Accounting for Uncertainty of Ensemble Streamflow Predictions in the Operations of Prado Reservoir in Riverside County, California

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Abstract

Forecast-Informed Reservoir Operations (FIRO) is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts. This study evaluated the forecast uncertainty quantified in ensemble streamflow predictions (ESPs) made by NOAA's California-Nevada River Forecast Center (CNRFC) to inform reservoir releases. A water management model was developed to simulate forecast-informed alternatives for Prado Reservoir, located in Riverside County, California, that is owned by the U.S. Army Corps of Engineers (USACE). Prado Reservoir is maintained dry for most of the year, however, during storm events, the USACE and Orange County Water District (OCWD) collaborate to temporarily detain and release stormwater at a rate that supports OCWD's managed aquifer recharge system downstream of Prado Dam. Reservoir operations were simulated for Prado Reservoir using a 30-year (1990-2019) ESP hindcast generated by the CNRFC. For each forecast cycle within the hindcast period, each member of an ESP is individually modeled to generate a storage ensemble forecast. A management policy was developed that evaluates the risk of exceeding critical storage thresholds. The goals of this policy were to minimize risk of uncontrolled spillway releases that can result in flooding of properties downstream, minimize high storage levels that cause flooding of properties within the reservoir, and maximize stormwater capture for water supply. Simulations of this forecast-informed policy yield higher storage levels during the flood season while maintaining flood storage by pre-releasing water in advance of large, forecasted storms. As a result of the higher storage levels maintained in the reservoir, additional water is available for release to OCWD's recharge facilities. Model results also show a decrease in the frequency of inundation of properties within the lower elevations of the reservoir and no increase in the frequency of spillway releases that could cause downstream flooding. These investigations demonstrate that the developed policy may be a viable flood risk management approach for Prado Reservoir and warrants further investigation through additional modeling and analysis.

Introduction

To address the severe flood threat posed by the Santa Ana River (SAR), Prado Dam was constructed by U.S. Army Corps of Engineers (USACE) in 1941. Prado Dam is located at the upper end of the Lower Santa Ana River Canyon, which is a natural constriction in the 6,345 2,450 mi^2 SAR watershed. The dam is located approximately 31 mi upstream of the Pacific Ocean. Figure 1 shows the location of the dam in relation to the SAR watershed. The dam is a "dry" dam in that it only contains water during the flood season, which generally occurs from October through March. For most of the year, there is no impoundment of water behind the dam. The dam is an earthen dam that is 124 ft high, 2,289 ft long and 30 ft wide at its crest. The total storage capacity up to the current spillway is 173,000 ac-ft.

