood Pool Elevation Targets. To provide for successful lake management, DWR will adjust the outflow based upon to the elevation triggers (Outflow Trigger Elevations). The Outflow Trigger Elevations are below the Enhanced Flood Pool Elevation Targets needed to pass the SPF. The purpose of operating to the Outflow Trigger Elevations is to moderate the increase in storage over the course of the rainy season. Under wetter hydrologic conditions it will not be possible to hold the lake level at these elevations due to limited outflow capabilities at these relatively low lake elevations.

These Outflow Trigger Elevations will be lowest early in the season and gradually increase as the winter progresses until March 1, 2018 when the Outflow Trigger Elevation matches the Enhanced Flood Pool Elevation Target.

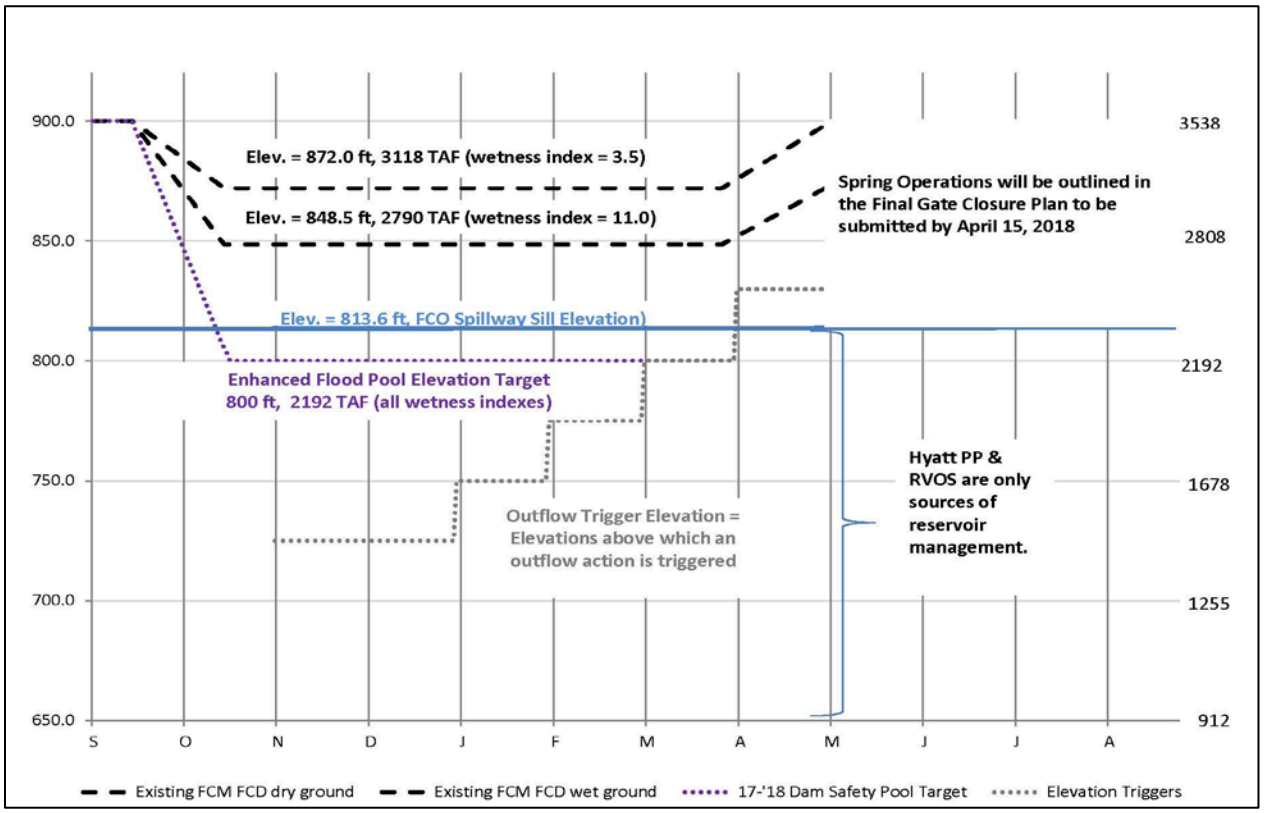
The actions prescribed by the Outflow Trigger Elevation are a much more aggressive Hyatt release operation than would otherwise be implemented and increases the likelihood of meeting the Enhanced Flood Pool Elevation Targets. The outflow action should be achievable without undue risk being placed on the Hyatt generating units. Two key elements of managing risk to the Hyatt generating units are 1) not running all the units continuously at maximum capacity, and 2) planning key outages to allow DWR to perform critical maintenance on the units.

Table 2: Trigger Elevations and Outflow Actions

Trigger Elevations and Outflow Actions							
	November	December	January	February	March	April	May
Trigger elevation (feet)	725	725	750	775	800	830	830
Elevation range (feet)	725-800	725-800	750-800	775-800	El>800	El>830	El>830
Outflow Action	10,000 cfs				14,700 cfs	7,500 cfs	Condition dependent[2]
Elevation range (feet)	800 -813.6[1]						
Outflow Action	Maximize Hyatt[3]	14,700 cfs[4]	14,700 cfs	14,700 cfs	14,700 cfs	N/A	Condition dependent[2]

1 – FCO gated spillway sill elevation
2 – The planned operations will be outlined in a FCO Gate Closure Plan to be provided by April 15, 2018. The Gate Closure Plan will outline operations to accommodate the 2018 construction season and will be updated with the current and forecast hydrological conditions.
3 – Maximum Hyatt based upon available units
4 – 14,700 cfs is the average flow of five Hyatt units at 800 foot elevation.
N/A – Not applicable

Figure 1: 2017-2018 Enhanced Flood Pool Elevation Targets and Outflow Trigger Elevations



If forecasts indicate that the lake elevation will increase beyond the FCO spillway elevation of 813.6 feet, then DWR will assess whether the FCO spillway use is necessary. DWR may elect to not use the FCO spillway if the Enhanced Flood Pool Elevation Target can be achieved through the use of Hyatt.

In the event that Lake Oroville is experiencing higher inflows, there may be continued storage gain between lake elevations 800 to 813.6 feet until sufficient head and outflow capacity is reached on the FCO spillway .

For all Feather River releases, DWR will follow the ramping criteria required in in the California Department of Fish and Wildlife 1983 Agreement, the 2004 National Marine Fisheries Service Biological Opinion and the 1970 WCM. The summary of the ramping rates and minimum Feather River flow criteria is provided in Appendix C.

c) Historical FCO Spillway Operations

The FCO spillway has been available for use since 1969. Including 2017, that is 49 years of operation. Since 1969, the FCO spillway has been used in 25 of those 49 years. Table 3 summarizes the annual historical maximum releases for the given ranges.

Table 3: Historical FCO Spillway Use

Outflow Range (cfs)	Number of Years (%)
0 – 25,000	9 (18%)
25,001 – 50,000	4 (8%)
50,001 – 75,000	6 (12%)
75,001 – 100,000	3 (6%)
Greater than 100,000	3 (6%)

d) 2017/2018 FCO Spillway Operations

If DWR determines that the FCO spillway use will be necessary to manage inflows, the operations will be in accordance with spillway Recommissioning Plan for 2017-2018 which is currently under development. The Recommissioning Plan includes objectives and guidance for operating, monitoring, and inspecting the FCO spillway during 2017-2018.

Outflow through the FCO spillway is dependent on lake elevation. Flow capacity will increase as the lake level increases, thereby providing sufficient outflow to manage a wetter hydrology. Included in Appendix D is a summary table of the FCO spillway outflow capacity at elevations above 813.6 feet.

The following actions will be implemented by DWR during FCO spillway operations:

- Prepare lake elevation and outflow forecasts at the same intervals as the California Nevada River Forecast Center inflow forecast issuance.
- Engage DWR's Division of Flood Management (DFM) to prepare reservoir forecasting modeling runs.
- Initiate regular coordination with USACE, DWR-DFM and Yuba County Water Agency (YCWA).
- Initiate regular coordination with dam safety regulators – DSOD and FERC.
- Initiate notifications to downstream communities and provide regular updates to local emergency officials and the media.

e) Key Consideration for Outflow Actions

Hyatt Powerplant

Maintaining reliability and sustainability of Hyatt units is a key consideration to the development of the outflow actions triggered by monthly elevations as shown in Table 2. In order to maintain Hyatt reliability in the short-term and long-term, DWR cannot operate the units on a continual basis. The outflow actions also include planned outages and the Feather River flow stability requirement as described below.

Fall 2017: October 15 - December 15 Outage

As described in DWR's May 12, 2017, *Near-Term Operation Plan for Lake Oroville*, an outage of Hyatt Penstock No. 1 is scheduled between October 15 to December 15 to allow for routine maintenance and the preparatory work necessary for installation of the remaining Hyatt unit so that the plant can have all six units available for operation in 2018. Although the outages provide for critical maintenance for the units, DWR commits to shortening the outages should hydrological conditions indicate that the additional outflow is necessary. If DWR elects to cancel in the midst of an outage, the penstock will be brought back online within two weeks. Although DWR anticipates that the penstock outage will establish the preparatory work needed for installation of the sixth unit sometime during the wet season, the technical analysis performed by Ford Engineers is conservative, and assumes that only five out of six units are available for the entire period.

Feather River Flow Requirement

In addition, during the outage window from mid-October through late November, a flow stability requirement for fish spawning on the Feather River is in effect. This flow is a requirement of the current FERC license and agreement with the California Department of Fish and Wildlife. This agreement requires flow to the Feather River to remain at a rate that is sustainable through the following March. Given the planned low lake elevations in the fall, coupled with the risk of dry hydrologic conditions through any winter period, if dry conditions persist in November, the Feather River flows are planned to be maintained at a sustainable rate of no more than 2,500 cfs from mid-October to the end of November.

Spring 2018 Hyatt Outage

Hyatt Penstock No.2 is scheduled for a two-week outage in the spring 2018 for routine maintenance. This outage is tentatively planned prior to the commencement of the 2018 spillway construction activities and final closure of the FCO gates. This outage will be postponed if hydrological conditions warrant the need for additional outflow capacity to manage lake levels.

River Valve Outlet System (RVOS)

As an additional conservative measure, the RVOS will only be used as a contingency in the event of an unexpected loss of capacity at Hyatt or for temperature management needs in the late summer into fall.

Minimum Feather River Releases

Although Lake Oroville's primary purposes are for flood control and water supply, the lake also provides for power generation, recreation, and fish and wildlife protection. Under drier hydrologic conditions when the Outflow Actions are not controlling, DWR will manage releases to meet vitally important fishery and water supply objectives.

f) 2018 Spring and Summer Operations

This Plan focuses on lake operations November 2017 through April 2018. DWR will prepare a Final Gate Closure Plan no later than April 15, 2018. The Final FCO Gate Closure Plan will incorporate snowpack conditions and operations that will support the earliest FCO spillway final gate closure in order to maximize the 2018 construction season.

g) Historical Wet Year Flood Routings

To test the performance of the proposed outflow operations strategy outlined in this Plan, DWR prepared sensitivity analyses using the USACE Reservoir System Simulation (ResSIM) for the significant historical wet years of 1986, 1997, and 2017. The modeling period covers the November 1, 2017 through April 30, 2018 operating period. The results of these modeling runs are attached in Appendix E.

Table 4 summarizes the results of these modeling runs following the proposed operations strategy.

Table 4: Summary Statistics of Wet Year ResSIM Routings

Time Period	Max elevation (feet) and date	Max outflow (cfs)	Days encroached within the 1970 WCM
1985-1986	857.5, 2/20/1986	100,000	4
1996-1997	858.6, 1/3/1997	100,000	4
2016-2017	856.0, 2/9/2017	100,000	3

At the maximum elevation shown above, DWR is encroached in the flood space between 7.5 to 10 feet equating to about 102 to 137 thousand acre-feet, which is about 14 to 18% encroached. DWR is able to manage inflows without exceeding the FCO spillway interim design capacity of 100,000 cfs and the lake elevations are reduced such that the time encroached above 848.5 feet (lower elevation of the 1970 WCM flood pool) is minimized to 3 to 4 days.

h) Ensemble Forecasts

The National Weather Service California-Nevada River Forecast Center (CNRFC) produces forecast ensembles which overlay 59 years (1950 to 2008) of historical events onto the current conditions in the basin and forecast the Lake Oroville inflows up to one year. The current conditions include antecedent watershed soil moisture, groundwater levels, and impounded surface water in upper watershed lakes and reservoirs. The ensemble inflows for this coming winter consider historical precipitation applied to the watershed following the wettest year on record. As a result, the anticipated inflows will be higher than the inflows that occurred historically for these same historical precipitation events.

The operations strategy in this plan was tested using all 59 historical ensemble traces and the results are presented in Figures 2 and 3 and Tables 5 and 6 for the operating period of October 5, 2017 through April 30, 2018, following the Plan Operations Strategy.

Figure 2: 2017/2018 Lake Oroville Operations Plan Ensemble Simulation Elevation and Releases Results

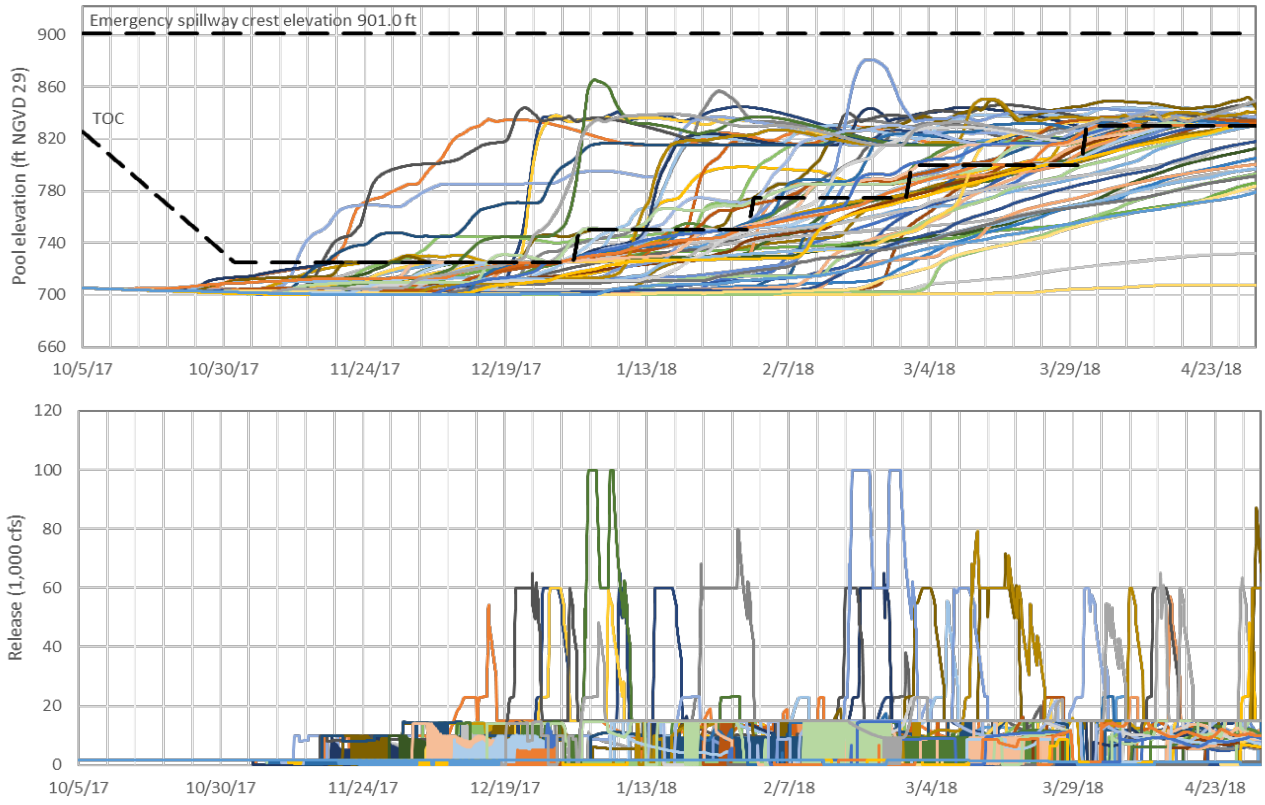


Figure 3: Variance of Ensemble Maximum Pool Elevation by Month

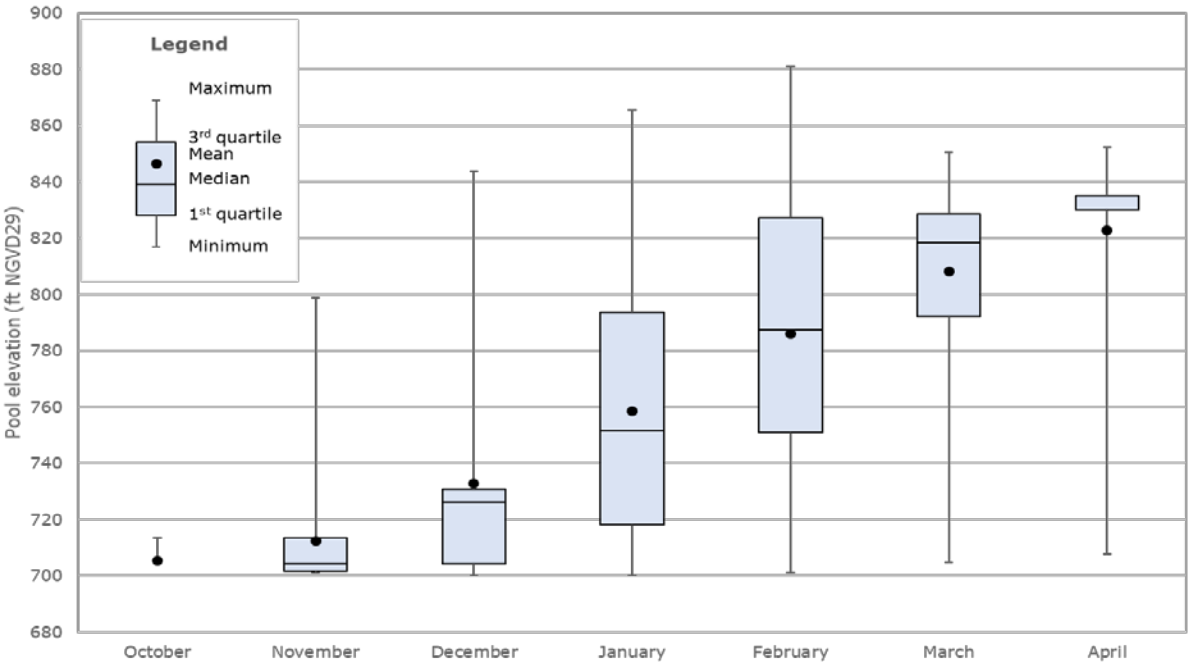


Table 5: Ensemble Routing Peak Pool Elevation and FCO Spillway Release Percentiles