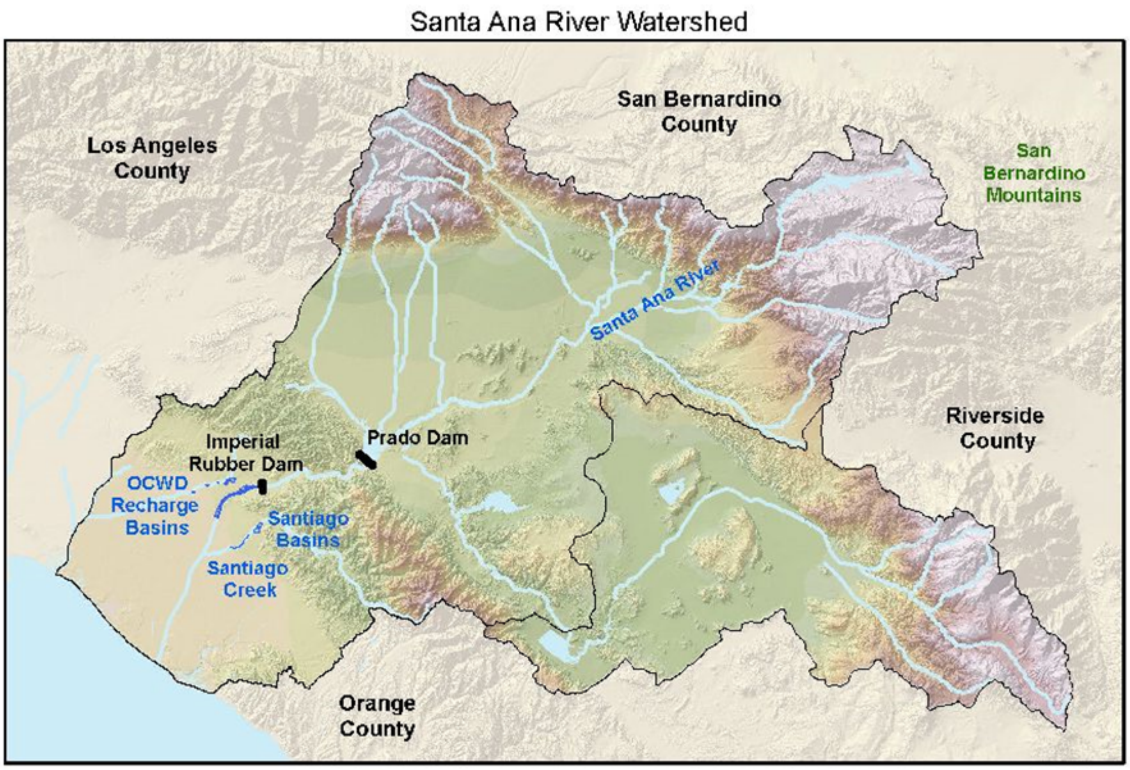

Figure 1. Santa Ana River Watershed and Location of Prado Dam (graphic provided by OCWD).

The Orange County Water District (OCWD) has been capturing and recharging stormwater from the Santa Ana River (SAR) since 1936. Since its construction, OCWD has worked collaboratively with the USACE to utilize Prado Dam to temporarily impound storm water, which is then released at a rate that can be diverted into OCWD's Managed Aquifer Recharge (MAR) system for recharge. Over the past 25 years, OCWD has recharged an average of 55,000 acre-feet (ac-ft) per year of stormwater with an annual maximum of 117,000 ac-ft in 1995. For planning purposes, OCWD assumes that 40,000 ac-ft of stormwater will be captured and recharged in an average year, which is enough water for 320,000 people annually. Local stormwater capture is important because it lessens demands on imported water supplies, which are more costly and increasingly unreliable. A schematic diagram of Prado Dam is provided in Figure 2 that depicts the coordinated operations of Prado Dam to support groundwater recharge operations as well as other constraints that affect the operations of the reservoir.

For water conservation, the USACE allows water to be stored up to elevation 505 ft. (19,500 ac-ft) to be temporarily impounded in what is called the "Buffer Pool." The Buffer Pool can be drained and refilled multiple times in a storm season if there is sufficient rainfall and downstream recharge capacity. The USACE releases water from the Buffer Pool at a rate that can be diverted and recharged by OCWD.

Prado Dam was primarily constructed to reduce flood risk to downstream reaches of the SAR, however since the construction of Prado Dam, infrastructure has been constructed within the flood pool of the reservoir (elevation 505 to 543 ft.). When water is impounded in the reservoir flood pool as part of the semi-routine flood control operations of the dam during the wet season, these structures can be temporarily flooded. Most notably a small municipal airport, Riverside Municipal Airport, was constructed in 1956 that is impacted from the encroachment of water in the flood pool above elevation 514 ft (as shown in Figure 2).

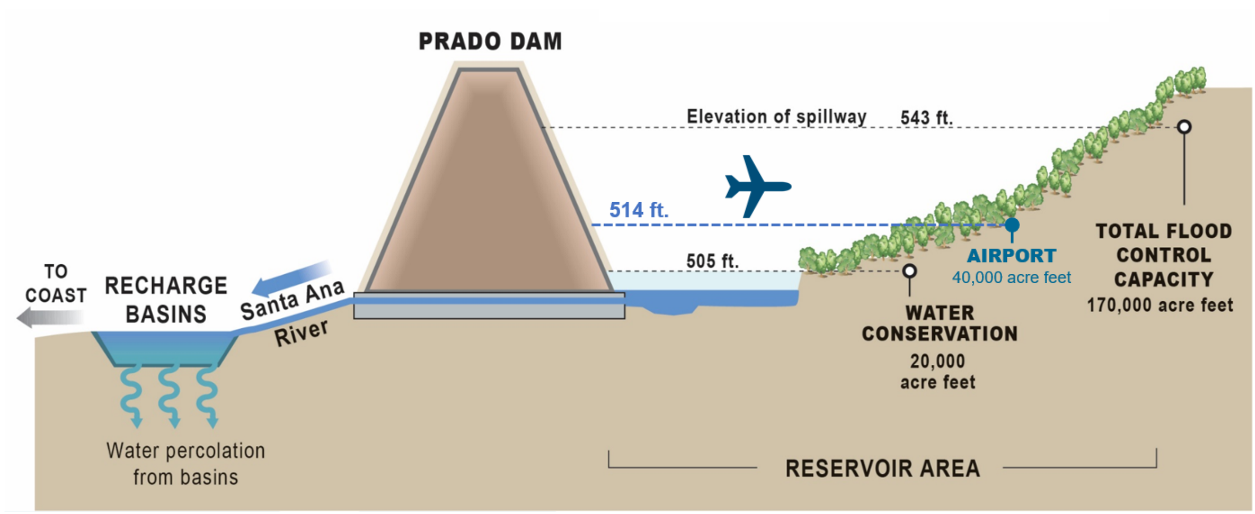

Figure 2. Schematic diagram of Prado Dam depicting the important issues and operational constraints that influence reservoir management.

Forecast Informed Reservoir Operations

The Prado Dam Water Control Manual currently does not account for weather or runoff forecasts in the determination of release rates. Release rates are primarily determined by the water surface elevation in the reservoir (USACE, 2021). Forecast Informed Reservoir Operations (FIRO) is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts (AMS, 2021). To explore FIRO as a viable approach to increase the efficiency of stormwater capture at Prado Dam, Steering Committee was formed with co-chairs from OCWD and the Center for Western Weather and Water Extremes (CW3E) at UC San Diego's Scripps Institution of Oceanography. Steering Committee members include major stakeholders including the USACE, the United States Fish and Wildlife Service, the

National Weather Service's California Nevada River Forecast Center (CNRFC), the California Department of Water Resources, and Orange County Public Works.

Using a collaborative Steering Committee process, FIRO has proven viable on Lake Mendocino in Northern California and is currently being assessed in the Yuba and Feather River watersheds, at New Bullards Bar Reservoir and Lake Oroville. The Prado Dam FIRO Steering Committee process is a phased approach that began with a scoping study to assess FIRO viability and then progressed to a Preliminary Viability Assessment (PVA). The PVA was published in July 2021 (Ralph, et al, 2021). A Final Viability Assessment (FVA) will be completed in 2023. The PVA provides an initial evaluation of the viability of FIRO as a strategy for improving water supply reliability for OCWD, while not impairing, and possibly, enhancing flood risk management.

Ensemble Forecast Operations

To evaluate FIRO at Prado Dam for the PVA a risk-based approach of reservoir flood control operations, Ensemble Forecast Operations (EFO), was evaluated that incorporates ensemble streamflow predictions (ESPs) made by the CNRFC. With EFO, each member of an ensemble streamflow prediction is individually modeled to forecast system conditions and the risk of exceeding the spillway crest of Prado Dam. Reservoir release decisions are simulated to manage forecasted risk with respect to established risk tolerance levels. For the PVA, EFO was simulated using a 27-year (1985-2011) ESP hindcast generated by the CNRFC with the Hydrologic Ensemble Forecast System (HEFS) (Demargne et al., 2014), which provides 61-member ensembles of 15-day flow forecasts.

To demonstrate how the EFO model uses the ensemble steam flow predictions to formulate a reservoir release, Figure 4 presents an example from the January 5, 2005 hindcast scaled to a 1 in 100-year frequency. The top panels of Figure 3 show the ensemble of forecasted storage levels of Prado Reservoir, and the bottom panels show forecasted risk of exceeding the spillway crest. The left-side panels show forecasted conditions before a release is formulated (assuming no release) and how forecasted risk (red line) exceeds the risk tolerance curve (blue dashed line). The EFO model formulates the required release to reduce storage levels and mitigate the forecasted risk (shown in the right-side panels), which is 10,000 cubic feet per second (cfs) for this example.