Statistic[1]	Maximum pool elevation (feet)	Maximum FCO release (feet)
Maximum	880.8	100,000
90% non-exceedence	849.6	54,917
80% non-exceedence	840.4	45,304
70% non-exceedence	835.3	14,036
60% non-exceedence	830.7	7,500
50% non-exceedence	830.0	7,500
40% non-exceedence	830.0	6,573
30% non-exceedence	830.0	3,882
20% non-exceedence	812.6	0
10% non-exceedence	791.4	0
Minimum	707.6	0

1 – For example, 90% non-exceedence means the maximum pool elevation and FCO spillway release was 849.6 feet and 54,917 cfs or less in 90% of the simulations (approximately 53 out of 59 ensemble members)

Table 6: Ensemble Routing Key Pool Elevations

Elevation (feet)	Number of simulations that exceeded specified pool elevation[1] (feet)	Associated non-exceedence percentile of specified pool elevation[2]	Notes
800.0	50	16%	Approximate flood management space required to pass SPF using 2017/2018 Lake Oroville Flood Control Season Operations Plan.
813.6	47	20%	FCO spillway sill elevation.
848.5	6	89%	1970 WCM flood management space requirement for wet conditions.

1 - For example, 50 out of 59 simulations had maximum pool elevations greater than 800.0 feet.
2 - For example, 16% non-exceedence means the maximum pool elevation was 800.0 feet or less in 16% of the simulations (approximately 9 out of 59 ensemble members)

In the 59 years of historical events, there are periods where the elevation increases above the Enhanced Flood Pool elevation (800 feet) and the FCO spillway (813.6 feet) however, this is primarily attributed to limited outflow capacity below the FCO spillway sill and this also occurs during April 2018 when the Enhanced Flood Pool Elevation increases to 830 feet. In all 59 traces, the maximum lake elevation is 880.8 feet and the 1970 WCM flood pool is encroached 6 of the 59 traces.

5) Extreme Hydrologic Event Contingency Planning

Although it is highly improbable that Lake Oroville will experience a storm with a re-occurrence interval rarer than the SPF or an event having a 0.2% chance of occurrence, DWR has incorporated this contingency into this Plan. The contingency planning addresses DWR's actions in the event of an extreme hydrology event. DWR held an internal workshop that included representation from DWR water operations, executive management, Oroville Field Division, and members of the spillways engineering team on October 4, 2017 to develop internal processes to address an extreme hydrological event. Appendix F includes a copy of the Contingency Plan that was developed from this workshop.

6) Reporting

DWR commits to submitting a report to the USACE, FERC, and DSOD at the beginning of each month highlighting the upcoming month's Outflow Trigger Elevation and respective outflow actions and the Enhanced Flood Pool Elevation Target consistent with this Plan. In addition, if the lake elevation exceeds the Enhanced Flood Pool Elevation Target, DWR will prepare weekly, or more often as necessary, lake and operation forecasts incorporating the most recent forecast issued by the CNRFC.

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MEMORANDUM

To: Molly White, PE
California Department of Water Resources

From: Teresa Bowen, PE (Lic # CA 40122); David Ford, PhD, PE; Nathan Pingel, PE; and Michael Konieczki, PE

Date: October 16, 2017

Subject: Lake Oroville November 2017 through May 2018 Operation Plan

Summary

The 1970 U.S. Army Corps of Engineers (USACE) Lake Oroville water control manual (1970 WCM) prescribes how the as-built reservoir must be operated for flood management (USACE 1970). During the 2017 Oroville spillway incident, the gated flood control spillway and the emergency spillway were damaged. A plan for operating the partially restored gated spillway from November 2017 through May 2018 is required to maintain dam safety and manage flood risk. To meet these goals, the operation plan, herein referred to as the Nov. 2017-May 2018 operation plan, should:

- Follow the scope of rules in the 1970 WCM.
- Efficiently use the partially restored project features.
- Pass the standard project flood (SPF) without using the emergency spillway. (The project features and 1970 WCM operation were developed based on the objective of passing the SPF without using the emergency spillway. The SPF is shown in the 1970 WCM.)
- Not increase the frequency at which critical pool elevations are exceeded.
- Not increase the frequency at which critical releases are exceeded (based on current release limitations).
- Not increase the frequency at which critical downstream flow levels are exceeded.

This memorandum describes the California Department of Water Resources (DWR) operation plan that satisfies these objectives by increasing flood management storage available in the reservoir from November 2017 to May 2018. In line with 1970 WCM operation, the Nov. 2017-May 2018 operation plan allows the reservoir to pass the SPF without use of the emergency spillway. The Nov. 2017-May 2018 operation plan achieves this while limiting flood control spillway releases to 100,000 cfs.

All elevations reported herein refer to the National Geodetic Vertical Datum of 1929 (NGVD29), unless otherwise stated.

Oroville dam and reservoir features

Lake Oroville is a keystone facility of the State Water Project (SWP) and is owned and operated by DWR. With a capacity of approximately 3.5 million acre-feet (ac-ft), it is the largest reservoir of the SWP. Lake Oroville and Oroville Dam, shown in Figure 1, are located on the Feather River, a major tributary of the Sacramento River, about 6 miles northeast of Oroville in Butte County, California.

Figure 1. Features of Oroville Dam and Reservoir (Source: DWR)

Lake Oroville's primary purposes are for water supply and flood control. It also provides power generation, recreation, and fish and wildlife protection. The reservoir is operated in a coordinated manner with other reservoirs to regulate flood flow within the Yuba-Feather basin and to supply water for the SWP.

Here, the focus is on flood management operation, which is governed by the 1970 WCM. In cooperation with USACE, DWR regulates excess inflow to reduce flood damage downstream to the extent practical, storing water and releasing it at a time and rate that would prevent further damage downstream. Water is released from Lake Oroville through a gated flood control spillway, uncontrolled emergency spillway, powerplant outlets, and river valve outlet system (RVOS).

1970 WCM operation for as-built structure condition

For nearly 50 years, Oroville Dam has been operated successfully by DWR for flood management following rules specified in the 1970 WCM. Key features of the 1970 WCM and the operation rules include the following:

1. A flood control diagram (FCD) specifies the allocation of storage for conservation purposes and flood management, adjusting these based on the time of year and a watershed wetness index that is a surrogate for inflow forecast. For example, as less storage is needed for flood management in the late spring months, more storage is made available for conservation.

2. The Hyatt Powerplant, when fully operational, can release up to 17,000 cfs. In addition, the dam's flood control outlet (FCO), a 3,055-ft long by 179-ft wide concrete lined chute spillway, can be used when higher releases need to be made. The FCO is designed to have a physical capacity of 296,000 cfs at elevation 916.8 ft as defined in the WCM (USACE 1970).
3. Releases can also be made using the emergency spillway, which has a capacity of 350,000 cfs. The emergency spillway is approximately 1,730 ft long. The left 930 feet consists of a concrete gravity ogee weir. The right 800 feet consists of a small broad-crested weir. When reservoir pool elevation exceeds 901 ft—the emergency spillway weir crest elevation—water flows uncontrolled over the ungated spillway and down an unlined hill slope into the Feather River. Use of the ungated spillway is required to pass safely the probable maximum flood (PMF). Use of the ungated spillway was anticipated in the original design for flood events greater than the SPF.
4. When water is stored in the flood management pool (depicted in Figure 2) of Lake Oroville, rules in the 1970 WCM specify rates of release and manner of use of the outlets to make those releases. The rules consider observed or forecasted inflow, downstream flow, maximum non-damaging release rates at communities downstream, and safe rates of release changes.
5. When release rules were developed for the 1970 WCM, the maximum non-damaging release rate was considered 150,000 cfs, based on analysis of downstream channel capacity. This maximum operational constraint is inherent in the rules and diagrams.
6. Oroville Dam release rules were developed considering joint operation of Oroville Dam and Marysville Dam and Reservoir. The latter never was constructed, but the 1970 WCM has not been formally modified to reflect the absence. Operation has been adjusted as necessary and appropriate to account for this.
7. An emergency spillway release diagram (ESRD) specifies minimum release from the dam for dam safety, considering current pool elevation and rate of rise of the pool. The objective of the ESRD is to prescribe operation that will ensure the integrity of the dam.
8. Use of the ESRD may result in releases greater than 150,000 cfs. At the onset of flow over the emergency spillway, the ESRD prescribes reduction of release from the FCO, thus limiting maximum release to 150,000 cfs until a greater total release is required.

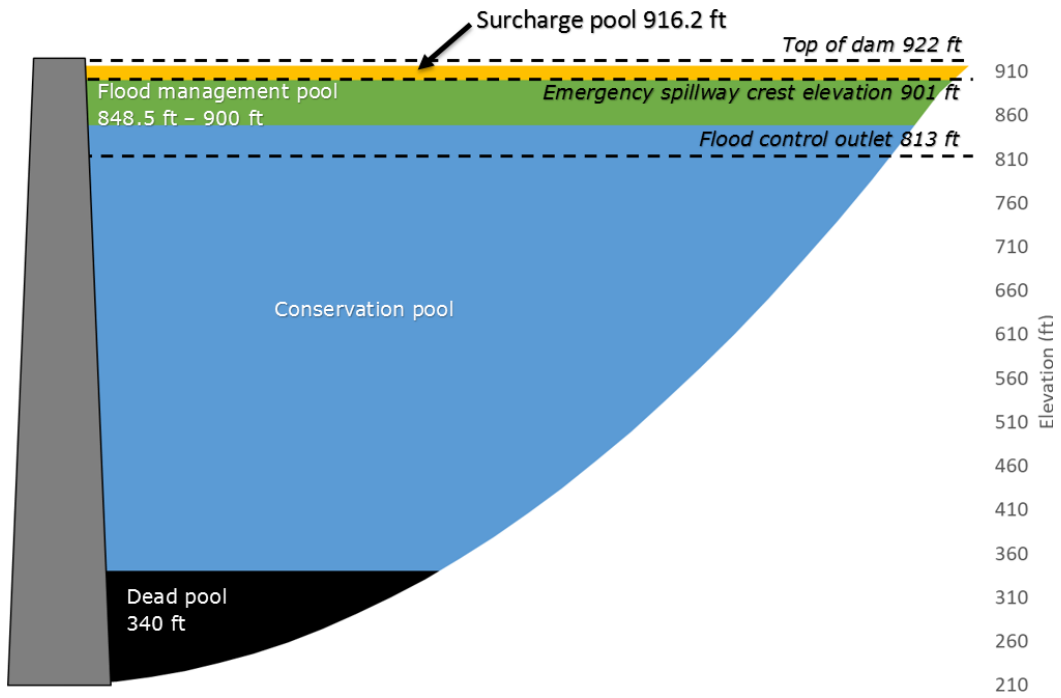

Figure 2. Key elevations of Oroville Reservoir

Nov. 2017-May 2018 operation plan for 2017 structure condition

The Nov. 2017-May 2018 operation plan for Oroville reservoir was developed because the properties and capabilities of the project features have changed in 2017. During flood operation consistent with the 1970 WCM, Oroville's gated chute spillway (FCO) failed, with a loss of a portion of the structural concrete. Reacting to that, DWR elected to deviate from the 1970 WCM operation. The 1970 WCM gives the Director of DWR authority to modify operation temporarily during emergency situations such as when dam safety is a concern. DWR coordinated this deviation with USACE, and USACE concurred. DWR reduced—and then halted—reservoir releases in the gated spillway. With continued reservoir inflow due to storm runoff, the reservoir pool level rose to elevation 901 ft. This led to the first-ever emergency spillway release. Flow down the unlined emergency spillway slope caused erosion and scour, raising concern about dam safety. Because of this concern, 180,000 people were evacuated from communities downstream of the dam. Since this incident in February, repairs have been made to prepare the dam for the upcoming flood season. (After this flood season, repair efforts will continue.)

Goals

The goals of the Nov. 2017-May 2018 operation plan are to maintain dam safety and provide flood control benefits produced by the reservoir for the period of November 2017 to May 2018.

Objectives

To meet these goals, the Nov. 2017-May 2018 operation plan must satisfy the following objectives:

- Follow the scope of rules in the 1970 WCM.
- Efficiently use the partially restored project features.
- Pass the SPF without using the emergency spillway.
- Do not increase the frequency at which critical pool elevations are exceeded.
- Do not increase the frequency at which critical releases are exceeded (based on current release limitations).
- Do not increase the frequency at which critical downstream flow levels are exceeded.

The current limitations of the project features are as follows:

- Avoid use of the emergency spillway to the extent possible. Following the approach of the 1970 WCM, DWR developed the Nov. 2017-May 2018 operation plan to avoid use of the emergency spillway for all events more likely than the SPF. The goal of the emergency spillway repair underway is to provide capability for safe releases of 30,000 cfs by January 2018.
- Limit FCO releases to 100,000 cfs for flood management operation (routing of SPF). The goal of the FCO spillway repair underway is to provide capability for safe releases of 100,000 cfs by November 2017. Operation to protect the integrity of the dam may require larger releases.

Performance metrics

Satisfaction of the objectives is determined by checking the following:

- Does the Nov. 2017-May 2018 operation plan allow the reservoir to pass the SPF without exceeding elevation 901 ft (the emergency spillway crest elevation) and without releasing greater than 100,000 cfs from the FCO spillway?
- Does the Nov. 2017-May 2018 operation plan avoid increasing maximum pool elevation values significantly on the pool elevation-frequency curves for events that require flood management storage?
- Does the Nov. 2017-May 2018 operation plan avoid increasing maximum reservoir outflow values significantly on the outflow-frequency curves for events that require flood management storage?
- Does the Nov. 2017-May 2018 operation plan avoid increasing peak flow values significantly on the flow-frequency curves for locations downstream for events that require flood management storage?

Nov. 2017-May 2018 operation plan development

DWR developed a Nov. 2017-May 2018 operation plan to satisfy the objectives, subject to the limitations shown. To develop the Nov. 2017-May 2018 operation plan, DWR followed the process outlined below:

1. Start with DWR's Oroville reservoir operation model and modify it for this application.
2. Validate the model by routing the SPF from the 1970 WCM.
3. Size the flood management pool through an iterative process of increasing the flood management pool, routing the SPF, and checking results.

4. Select a flood management pool size.
5. Evaluate flood management performance of a candidate Nov. 2017-May 2018 operation plan with the selected flood management pool size; refine as needed.
6. Select a plan.
7. Confirm flood management performance with the selected plan.

Reservoir operation model development

Under a previous effort to support the Oroville emergency recovery effort, DWR developed a reservoir operation model for the Yuba-Feather river system. That model includes Lake Oroville and New Bullards Bar Reservoir and follows 1970 WCM rules. The model uses HEC-ResSim, the USACE standard-of-practice software (http://www.hec.usace.army.mil/software/hec-ressim/). Given a reservoir network, physical properties, operating rules and constraints, and a set of flows, HEC-ResSim routes the flows through the system, following the rules to select releases for the reservoirs. The model is described in detail in the memorandum, "Reservoir Pool Elevation-Frequency Curves for Long-term Risk Assessment," SRT-RES-HY-02 (DWR 2017).