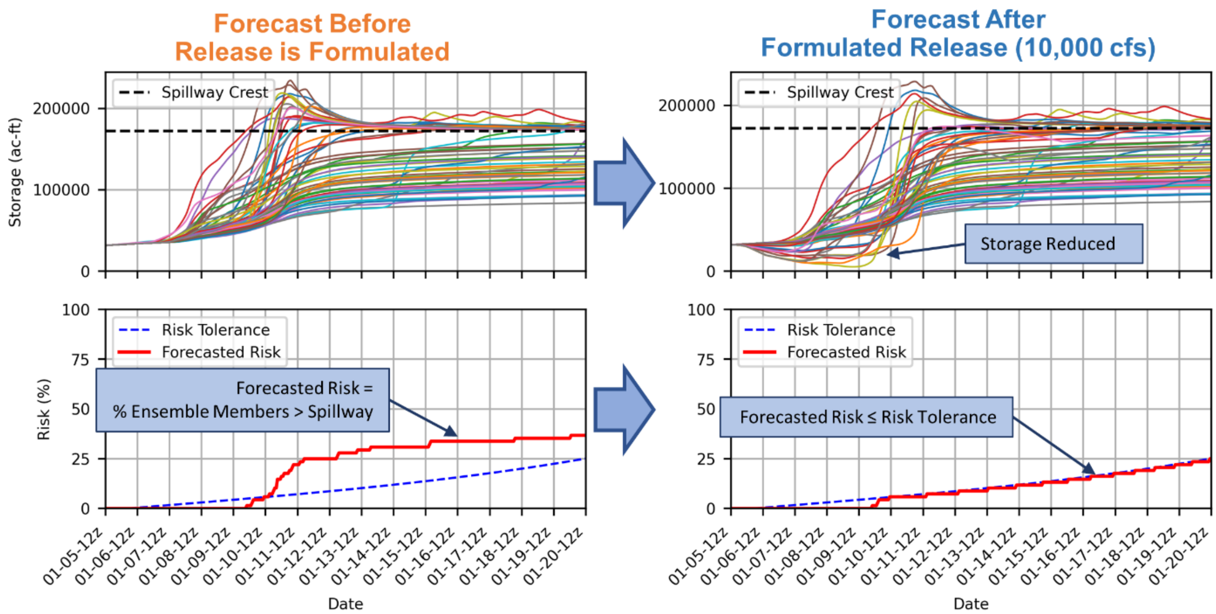

Figure 3. EFO model example forecast for the January 5, 2005 hindcast.

FIRO alternatives were evaluated that set a higher buffer pool (elevations 508 and 512 ft.), to retain additional water to support downstream groundwater recharge operations. The increased risk of overtopping the spillway due to the storage of additional water with the FIRO alternatives was mitigated by using the EFO methodology to strategically pre-release water in advance of forecasted storm events based on forecasted risk of exceeding the spillway crest. Simulations of the FIRO alternatives generally yield higher storage levels during the flood management season while maintaining flood storage capacity by strategically pre-releasing water in advance of large, forecasted storms. As a result of the higher storage levels maintained in the reservoir under EFO, additional water is available for release to OCWD's MAR system. Simulation of the FIRO alternatives from the PVA also showed an increased frequency of flooding the Riverside Municipal Airport, which was identified as a potential impact of FIRO.

Dual Objective Flood Risk Management

The Prado Dam FIRO Steering Committee is currently working to prepare the FVA, which builds on the work completed in the PVA to complete a thorough evaluation of the viability of FIRO at Prado Dam. As part of the water resources engineering analysis of FIRO alternatives at Prado Dam, CW3E is exploring alternatives that utilize the EFO methodology that manage for 2 flood risk objectives: 1) manage to risk of forecasted storage exceeding the spillway as evaluated in the PVA, and 2) manage to risk of forecasted storage exceeding the airport at elevation 514 ft. An example forecast for this alternative is shown in Figure 4 for February 19, 1998. The top panel shows the ensemble storage forecast using the CNRFC HEFS hindcast for the 1998 flood event scaled to a 1 in 200-year magnitude. The bottom shows the forecasted risk for both flood management objectives. The solid red line of the bottom panel is the forecasted risk of exceeding the spillway crest and corresponding risk tolerance as the dashed red line. The solid blue line of the bottom panel is the forecasted risk of exceeding elevation 514 ft. and corresponding risk tolerance as the dashed blue line. The model evaluates the required release to mitigate the forecasted risk to at or below their respective risk tolerance curves for each of the flood objectives and implements the highest release of the two objectives.

For the example forecast provided in Figure 4, the model estimates a release of 5,000 cfs to mitigate risk of flooding the airport (the defined maximum release for managing airport flooding), and a release of 10,000 cfs to mitigate risk of storage cresting above the uncontrolled spillway, which is the defined maximum release for managing for spillway releases. In this case the model implements the 10,000 cfs since that is the highest release of the management objectives.

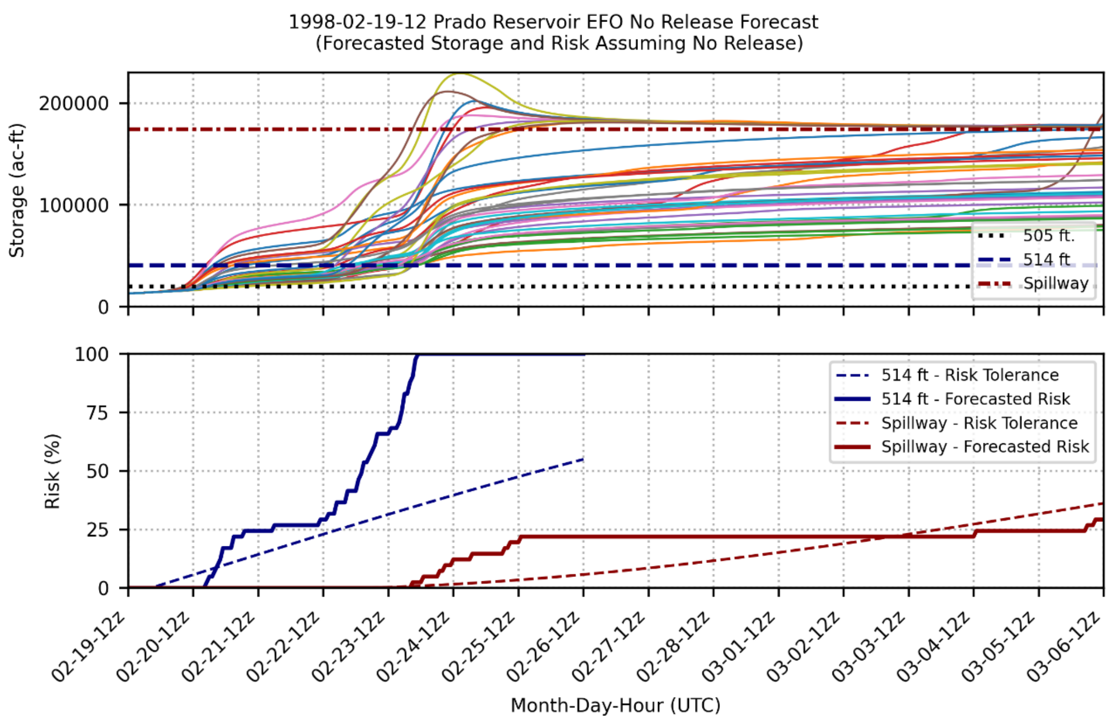

Figure 4. Dual objective EFO example forecast using the February 19, 1998 hindcast scaled to a 200-year return period prepared by the CNRFC .

Simulation of FIRO at Prado Dam

Four alternatives were simulated at Prado Dam using the EFO Model, a model developed to simulate the EFO methodology as well as non-forecast-based alternatives. The alternatives evaluated in the study are summarized below:

1. WCM – Simulates operations consistent with the Prado Dam Water Control Manual with a buffer pool elevation of 505 ft. (20,000 ac-ft),
2. EFO – Simulates operations consisted with the EFO methodology as previously described, with an increased buffer pool elevation of 514-ft. (40,500 ac-ft storage) for improved water supply, and uses ensemble forecasts to manage for flooding within the reservoir at the airport and minimize uncontrolled spillway releases,

3. PFO – Consistent with the EFO alternative but uses observed reservoir inflows in place of hindcasts to simulate EFO with perfect forecast skill, and
4. NF – "No Forecast" alternative which, like EFO and PFO, raises the buffer pool to elevation 514-ft., but does not use forecast to manage the additional stored water.