DWR truncated the model to extend from Lake Oroville on the Feather River and New Bullards Bar Reservoir on the Yuba River to Nicolaus downstream. This truncation removed the headwater reservoirs in the Feather River watershed; operation of these reservoirs is not part of the Oroville plan. However, the boundary conditions used to assess performance account implicitly for performance of the headwaters reservoirs.

To validate the model and size the flood management pool, DWR:

- Used the wet ground condition SPF from the 1970 WCM as inflow. There is also an SPF routing on dry ground in the 1970 WCM, but our analysis is based on the wet condition, which is more conservative.
- Configured alternatives to reflect candidate Nov. 2017-May 2018 operation plans.
- Used balanced hydrographs to evaluate the performance of candidate plans.
- Selected the Nov. 2017-May 2018 operation plan.

Details are described below.

Reservoir operation model validation

To validate the model, DWR routed the SPF for the wet condition with 1970 WCM operation and compared pool elevation and outflow results to those shown in the 1970 WCM (Chart 11, Routing No. 1). The model matches values in the 1970 WCM manual well, as shown in Table 1. Table 2 lists the annual exceedence probabilities (AEPs) associated with the SPF using the most current volume-frequency analysis (DWR 2015). The 3-day volume return period of the SPF is 168 yr.

Table 1. HEC-ResSim model validation: Comparison of simulated results to values shown in the WCM

Result (1)	WCM[1] (2)	HEC-ResSim model (3)
Max pool elevation (ft)	898.4	900.4
Max outflow (cfs)	150,000	150,000

1. DWR digitized the SPF information from Chart 11 of the 1970 WCM and estimated values shown on the chart.

Table 2. Annual exceedence probabilities of the SPF

Duration (days) (1)	Flow[1] (cfs) (2)	AEP[2] (3)	Return period (1/AEP) (4)
1	374,583	0.0038	260
2	305,917	0.0041	244
3	256,389	0.0060	168
5	194,200	0.0062	160

1. Average flow for the given duration.
2. AEP values were computed using the volume-frequency statistics developed in the DWR Central Valley Hydrology Study (DWR 2015).

Flood management pool sizing

The WCM was developed such that the reservoir could pass the SPF without use of the emergency spillway. To maintain this—given the 2017 state of the project features—the volume of storage used for flood management storage must be increased. To determine by how much, DWR followed an iterative process:

- Increase the volume of the flood management pool represented in the HEC-ResSim model. The 1970 WCM allocation is 750,000 ac-ft. This corresponds to elevation 848.5 ft at the bottom of the flood management pool (referred to in the WCM and in this memo as the top of conservation pool [TOC]).
- Route the SPF using the limitations defined by DWR and specified in the model for the Nov. 2017-May 2018 operation plan: FCO release is limited to 100,000 cfs, only 5 of the 6 powerhouse units can release water (unit 1 is unavailable for spring 2018), and flow through the RVOS is 0 cfs.
- Review results and check whether the emergency spillway crest elevation, 901 ft, is exceeded. If so, increase the flood management pool and repeat.
- If objectives are met, select a flood volume (restricted pool elevation) for the candidate Nov. 2017-May 2018 operation plan.

Initial flood management pool size

Using this process, DWR determined that a flood volume of approximately 1.3 million ac-ft of flood management storage (restricted pool elevation of 805 ft) is required to pass the SPF without using the emergency spillway, limiting FCO releases to 100,000 cfs and subject to the other limitations above.

Figure 3 shows this SPF routing. DWR also routed the SPF for 2 system routings, 1 centered over the Feather River above Oroville Dam (1970 WCM, Chart 32, Routing No. 1) and 1 centered on the Yuba River below New Bullards Bar Dam (1970 WCM, Chart 32, Routing No. 2). Local flows for these routings were obtained from supplemental information dated August 1973 provided by the USACE Sacramento District (USACE 1973). The system routings consider not only operation at Lake Oroville, but also operation at New Bullards Bar Reservoir and local inflows. Figure 4 through Figure 9 show results from the system routings. Table 3 below is a summary of the results.

Table 3. Summary of SPF routing results for restricted pool elevation 805.0 compared with 1970 WCM TOC of 848.5 ft

ID (1)	SPF description (2)	1970 WCM (as-built condition) [TOC = 848.5 ft, flood management storage = 750,000 ac-ft]			Resized flood management space [Restricted pool elev. = 805.0 ft, flood management storage = 1,288,400 ac-ft]		
		Maximum pool elevation (ft) (3)	Maximum storage (1,000 ac-ft) (4)	Maximum outflow from dam (1,000 cfs) (5)	Maximum pool elevation (ft) (6)	Maximum storage (1,000 ac-ft) (7)	Maximum outflow from dam (1,000 cfs) (8)
1	Wet conditions	900.0	3,538	150	900.7	3,549	100
2	System routing, Feather River above Oroville Dam	900.9	3,552	150	900.6	3,547	100
3	System routing, Yuba River below New Bullards Bar Dam	894.5	3,451	150	886.6	3,330	100

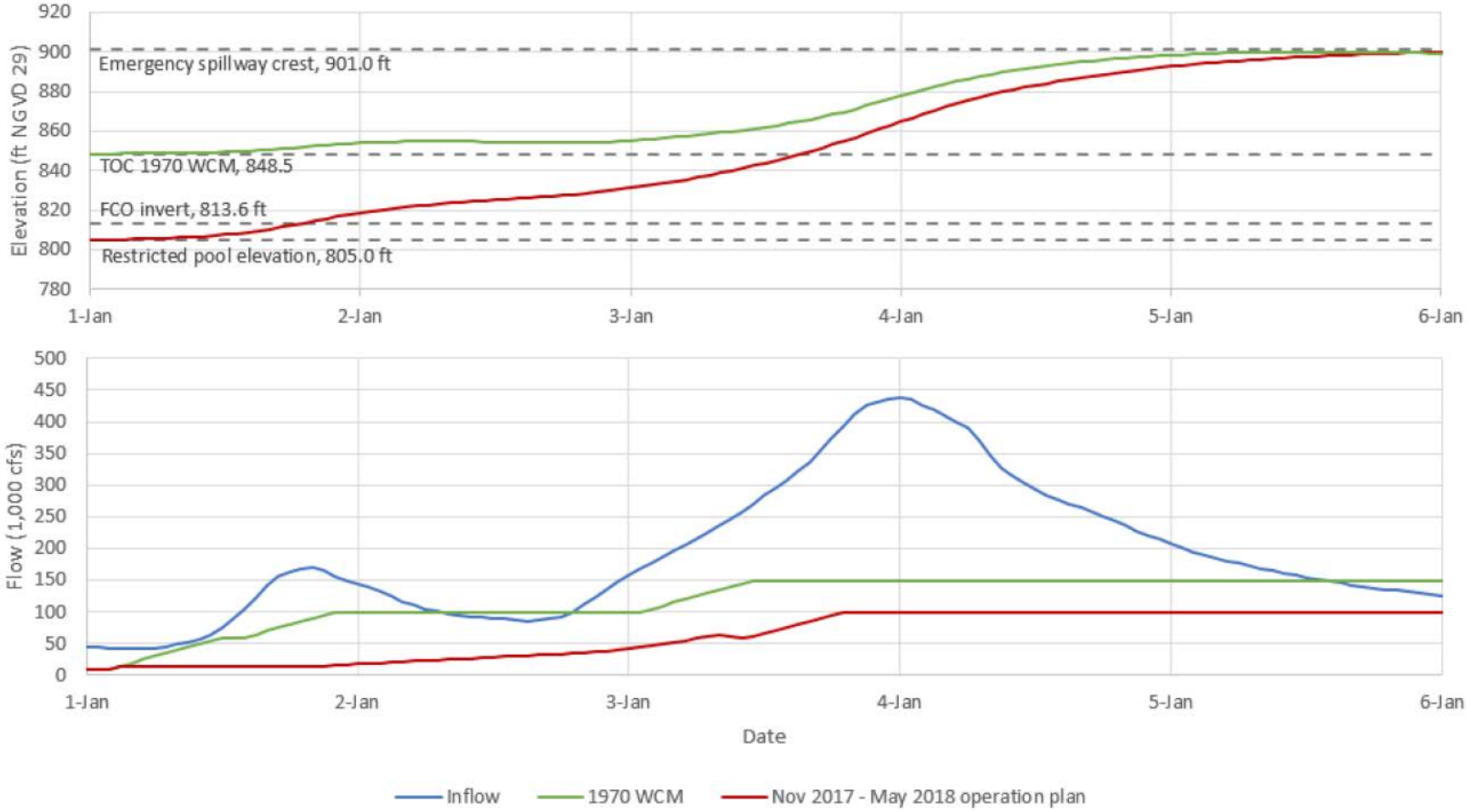

Figure 3. Lake Oroville SPF wet conditions routing: Comparison of 1970 WCM operation (green) and initial Nov. 2017-May 2018 operation plan with restricted pool elevation of 805.0 ft (red) — The elevation target in the Nov. 2017-May 2018 operation plan maintains pool elevation below the emergency spillway crest. (Dates here are for reference only and do not represent actual time of event occurrence.)

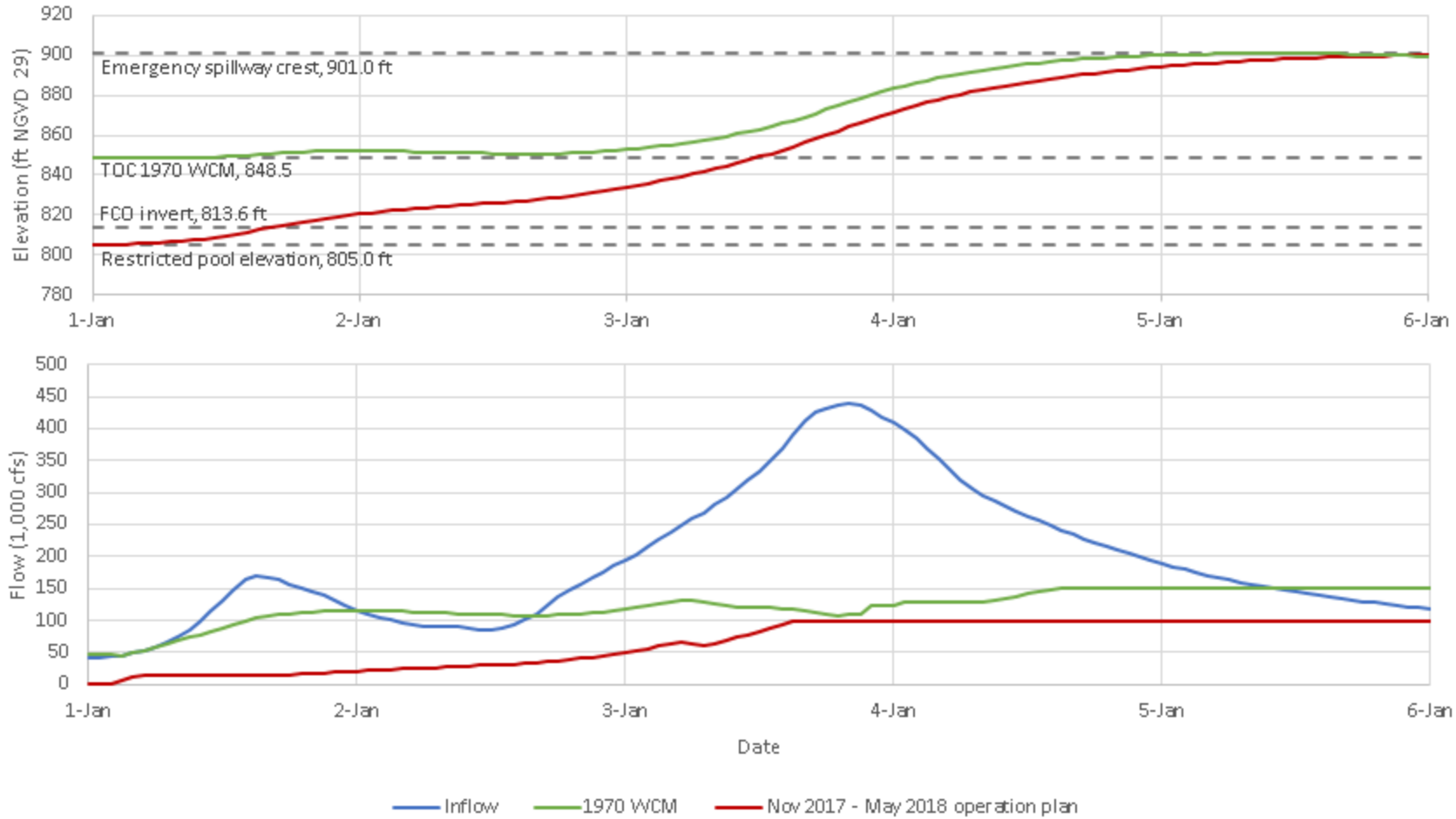

Figure 4. Lake Oroville SPF system routing centered on the Feather River above Oroville Dam: Comparison of 1970 WCM operation (green) and initial Nov. 2017-May 2018 operation plan with restricted pool elevation of 805.0 ft (red) —The elevation target in the Nov. 2017-May 2018 operation plan maintains pool elevation below the emergency spillway crest. (Dates here are for reference only and do not represent actual time of event occurrence.)

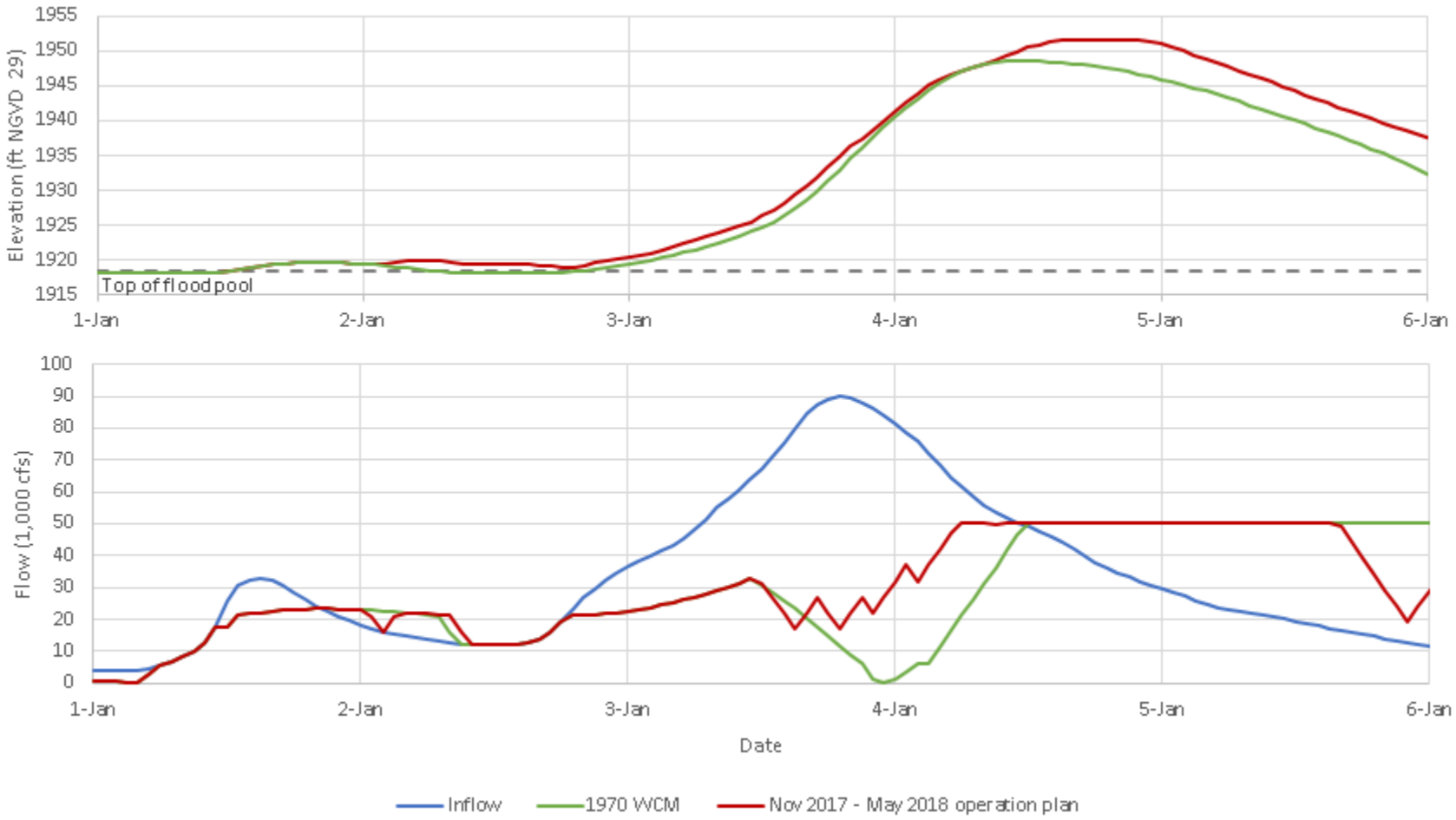

Figure 5. New Bullards Bar Reservoir operation for SPF system routing centered on the Feather River above Oroville Dam. New Bullards Bar Reservoir is operated according to its WCM for 2 scenarios: 1970 WCM operation at Lake Oroville (green) and with restricted pool elevation of 805.0 ft at Lake Oroville (red) as part of this initial Nov. 2017-May 2018 operation plan. New Bullards Bar maximum pool elevation is higher and Lake Oroville's releases reflect the limited flow identified in the Nov. 2017-May 2018 operation plan for Lake Oroville. (Dates here are for reference only and do not represent actual time of event occurrence.)

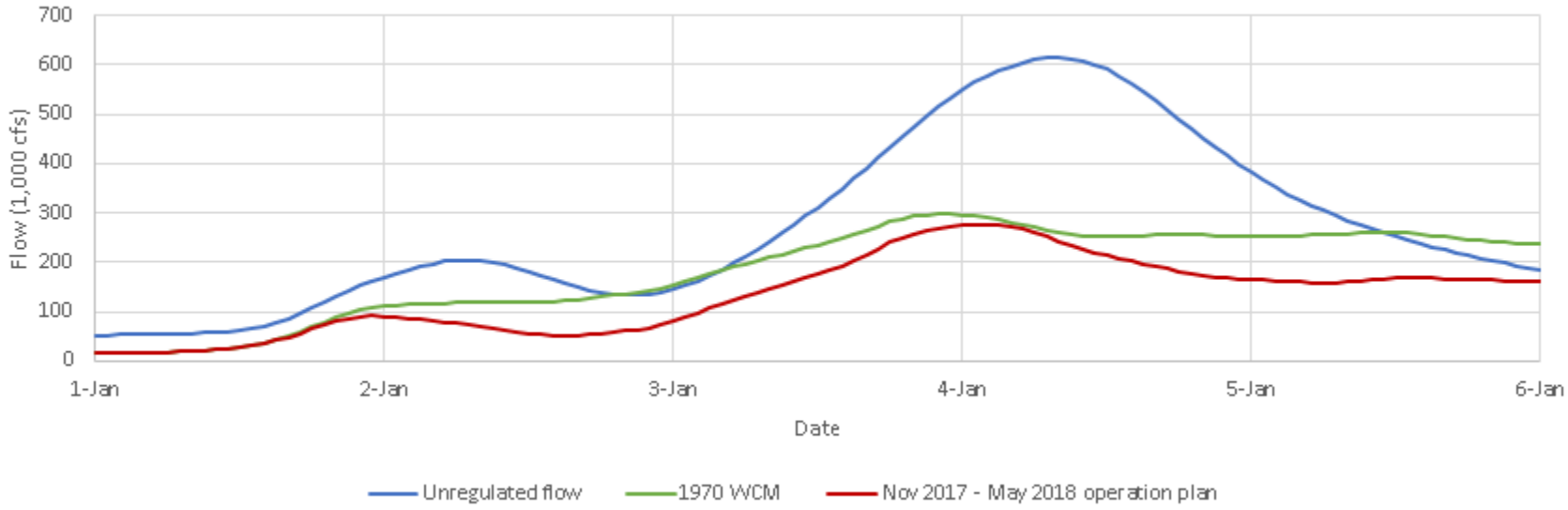

Figure 6. Flow at the Feather-Yuba River confluence for the SPF system routing centered on the Feather River above Oroville Dam for 2 scenarios: 1970 WCM operation at Lake Oroville (green) and initial Nov. 2017-May 2018 operation plan with restricted pool elevation of 805.0 ft at Lake Oroville (red). Peak flow at the confluence is reduced due to Lake Oroville's limited releases identified in the Nov. 2017-May 2018 operation plan. Flow remains below the 300,000 cfs maximum target flow. (Dates here are for reference only and do not represent actual time of event occurrence.)

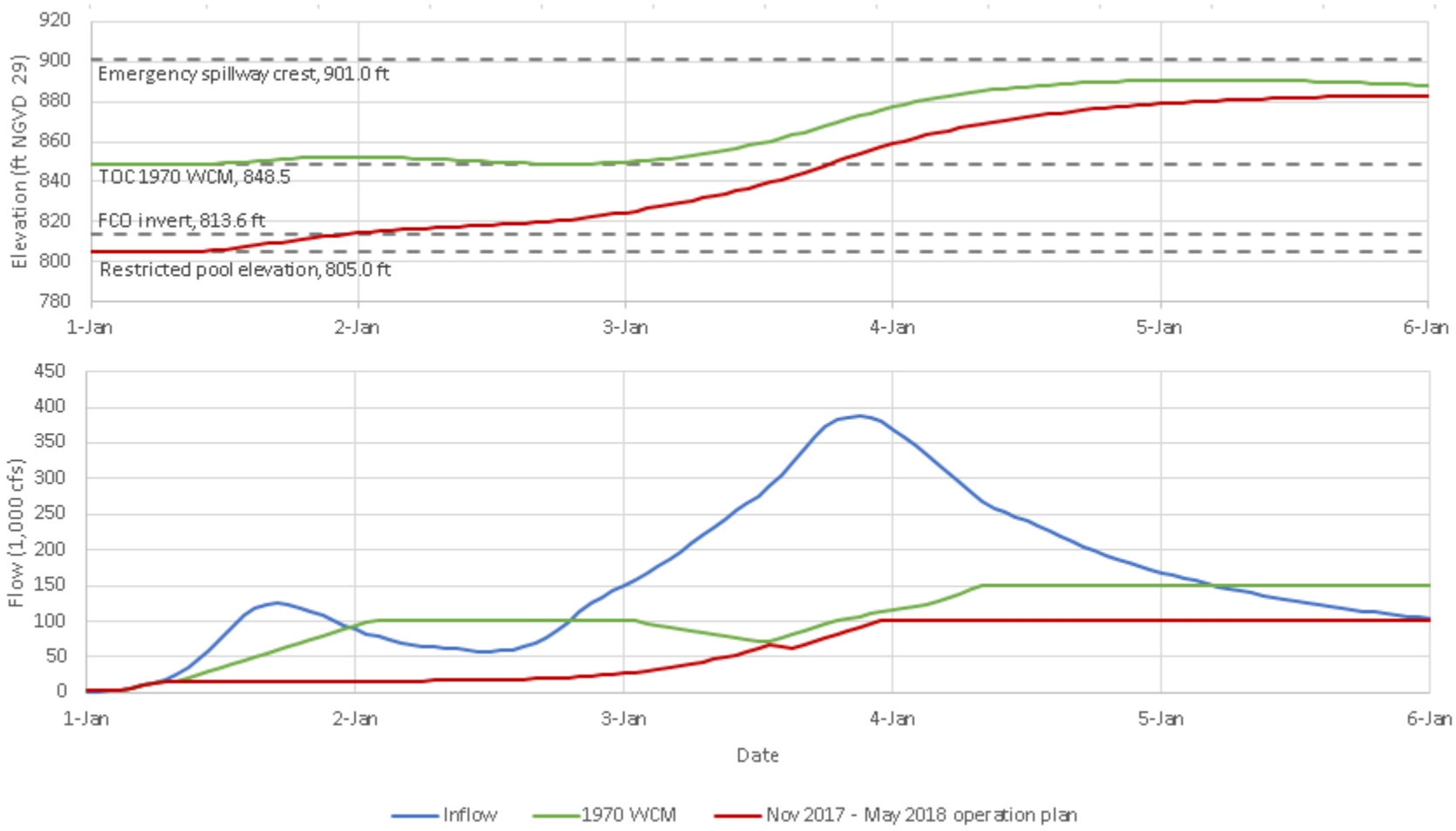

Figure 7. Lake Oroville SPF system routing centered on the Yuba River below New Bullards Bar Dam: Comparison of 1970 WCM operation (green) and initial Nov. 2017-May 2018 operation plan with restricted pool elevation of 805.0 ft (red) — The elevation target in the Nov. 2017-May 2018 operation plan maintains pool elevation below the emergency spillway crest. (Dates here are for reference only and do not represent actual time of event occurrence.)

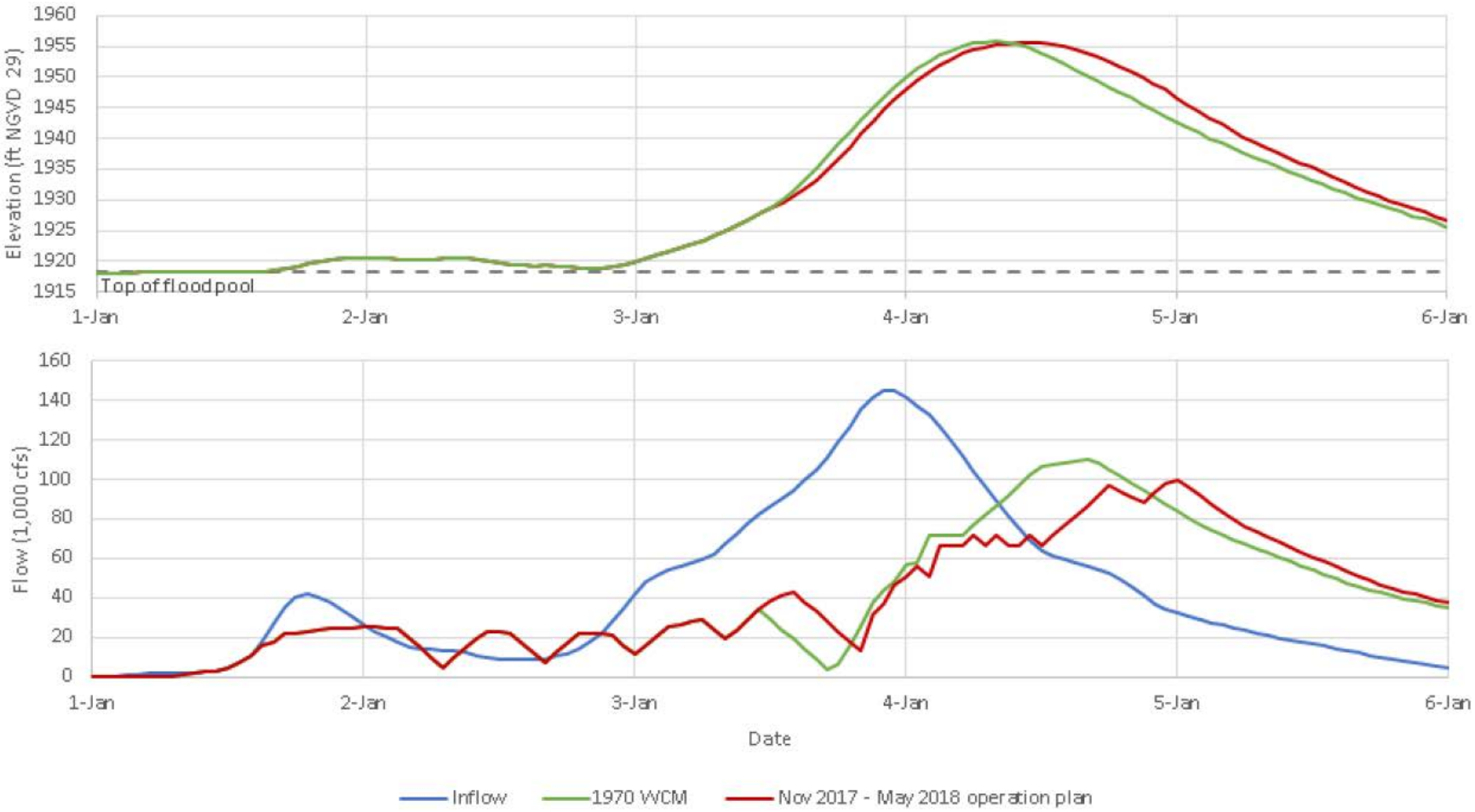

Figure 8. New Bullards Bar Reservoir operation for SPF system routing centered on the Yuba River below New Bullards Bar Dam. New Bullards Bar Reservoir is operated according to its WCM for 2 scenarios: 1970 WCM operation at Lake Oroville (green) and with restricted pool elevation of 805.0 ft at Lake Oroville (red) as part of this initial Nov. 2017-May 2018 operation plan. New Bullards Bar maximum pool elevation and maximum outflow are reduced under the Nov. 2017-May 2018 operation plan at Lake Oroville. (Dates here are for reference only and do not represent actual time of event occurrence.)

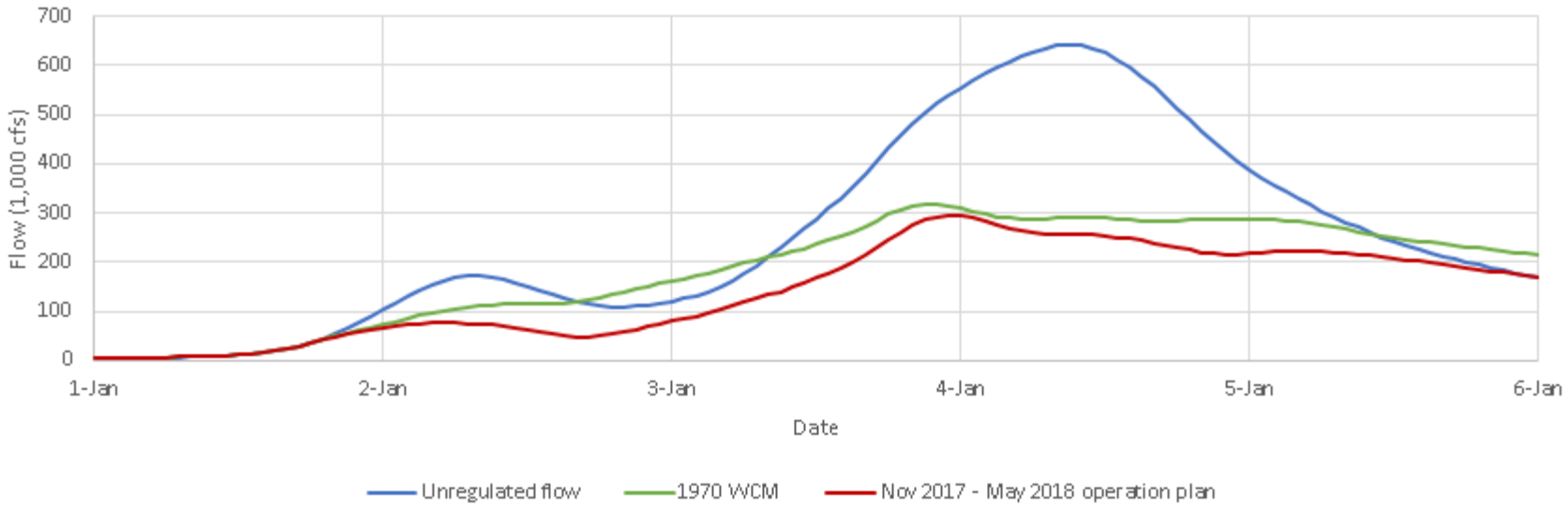

Figure 9. Flow at the Feather-Yuba River confluence for the SPF system routing centered on the Yuba River below New Bullards Bar Dam for 2 scenarios: 1970 WCM operation at Lake Oroville (green) and with restricted pool elevation of 805.0 ft at Lake Oroville (red) as part of this initial Nov. 2017-May 2018 operation plan. Peak flow at the confluence is reduced due to Lake Oroville's limited releases identified in the Nov. 2017-May 2018 operation plan. (Dates here are for reference only and do not represent actual time of event occurrence.)

Selected flood management pool size

DWR selected a flood management pool volume of 1,346,000 ac-ft. This corresponds to a restricted pool elevation of 800.0 ft. This is a conservative allocation based on analysis results, accounting for uncertainty about inputs.

Performance evaluation

To evaluate the performance of the candidate Nov. 2017-May 2018 operation plans, DWR developed pool elevation-frequency, reservoir outflow-frequency, and downstream flow-frequency curves for candidate plans and compared those to frequency curves developed based on 1970 WCM operation. DWR developed the WCM operation curves under the previous Oroville emergency recovery analysis described in SRT-RES-HY-02 (DWR 2017).

The evaluation informed an iterative process in which DWR defined the plan based on routing results, evaluated performance, refined as needed, and routed and evaluated again. Comparison of frequency curves, specifically checking whether values for the Nov. 2017-May 2018 operation plan are equal to or lower than values for the 1970 WCM, allowed us to determine whether flood management objectives, and in turn the flood management goal, are satisfied.

To develop the frequency curves for the Nov. 2017-May 2018 operation plan, DWR:

- Configured the Nov. 2017-May 2018 operation plan in the HEC-ResSim model with restricted pool elevation of 800 ft. Just as the simulations for flood management pool sizing, FCO release is limited to 100,000 cfs, only 5 of the 6 powerhouse units can release water, and flow through the RVOS is 0 cfs.
- Routed a set of balanced hydrographs associated with a range of frequencies through Lake Oroville (a risk-informed approach). DWR developed the balanced hydrographs under the previous Oroville emergency recovery analysis described in SRT-RES-HY-02. The hydrographs are representative of design events with return intervals of 2, 5, 10, 25, 50, 100, 200, and 500 years. For pool elevation and outflow results, these balanced hydrographs with frequencies specific for the months of November through May are used. For flow at downstream locations, scaled historical hydrographs developed based on annual frequency statistics are used consistent with the Central Valley Hydrology Study (CVHS) (DWR 2015).
- Compiled the set of pool elevation, outflow, and downstream flow results for the design events of each frequency and compared them to the values determined previously for WCM operation.
- Reviewed results, refined, and repeated until the Nov. 2017-May 2018 operation plan objectives and additional specifications were met. Specifically, DWR evaluated initial findings of the minimum flood management space required to pass the SPF under the current outlet limitations. DWR then proposed alternatives (for example, monthly starting storages and target pool elevations) which were tested using the reservoir simulation model. This process was repeated until all identified objectives were met.

- Once refinement was complete, DWR finalized the criteria within the Nov. 2017-May 2018 operation plan.

Nov. 2017-May 2018 operation plan criteria

The Nov. 2017-May 2018 operation plan has the following key aspects:

- The restricted pool elevation is 800 ft during flood season, as shown in Figure 10. Thus, the volume available for flood management storage is 1,346,000 ac-ft. This volume exceeds the volume called for in the 1970 WCM by approximately 596,000 ac-ft.
- FCO release will not exceed 100,000 cfs unless required by ESRD operation.
- The powerhouse discharge is limited to what is possible with 5 units (a unit is assumed offline for the 2018 flood season).
- The RVOS is reserved for contingencies. Flood management release is 0 cfs.
- The target pool elevation at the start of the month and the associated trigger elevations for using maximum release capacity from the powerhouse and FCO are those defined in Table 4.

Table 4. Monthly operation target elevations

ID (1)	Month (2)	Operational target[1] (ft) (3)
1	November	700
2	December	800
3	January	800
4	February	800
5	March	800
6	April	830
7	May	830

1. This is the target pool elevation at the start of the given month.

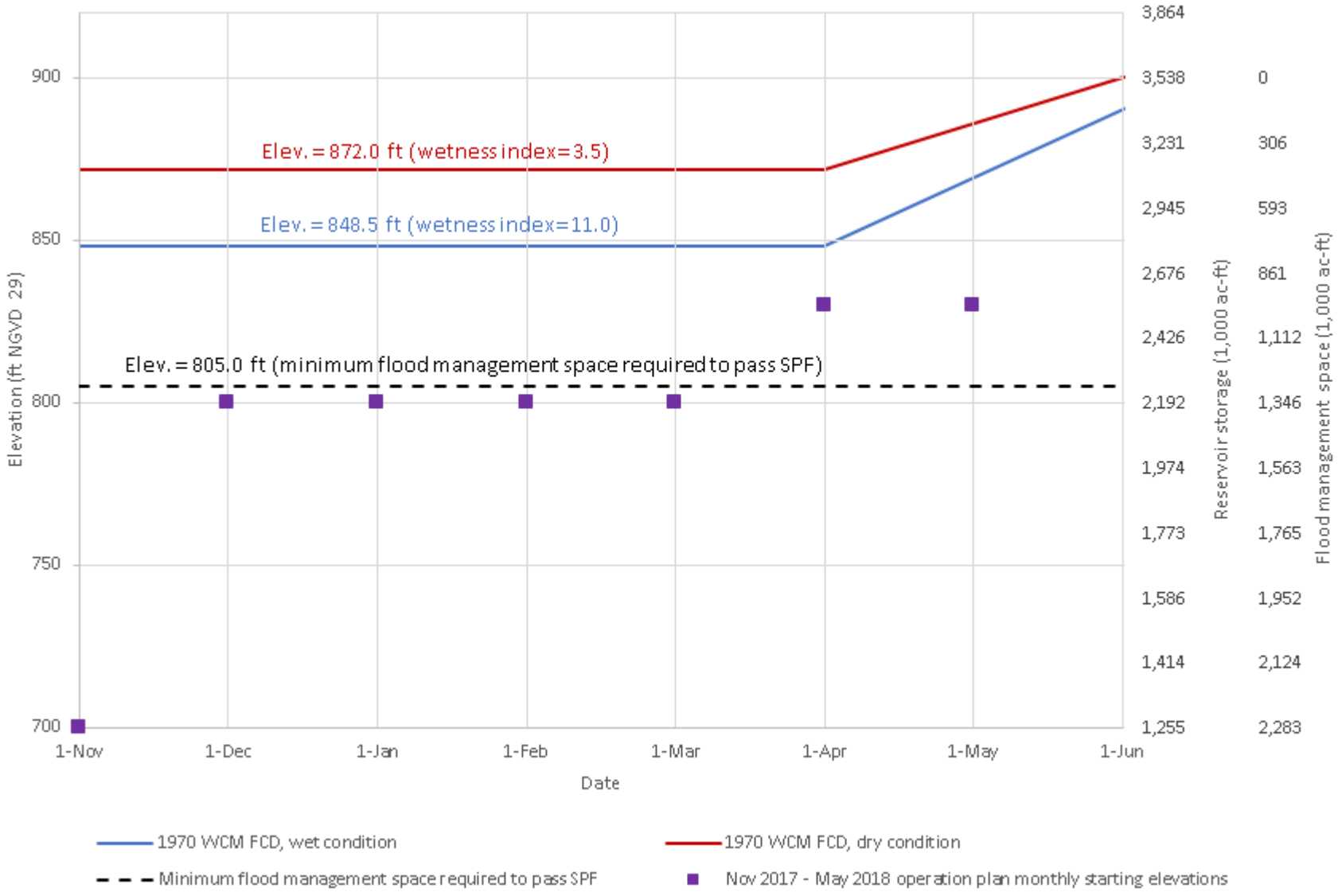

Figure 10. 1970 WCM FCD, minimum flood management space requirements, and Nov. 2017-May 2018 operation plan target monthly starting elevations

Nov. 2017-May 2018 operation plan performance

DWR confirmed that the Nov. 2017-May 2018 operation plan satisfies the objectives:

- The Nov. 2017-May 2018 operation plan allows the reservoir to pass the SPF without exceeding the emergency spillway crest elevation of 901 ft and without releasing greater than 100,000 cfs from the FCO spillway.
- The Nov. 2017-May 2018 operation plan avoids increasing pool elevation values significantly on the reservoir pool elevation-frequency curves for events that require flood management storage.
- The Nov. 2017-May 2018 operation plan avoids increasing outflow values significantly on the reservoir outflow-frequency curves for events that require flood management storage.
- The Nov. 2017-May 2018 operation plan avoids increasing peak flow values significantly on the peak flow-frequency curves for locations downstream for events that require flood management storage.

Table 5 and Table 6 show pool elevation-frequency and outflow-frequency curve values for 1970 WCM operation and the Nov. 2017-May 2018 operation plan, respectively. Table 7 shows flow-frequency curve values for both 1970 WCM operation and the Nov. 2017-May 2018 operation plan for downstream locations.

In summary, the results show the following for the pool elevation-frequency and outflow-frequency curves:

- 200-yr design event — The Nov. 2017-May 2018 operation plan allows the reservoir to pass the 200-yr event without exceeding 901 ft. The maximum values for the 200-yr event are less than or equal to those yielded with 1970 WCM operation, with the exception of December, January, and February (months for which frequency statistics are based on annual maximums). For those months, maximum pool elevations are approximately 0.2 ft higher than the baseline, an insignificant increase.

  Maximum outflow for the Nov. 2017-May 2018 operation plan is 100,000 cfs or below for all months except December, January, and February, when it is 110,000 cfs. For the Nov. 2017-May 2018 operation plan, releases in excess of 100,000 are a result of minimum releases required by the ESRD for dam safety.

- 500-yr design event — For the Nov. 2017-May 2018 operation plan, pool elevations exceed the emergency spillway crest elevation for December, January, February, and March, which is also the case for 1970 WCM operation.

  Correspondingly, releases exceed 100,000 cfs for these months. For the Nov. 2017-May 2018 operation plan, releases in excess of 100,000 are a result of minimum releases required by the ESRD for dam safety. Similarly, for 1970 WCM operation, releases exceed 150,000 cfs for the same months. For 1970 WCM operation, releases in excess of 150,000 are a result of minimum releases required by the ESRD for dam safety.

In summary, the results show the following for the downstream flow-frequency curve values:

- For the Nov. 2017-May 2018 operation plan, downstream maximum target flows are exceeded at Marysville for the 200-yr and rarer events. For all locations, downstream maximum target flows are exceeded for the 500-yr and rarer events. For WCM operation, downstream maximum target flows are exceeded for 200-yr and rarer events for all locations.

Table 5. Oroville reservoir frequency curve values for 1970 WCM operation: Operation follows the 1970 WCM for the as-built condition (all 6 powerhouse units are available and RVOS flow = 0 cfs)

Design event chance exceedence (CE)[1] (1)	Maximum pool elevation (ft)[2]							Maximum outflow (1,000 cfs)[2]						
	Nov. (2)	Dec. (3)	Jan. (4)	Feb. (5)	Mar. (6)	Apr. (7)	May (8)	Nov. (9)	Dec. (10)	Jan. (11)	Feb. (12)	Mar. (13)	Apr. (14)	May (15)
50%	848.5	852.0	852.0	852.0	852.3	868.8	890.1	15	60	60	60	60	15	15
20%	850.4	861.1	861.1	858.8	855.8	868.9	890.4	15	60	60	60	60	60	57
10%	850.4	861.1	861.1	858.8	859.0	870.9	891.7	60	100	100	100	60	60	58
4%	851.7	866.2	866.2	865.1	859.9	872.4	891.7	60	150	150	150	100	60	59
2%	855.5	873.5	873.5	873.5	865.5	872.9	893.1	60	150	150	150	125	100	60
1%	857.3	884.8	884.8	884.8	870.1	872.9	893.1	100	150	150	150	150	100	60
0.5%	861.5	900.6	900.6	900.6	880.5	872.9	893.1	145	150	150	150	150	150	60
0.2%	874.3	905.2	905.2	905.2	904.3	882.0	893.1	150	267	267	267	181	150	60

1. For example, 1% means the pool elevation would exceed 857.3 ft in 1 out of 100 Novembers.
2. These results are based on the reservoir routings of balanced inflow hydrographs. These routings do not account for downstream control.

Table 6. Oroville reservoir frequency curve values for the Nov. 2017-May 2018 operation plan: Application of monthly varying starting pool and operational elevations, FCO spillway flow is limited to 100,000 cfs, 5 powerhouse units available, and RVOS flow = 0 cfs (italicized values indicate increase over WCM operation)

Design event chance exceedence (CE)[1] (1)	**Maximum pool elevation (ft)[2]**							**Maximum outflow (1,000 cfs)[2]**						
	Nov. (2)	**Dec. (3)**	**Jan. (4)**	**Feb. (5)**	**Mar. (6)**	**Apr. (7)**	**May (8)**	**Nov. (9)**	**Dec. (10)**	**Jan. (11)**	**Feb. (12)**	**Mar. (13)**	**Apr. (14)**	**May (15)**
50%	700.2	816.6	816.6	816.6	809.4	836.6	832.9	13	16	16	16	15	15	15
20%	704.6	830.4	830.4	829.9	824.7	836.6	837.1	13	40	40	40	25	56	55
10%	712.3	839.0	839.0	839.0	830.1	837.2	838.8	14	64	64	64	39	56	58
4%	731.7	851.8	851.8	851.8	839.6	838.3	838.8	14	97	97	97	64	60	58
2%	752.5	865.0	865.0	865.0	849.0	844.2	838.8	15	100	100	100	86	69	58
1%	782.5	882.4	882.4	882.4	860.2	850.2	838.8	15	100	100	100	100	91	58
0.5%	820.8	*900.8*	*900.8*	*900.8*	878.2	858.9	838.8	16	110	110	110	100	100	58
0.2%	836.6	904.6	904.6	904.6	903.3	877.7	839.7	59	230	230	230	155	100	60
Starting and operational elevation[3] (ft)	700	800	800	800	800	830	830	700	800	800	800	800	830	830

1. For example, 1% means the pool elevation would exceed 782.5 ft in 1 out of 100 Novembers.
2. These results are based on the reservoir routings of balanced inflow hydrographs. These routings do not account for downstream control.
3. This is the pool elevation at the start of the design event simulation, and the elevation the reservoir is operating to, for the indicated month.

Table 7. Downstream flow-frequency curve values for 1970 WCM operation and Nov. 2017-May 2018 operation plan

Annual chance exceedence (CE) (1)	Peak regulated flow (1,000 cfs) at given location: 1970 WCM operation[1,2]				Peak regulated flow (1,000 cfs) at given location: operation plan[1,3]			
	Marysville[4] (2)	Yuba City[4] (3)	Feather-Yuba confluence[5] (4)	Nicolaus[6] (5)	Marysville[4] (6)	Yuba City[4] (7)	Feather-Yuba confluence[5] (8)	Nicolaus[6] (9)
20%	50	86	127	143	50	38	78	94
10%	72	115	172	196	72	58	113	136
4%	110	155	241	272	110	90	170	199
2%	142	172	280	309	142	112	216	250
1%	171	178	297	329	171	128	260	296
0.5%	195	188	314	347	195	150	278	316
0.2%	284	265	399	432	283	218	303	334

1. These results are based on the reservoir routings of the scaled hydrographs from the CHVS flow dataset for entire system (DWR 2015).
2. 1970 WCM: no powerhouse capacity, no RVOS.
3. Restricted pool elevation = 800 ft, FCO capped at 100,000 cfs, 5 powerhouse units available, and RVOS flows = 0 cfs.
4. The maximum target flow at Marysville and Yuba City is 180,000 cfs.
5. The maximum target flow at the confluence of the Feather and Yuba rivers is 300,000 cfs.
6. The maximum target flow at Nicolaus, just downstream of the confluence of the Feather and Bear rivers, is 320,000 cfs.

References

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U.S. Army Corps of Engineers (USACE). (1970). *Oroville Dam and Reservoir: Report on reservoir regulation for flood control*. Sacramento, California. August.

USACE. (1973). Supplemental information in files – "SPF systems analysis: Feather River – Yuba river drainage basins." Sacramento District. August.

Oroville operation simulation methods

Webinar
Wednesday, September 20, 2017

1

Agenda

1. Introduction
2. Relevant features of Oroville Dam
3. HEC-ResSim model
4. Inflow volume-frequency analysis
5. Boundary condition development
6. Example analysis results
7. Technical Q&A
8. Next steps

2

Introduction

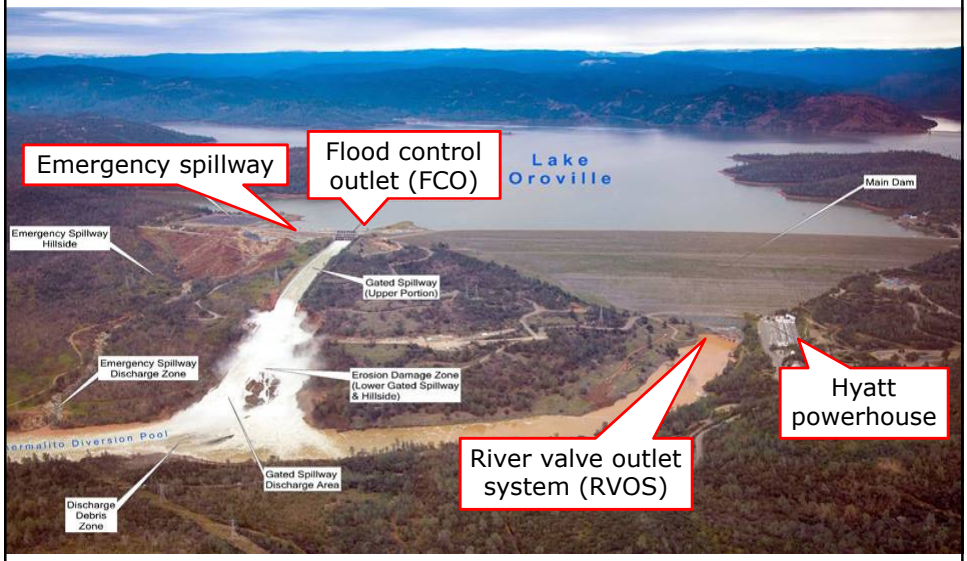
- Objective: Share analysis strategy
- Constraints: Not sharing results at this time, just methods

3

RELEVANT FEATURES OF OROVILLE DAM

4

Oroville outlets



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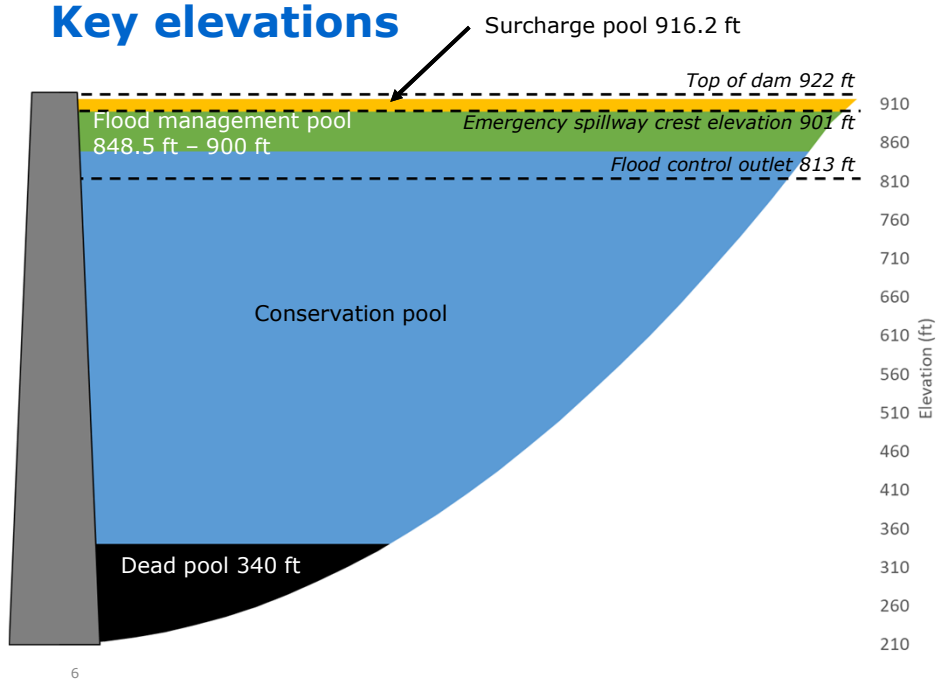
Key elevations



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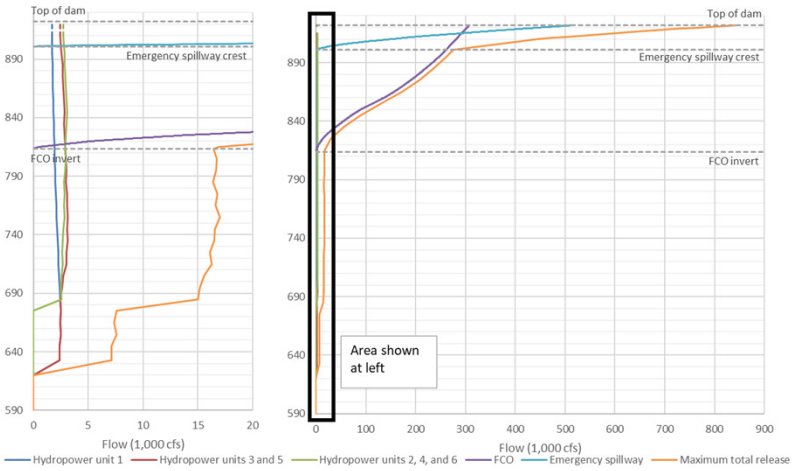
Outlet ratings



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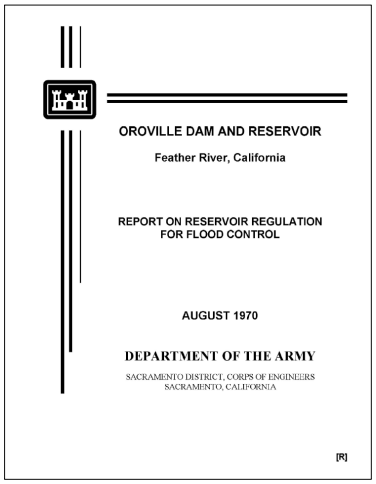
Operations governed by water control manual (1970)

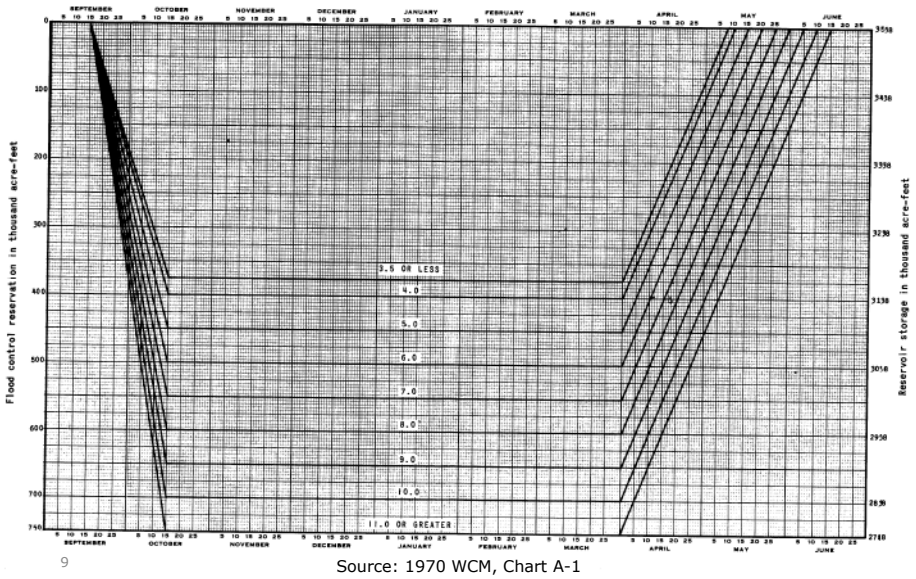


- Flood control diagram (FCD)
- Downstream flow constraints
- Release schedule
- Spillway release for dam safety (ESRD)

8

Flood control diagram (FCD)

-defines required flood management space

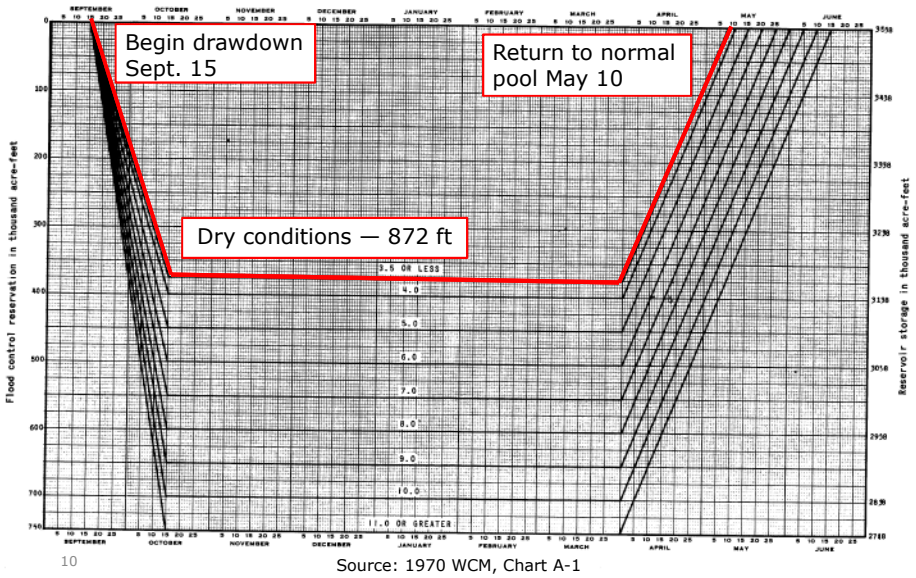


9

Source: 1970 WCM, Chart A-1

Flood control diagram (FCD)

-defines required flood management space

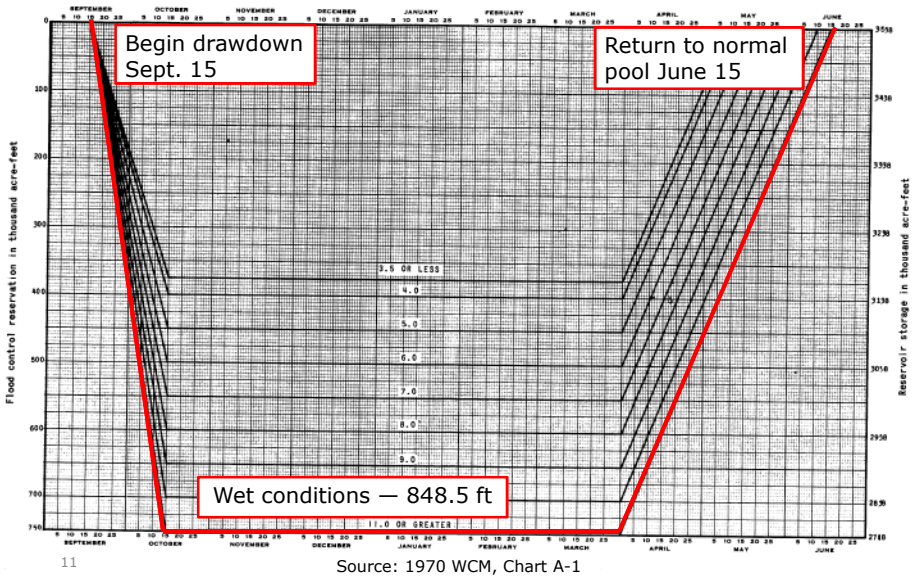


10

Source: 1970 WCM, Chart A-1

Flood Control Diagram (FCD)

-defines required flood management space



11

Source: 1970 WCM, Chart A-1

Use of FCD

1	Parameters are computed daily from the weighted accumulation of seasonal basin mean precipitation by multiplying the preceding day's parameter by 0.97 and adding the current day's precipitation in inches.	How to compute wetness index
2	Except when releases are governed by the emergency spillway release diagram currently in force, water stored in the flood control reservation, defined herein, shall be released as rapidly as possible, subject to the following conditions:	
a	That releases are made according to the release schedule herein.	Consider downstream channel capacities
b	That flows in Feather River above Yuba River do not exceed 180,000 cfs.	
c	That flows in Feather River below Yuba River do not exceed 300,000 cfs.	
d	That flows in Feather River below Bear River do not exceed 320,000 cfs insofar as possible.	
e	That releases are not increased more than 10,000 cfs or decreased more than 5,000 cfs in any 2-hr period.	Consider release rate of change

Source: 1970 WCM, Chart A-1

12

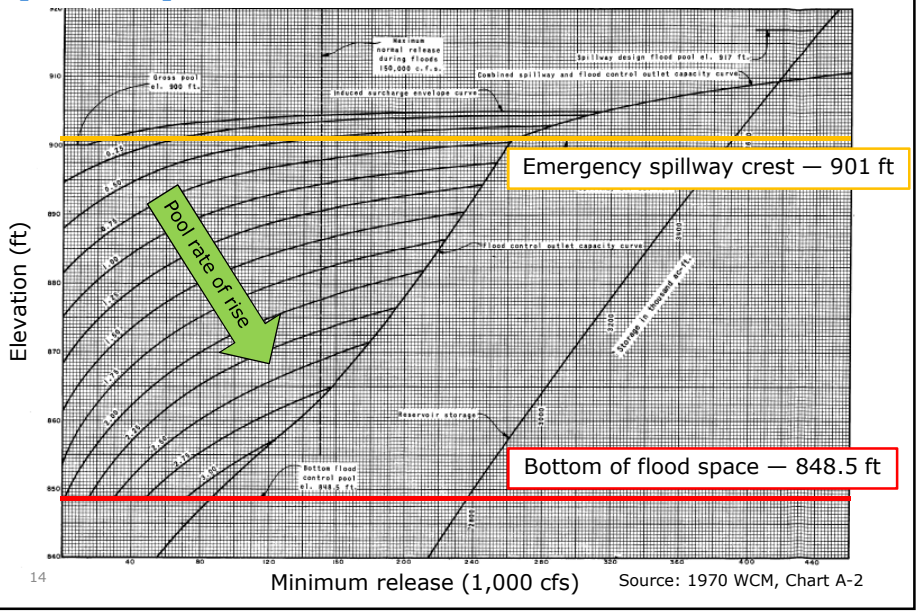
Flood release schedule

Inflow (cfs) (1)	Flood control space used (ac-ft) (2)	Required releases (cfs) (3)
0 – 15,000	0 – 5,000	Power demand
0 – 15,000	Greater than 5,000	Inflow
15,000 – 30,000	0 – 30,000	Lesser of 15,000 or maximum inflow
0 – 30,000	Greater than 30,000	Maximum inflow for flood
30,000 – 120,000	—	Lesser of maximum inflow or 60,000 cfs
120,000 – 175,000	—	Lesser of maximum inflow or 100,000 cfs
Greater than 175,000	—	Lesser of maximum inflow or 150,000 cfs

Source: 1970 WCM, Chart A-1

13

Spillway release for dam safety (ESRD)



14

Source: 1970 WCM, Chart A-2

How flood releases are made from Oroville Reservoir

Outlets

- Hyatt powerhouse
- Flood control outlet (FCO)
- Emergency spillway

Operations

- Governed by 1970 water control manual
  - Flood control diagram (FCD)
  - Downstream flow constraints
  - Release schedule
  - Spillway release for dam safety (ESRD)

15

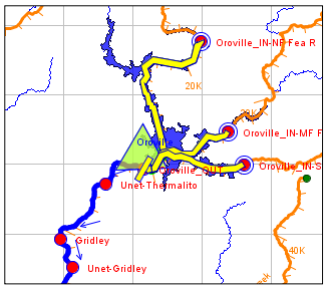
HEC-RESSIM MODEL

16

Reservoir simulation model overview

Why HEC-ResSim?

- Publicly available
- Widely tested
- Portable
- Corps accepted



Model history

- Developed and approved by USACE Sacramento District
- Modified for use by DWR for operation studies
- Adapted for recovery and interim operations efforts

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Physical features represented in HEC-ResSim model

- Storage-area-elevation curve
- Outlets
  - Hyatt powerhouse
    - 6 turbine units
    - Controlled flows, limited by individual rating curves
  - Flood control outlet (FCO)
    - Controlled flow, limited by a rating curve
  - Emergency spillway
    - Uncontrolled flow, using rating curve for weir
  - River valve outlet system (RVOS)
    - Controlled flow, limited by a rating curve

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Operations represented in HEC-ResSim model

- Spillway release for dam safety (ESRD)
- Rate-of-increase (ROI):
  max 5,000 cfs/hr
- Rate-of-decrease (ROD):
  max 2,500 cfs/hr
- Max flows for downstream channel capacities
- Inflow-based release schedule:
  max release = 150,000 cfs

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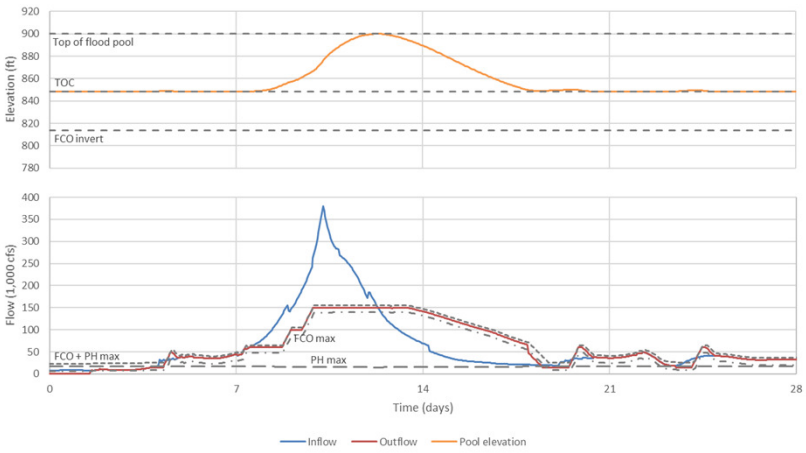
What does HEC-ResSim need for a simulation?

- Boundary conditions
  - Inflow hydrographs
- Initial conditions
  - Flood management space available (basin wetness)
  - Usable outlet capacities
    - Flood control outlet (FCO)
    - Powerhouse
    - River valve outlet system (RVOS)
  - Starting storage/elevation

20

HEC-ResSim results



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INFLOW VOLUME-FREQUENCY ANALYSIS AND BOUNDARY CONDITION DEVELOPMENT

22

Boundary conditions considered

- Frequency-based design hydrographs
- Standard project flood (SPF)
- Historical flow data
- Ensemble forecast flows: from National Weather Service California-Nevada River Forecast Center (CNRC)

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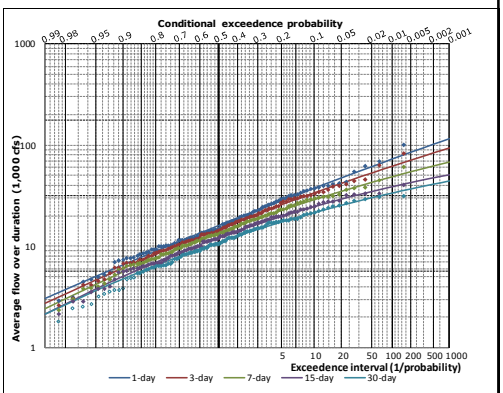
Inflow volume-frequency analysis

- Results and methods described in technical memo *SRT-RES-HY-02* (May 16, 2017)
- Developed Oroville inflow-volume frequency functions by month for 1-, 3-, 7-, 15-, and 30-day durations
- Followed standard of practice using 1902-2008 hydrologic dataset



Adopted statistics:

Duration	Mean	Std. dev.	Skew	Low outliers
1-day	4.199	0.295	-0.121	0
3-day	4.160	0.291	-0.226	0
7-day	4.116	0.280	-0.388	0
15-day	4.064	0.272	-0.521	14
30-day	4.017	0.258	-0.482	0

Oroville Reservoir
Conditional Unregulated Inflow Volume Frequency Curves: May

Notes:

- Median plotting positions.
- Drainage area: 3,639 sq. miles.
- Average basin elevation: 4,965 ft.
- Period of record: 1902-2008.
- Expected moments algorithm, multiple Grubbs-Beck test.
- Events extracted by month with a 15-day buffer window before and after.
- Skew manually adjusted: 30-day.
- Hollow points are censored low outliers.

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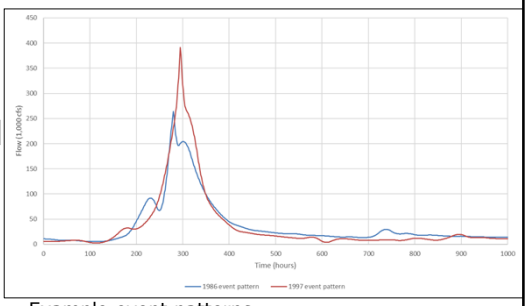
Design hydrograph development

1. Obtain Lake Oroville unregulated inflow hydrographs from CVHS for the 1986 and 1997 events

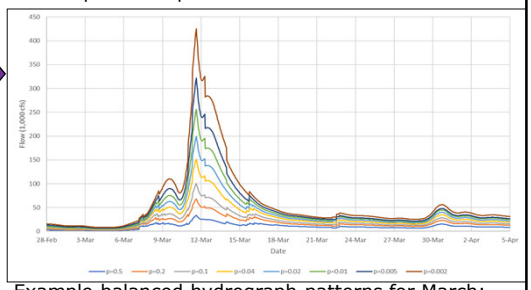
2. Assign the hydrographs to occur in each month for the subsequent reservoir operation simulations

3. Adjust the hydrographs to reflect a wide range of events

4. Adopt the set of hydrographs



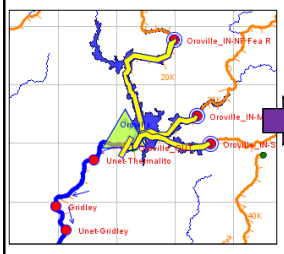
Example event patterns



Example balanced hydrograph patterns for March: 1986 event

25

Analysis strategy

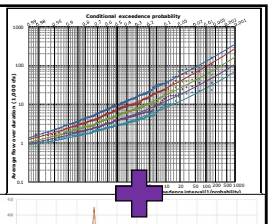


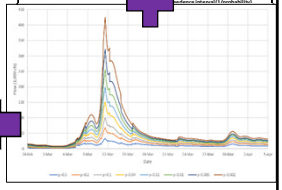
1. Develop the HEC-ResSim reservoir operation model

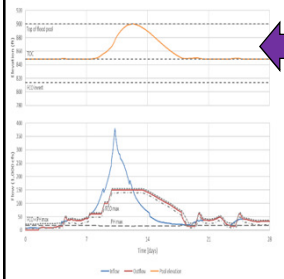
2. Configure the model with the frequency-based hydrographs

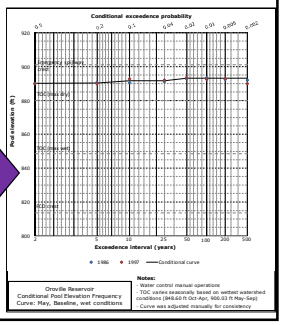
3. Simulate operation and determine maximum pool elevation

4. Develop the baseline maximum pool elevation-frequency curves









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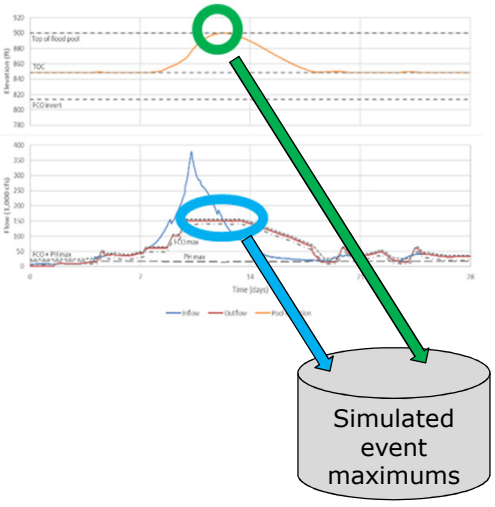
EXAMPLE ANALYSIS RESULTS

27

Pool elevation and outflow frequency



1. Simulate, then identify the max pool elevation and release from the October simulation results of the 1986 pattern for the 2-yr design event
2. Repeat step 1 for 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr design events
3. Repeat steps 1 and 2 for the 1997 pattern
4. Average 1986 and 1997 results by return interval to develop frequency
5. Repeat for the other months

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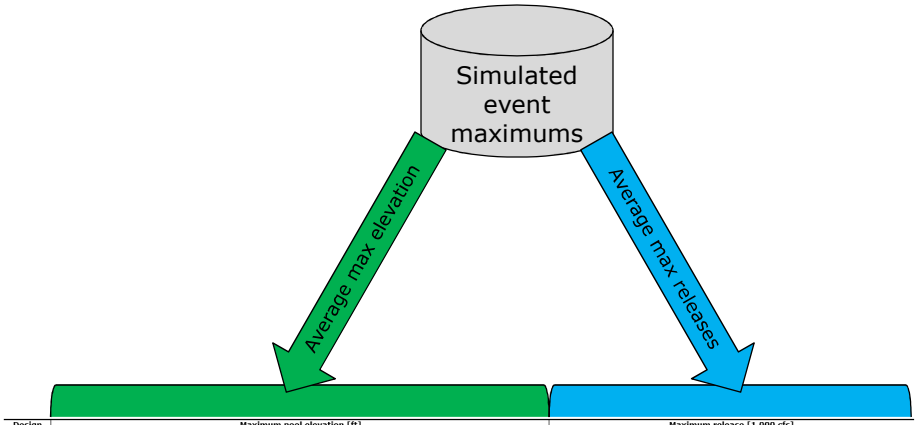
Example analysis results



Design event return interval[1] (1)	Maximum pool elevation [ft]													Maximum release [1,000 cfs]										
	Oct. (2)	Nov. (3)	Dec. (4)	Jan. (5)	Feb. (6)	Mar. (7)	Apr. (8)	May (9)	Jun. (10)	Jul. (11)	Aug. (12)	Sep. (13)	Oct. (14)	Nov. (15)	Dec. (16)	Jan. (17)	Feb. (18)	Mar. (19)	Apr. (20)	May (21)	Jun. (22)	Jul. (23)	Aug. (24)	Sep. (25)
2	870.90	848.50	851.95	851.95	851.95	852.30	868.77	890.07	900.03	900.03	900.03	900.03	15	15	60	60	60	60	15	15	14	10	8	15
5	870.90	850.38	861.13	861.13	858.81	855.82	868.91	890.40	900.19	900.03	900.03	900.03	15	15	60	60	60	60	60	57	18	14	9	15
10	870.90	850.38	861.13	861.13	858.81	859.02	870.89	891.66	900.26	900.04	900.03	900.03	15	60	100	100	100	60	60	58	52	16	10	15
25	870.90	851.72	866.20	866.20	865.08	859.87	872.44	891.66	900.55	900.17	900.03	900.03	60	60	150	150	150	100	60	59	50	19	11	15
50	870.90	855.50	873.54	873.54	873.54	865.52	872.90	893.13	900.60	900.40	900.03	900.12	60	60	150	150	150	125	100	60	46	21	12	18
100	870.90	857.26	884.78	884.78	884.78	870.06	872.90	893.13	900.70	900.70	900.03	900.45	60	100	150	150	150	150	100	60	52	25	13	31
200	872.56	861.50	900.59	900.59	900.59	880.55	872.90	893.13	900.70	900.86	900.03	900.61	60	145	150	150	150	150	150	60	57	50	14	58
500	880.02	874.26	905.19	905.19	905.19	904.26	882.04	893.13	900.70	900.86	900.03	901.53	150	150	267	267	267	181	150	60	60	54	16	67

1. For example, 100 means the pool elevation would exceed 870.9 ft in 1 out of 100 Octobers.

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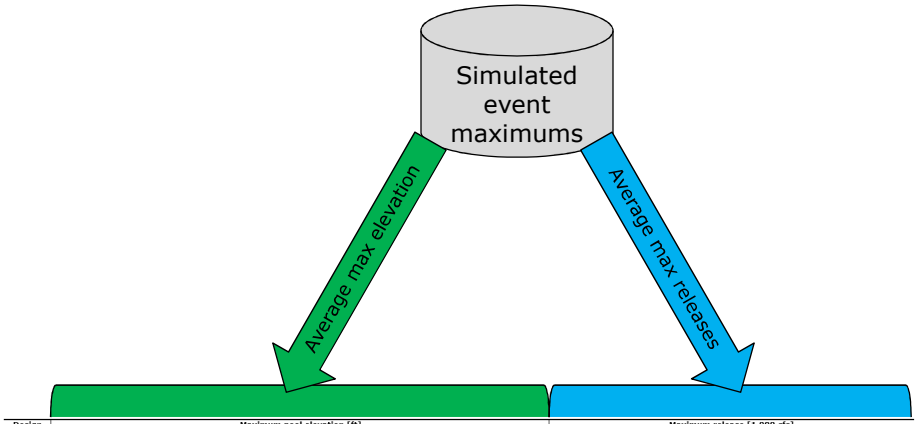
Example analysis results



Design event return interval[1] (1)	Maximum pool elevation [ft]													Maximum release [1,000 cfs]										
	Oct. (2)	Nov. (3)	Dec. (4)	Jan. (5)	Feb. (6)	Mar. (7)	Apr. (8)	May (9)	Jun. (10)	Jul. (11)	Aug. (12)	Sep. (13)	Oct. (14)	Nov. (15)	Dec. (16)	Jan. (17)	Feb. (18)	Mar. (19)	Apr. (20)	May (21)	Jun. (22)	Jul. (23)	Aug. (24)	Sep. (25)
2	870.90	848.50	851.95	851.95	851.95	852.30	868.77	890.07	900.03	900.03	900.03	900.03	15	15	60	60	60	60	15	15	14	10	8	15
5	870.90	850.38	861.13	861.13	858.81	855.82	868.91	890.40	900.19	900.03	900.03	900.03	15	15	60	60	60	60	60	57	18	14	9	15
10	870.90	850.38	861.13	861.13	858.81	859.02	870.89	891.66	900.26	900.04	900.03	900.03	15	60	100	100	100	60	60	58	52	16	10	15
25	870.90	851.72	866.20	866.20	865.08	859.87	872.44	891.66	900.55	900.17	900.03	900.03	60	60	150	150	150	100	60	59	50	19	11	15
50	870.90	855.50	873.54	873.54	873.54	865.52	872.90	893.13	900.60	900.40	900.03	900.12	60	60	150	150	150	125	100	60	46	21	12	18
100	870.90	857.26	884.78	884.78	884.78	870.06	872.90	893.13	900.70	900.70	900.03	900.45	60	100	150	150	150	150	100	60	52	25	13	31
200	872.56	861.50	900.59	900.59	900.59	880.55	872.90	893.13	900.70	900.86	900.03	900.61	60	145	150	150	150	150	150	60	57	50	14	58
500	880.02	874.26	905.19	905.19	905.19	904.26	882.04	893.13	900.70	900.86	900.03	901.53	150	150	267	267	267	181	150	60	60	54	16	67

1. For example, 100 means the pool elevation would exceed 870.9 ft in 1 out of 100 Octobers.

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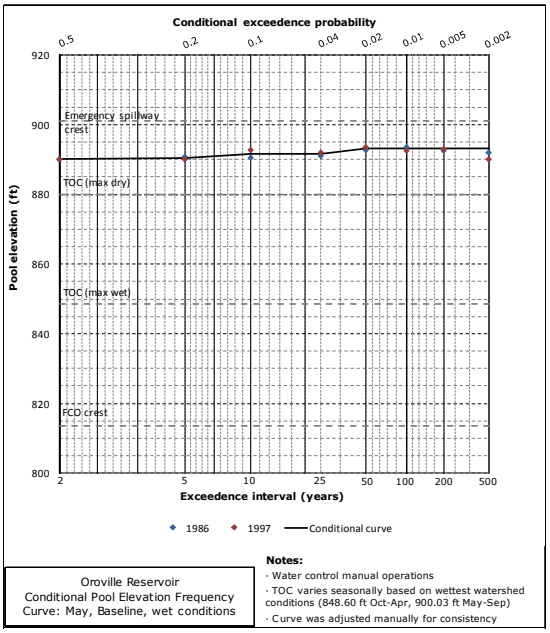
Example elevation-frequency curve

Design event return interval[1] (1)	Maximum pool elevation (ft) (2)	Maximum release (1,000 cfs) (3)
2	890.07	15
5	890.40	57
10	891.66	58
25	891.66	59
50	893.13	60
100	893.13	60
200	893.13	60
500	893.13	60

1. For example, 100 means the pool elevation would exceed 893.13 ft in 1 out of 100 Mays.



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Technical Q&A

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Next steps

- Finalize operations strategy
- Complete analysis
- Document findings

33

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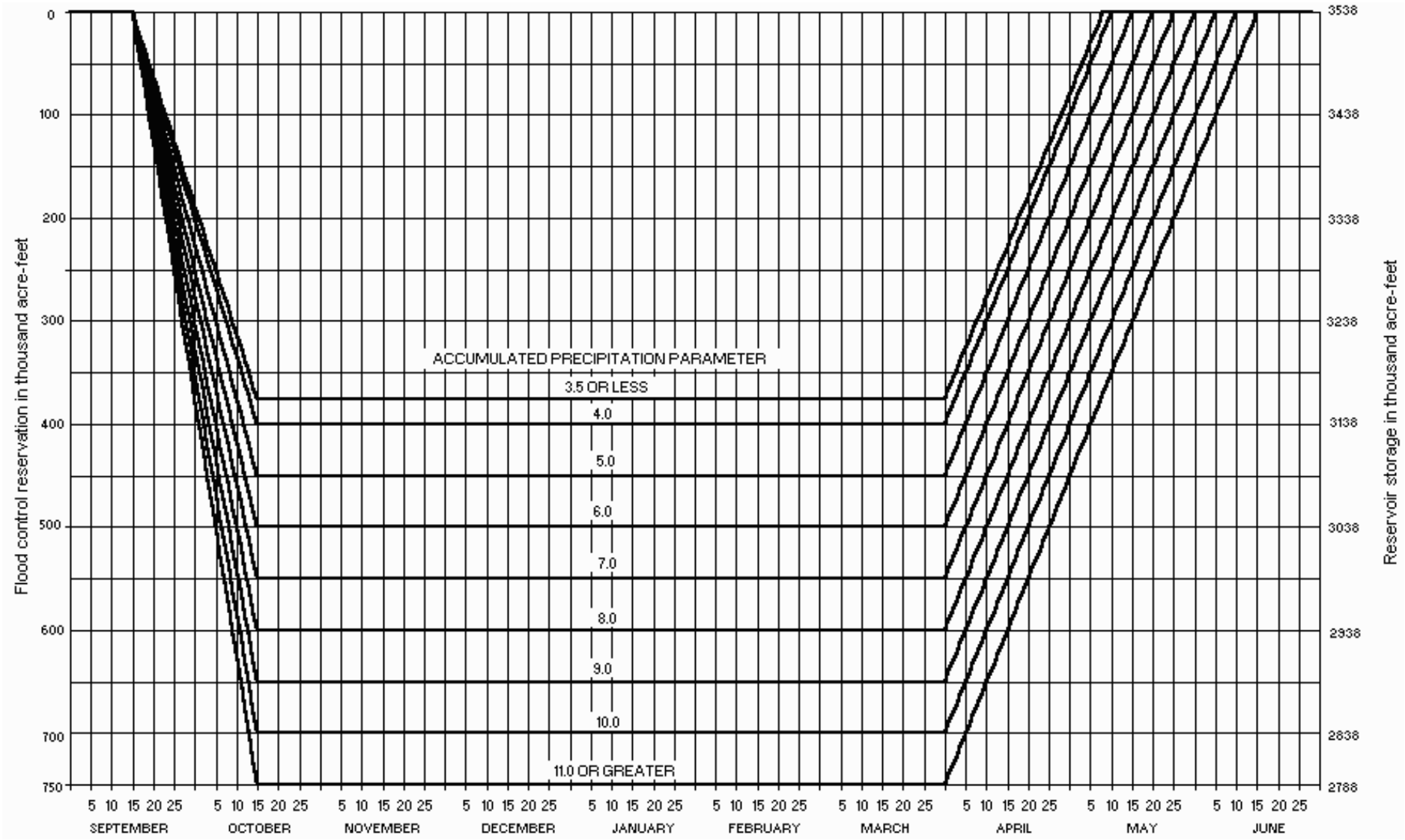
APPENDIX B

Department of the Army, Corps of Engineers
Sacramento District, Sacramento, CA
Oroville Flood Control Diagram



Feather River Minimum Flow Criteria – Low Flow Channel
600 cfs

Feather River Maximum Rate of Change - Low-Flow Channel	
Feather River Release (cfs)	**Rate of Decrease (cfs)**
5,000 - 3,501	1,000 per 24-hours
3,500 - 2,501	500 per 24-hours
2,500 - 600	300 per 24-hours

Feather River Minimum Flow Criteria below Thermalito Afterbay[1]			
Preceding April through July Unimpaired Feather River Runoff near Oroville, Percent of Normal Runoff	Minimum Flow October through February	Minimum Flow March	Minimum Flow April through September
55% or greater	1,700 cfs	1,700 cfs	1,000 cfs
Less than 55%	1,200 cfs	1,000 cfs	1,000 cfs

[1]If the April runoff forecast in a given water year indicates that under normal operation of the State Water Project the reservoir level will be drawn down to elevation 733 feet (approximately 1,500,000 acre-feet), releases for fish life in the above-referenced schedule may experience monthly deficiencies in the same proportion as the respective monthly deficiencies imposed on water deliveries for agricultural use from the Project. However, in no case shall the fish water releases in the above schedule be reduced by more than 25 percent.

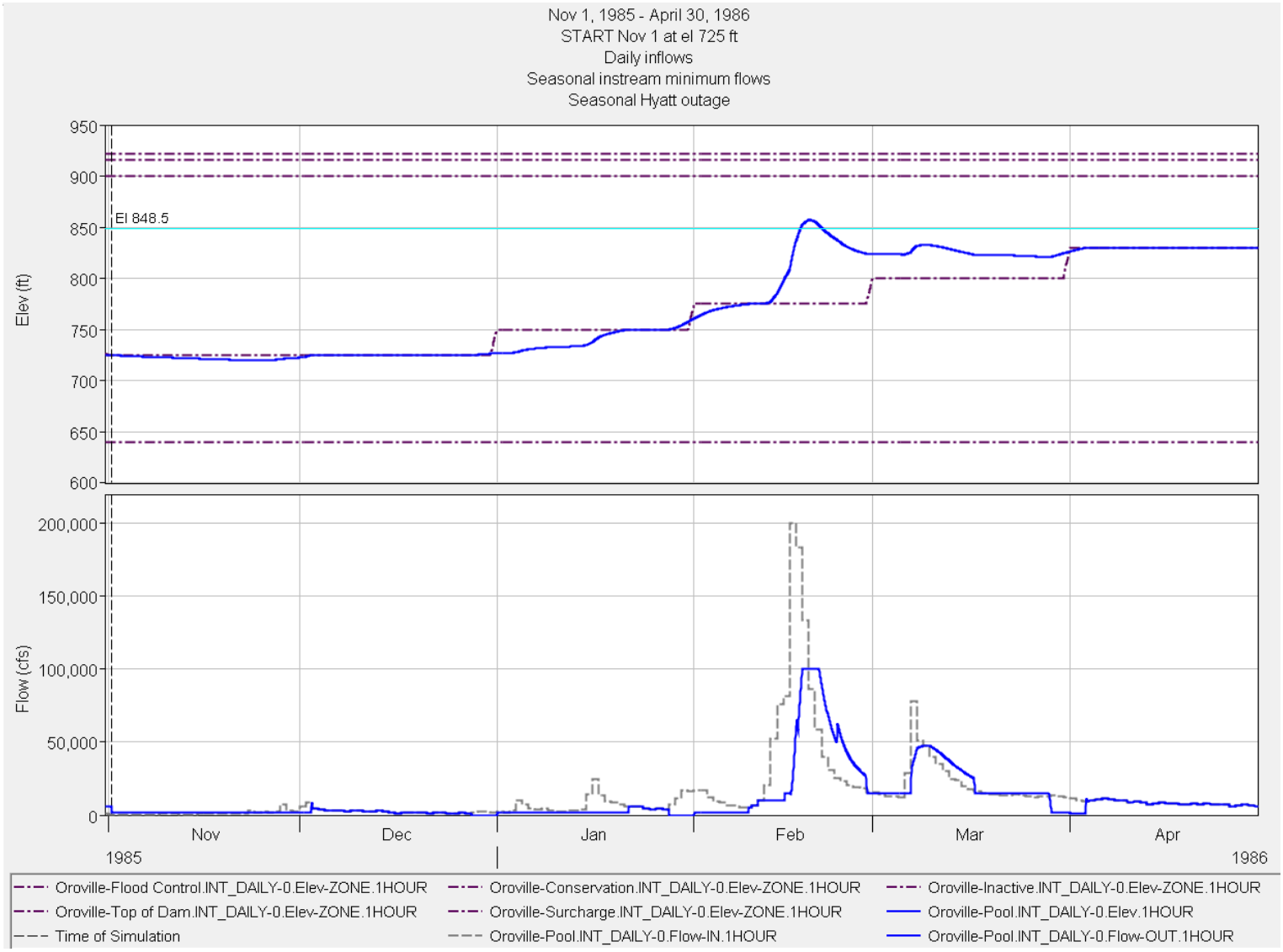
1. Preceding April through July Unimpaired Runoff as computed for inclusion in Department of Water Resources Bulletin 120, "Water Conditions in California – Fall Report".
2. Normal runoff is defined as the April through July 1911-1960 mean unimpaired runoff near Oroville of 1,942,000 acre-feet.
3. Referenced flows are to be maintained below said outlet to the mouth of the Feather River at Verona, provided that such additional releases will not cause Oroville Reservoir to be drawn down below elevation 733 feet (approximately 1,500,000 acre-feet).

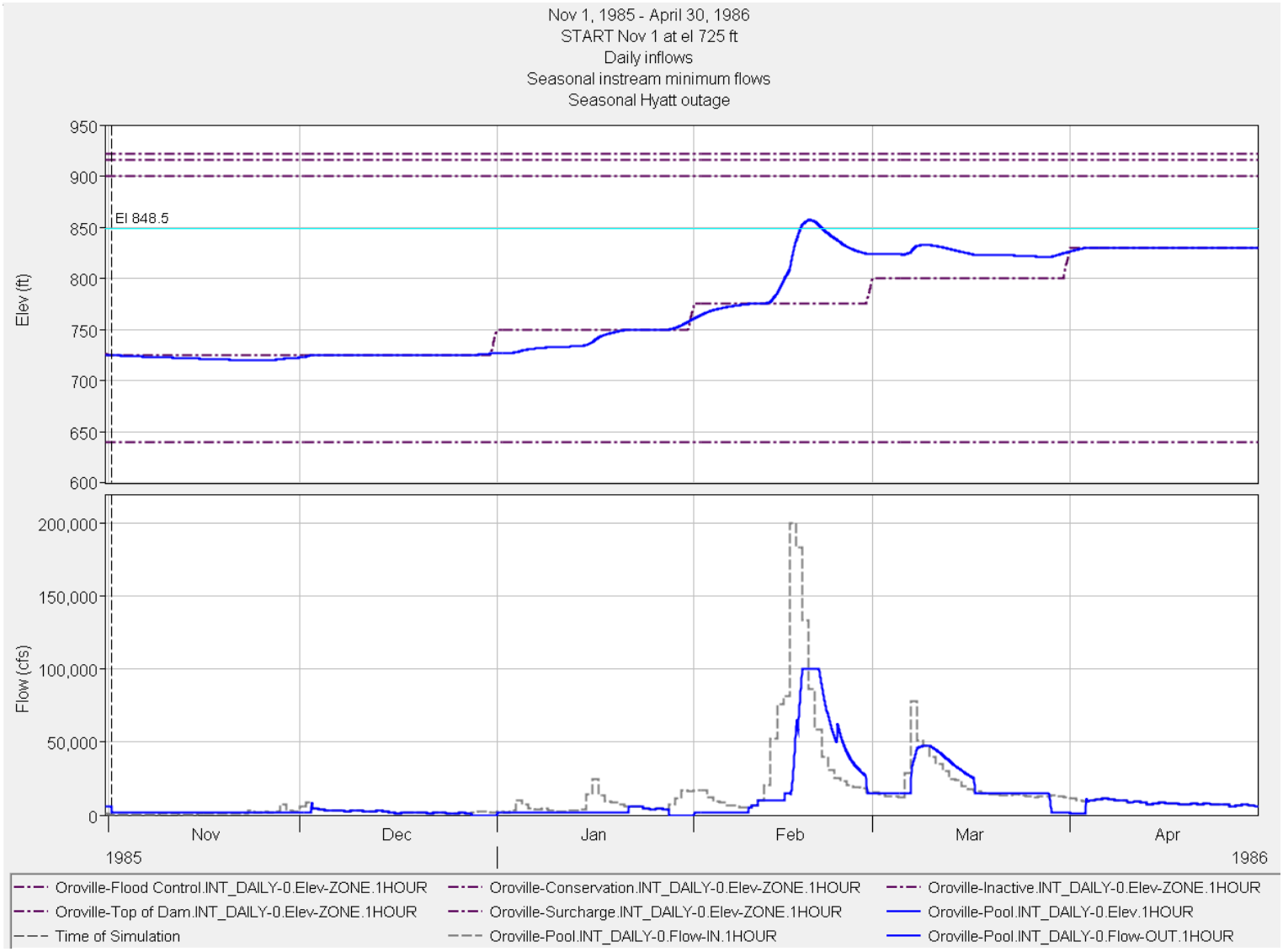
Feather River Rate of Change Below Thermalito Afterbay River Outlet (cfs)	**Rate of Decrease (cfs)**
2,500 or less	200 per 24-hours

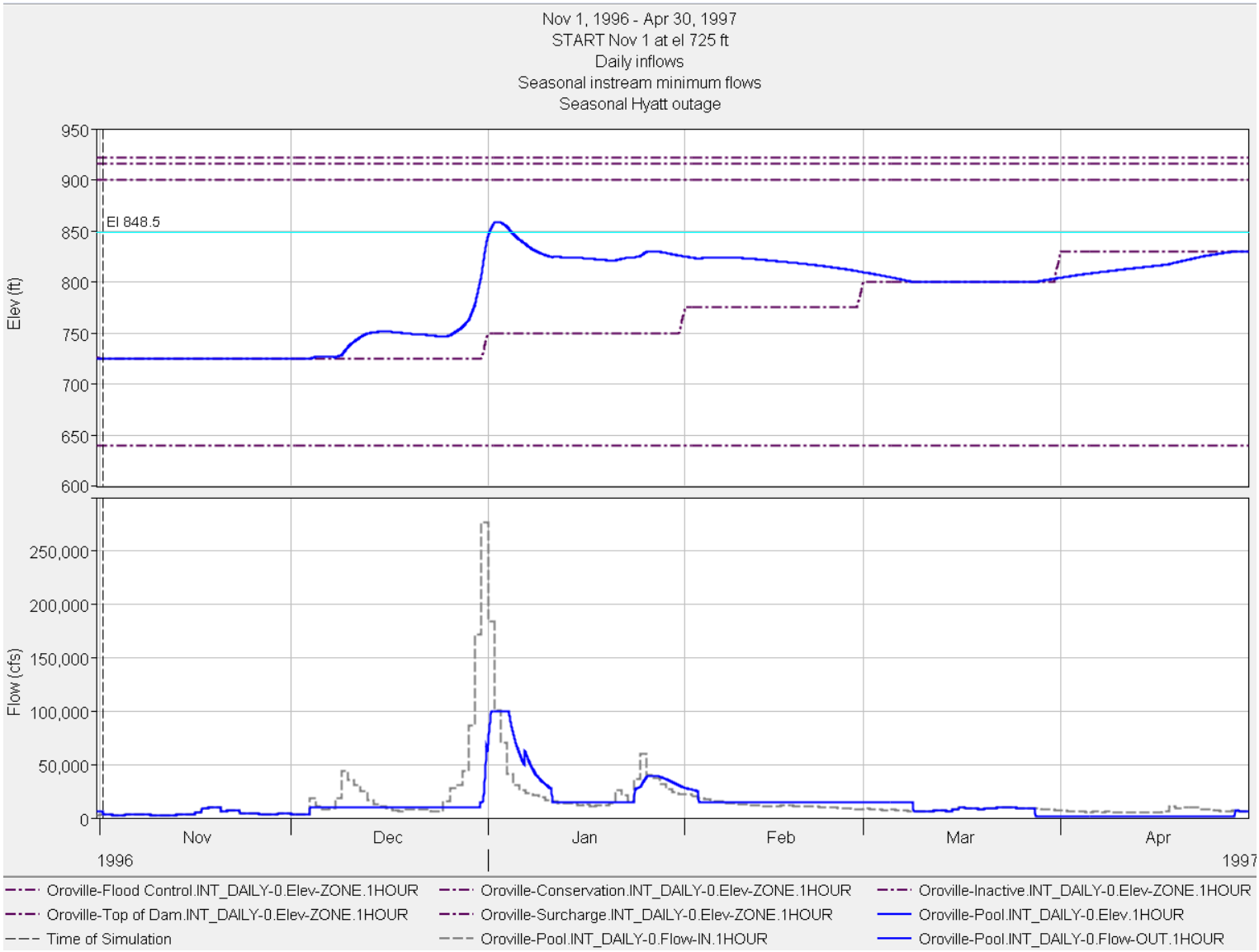
If the average flow of the combined releases into the Feather River during the period of October 15th through November 30th of each year exceeds 2,500 cfs, except due to flood control releases, accident, Project failure, major or unusual maintenance, the minimum flow in the Feather River for fishery purposes will be modified as follows:

If Average Feather River Flow Within Any 1-hour Period	**Minimum Flow, October 1 through March 31**
Exceeds 2,500 cfs	Not less than 500 cfs below the average highest 1-hour flow

Flood Control Release Rate of Change	Rate (cfs)
Maximum Increase	10,000 per 2-hours
Maximum Decrease	5,000 per 2-hours


Nov 1, 1985 - April 30, 1986
START Nov 1 at el 725 ft
Daily inflows
Seasonal instream minimum flows
Seasonal Hyatt outage
Elev (ft)
950
900
850
800
750
700
650
600
El 848.5
Flow (cfs)
200,000
150,000
100,000
50,000
0
Nov
Dec
Jan
Feb
Mar
Apr
1985
1986
Oroville-Flood Control.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Conservation.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Inactive.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Top of Dam.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Surcharge.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Pool.INT_DAILY-0.Elev.1HOUR
Time of Simulation
Oroville-Pool.INT_DAILY-0.Flow-IN.1HOUR
Oroville-Pool.INT_DAILY-0.Flow-OUT.1HOUR


Nov 1, 1985 - April 30, 1986
START Nov 1 at el 725 ft
Daily inflows
Seasonal instream minimum flows
Seasonal Hyatt outage
Elev (ft)
950
900
850
800
750
700
650
600
El 848.5
Flow (cfs)
200,000
150,000
100,000
50,000
0
Nov
Dec
Jan
Feb
Mar
Apr
1985
1986
Oroville-Flood Control.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Conservation.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Inactive.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Top of Dam.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Surcharge.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Pool.INT_DAILY-0.Elev.1HOUR
Time of Simulation
Oroville-Pool.INT_DAILY-0.Flow-IN.1HOUR
Oroville-Pool.INT_DAILY-0.Flow-OUT.1HOUR


Nov 1, 1996 - Apr 30, 1997
START Nov 1 at el 725 ft
Daily inflows
Seasonal instream minimum flows
Seasonal Hyatt outage
Elev (ft)
950
900
850
800
750
700
650
600
El 848.5
Flow (cfs)
250,000
200,000
150,000
100,000
50,000
0
Nov
Dec
Jan
Feb
Mar
Apr
1996
1997
Oroville-Flood Control.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Conservation.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Inactive.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Top of Dam.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Surcharge.INT_DAILY-0.Elev-ZONE.1HOUR
Oroville-Pool.INT_DAILY-0.Elev.1HOUR
Time of Simulation
Oroville-Pool.INT_DAILY-0.Flow-IN.1HOUR
Oroville-Pool.INT_DAILY-0.Flow-OUT.1HOUR