Simulation of the EFO alternative was enabled by the development of hindcasts of the HEFS for inflow into Prado Reservoir for water years 1990 to 2019 by the CNRFC. These are updated hindcasts from those used in the PVA using version 12 of the Global Ensemble Forecast System (GEFS) that is currently used operationally for the generation of HEFS forecasts. The period of the hindcasts includes a variety of hydrologic conditions from wet years to dry years, but this period does not include any extreme flood events. Therefore, to enable simulations of extreme flood events, the CNRFC also developed scaled hindcasts of 100, 200 and 500-year return periods using flood events in the unscaled hindcast period from 1998, 2005 and 2010.

Simulation results show increased water supply through the simulation of water diverted to groundwater recharge facilities downstream of Prado Dam that are owned and operated by OCWD. Figure 5 shows simulated water year groundwater recharge volumes as probability distribution in the left panel, and as box and whisker plots in the right panel. These results only show benefits to water supply for wetter years (less than 50% exceedance). Figure 5 shows the greatest benefits for the NF and PFO alternatives, and the EFO alternative shows more modest benefits when the reservoir is operated with forecast uncertainty as quantified in the hindcast. The box and whisker plots show an increase of 5% in average annual recharge for EFO relative to the WCM alternative.

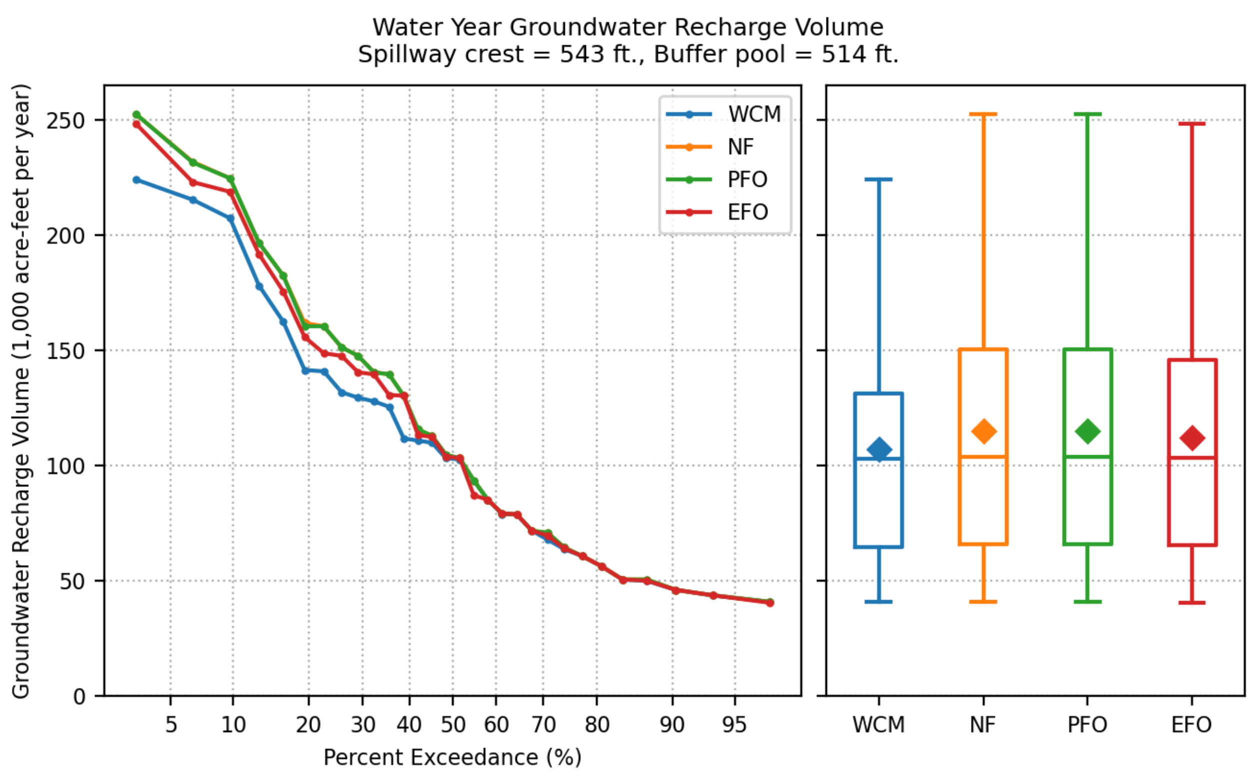

Figure 5. Simulated groundwater recharge volumes through the OCWD facilities downstream of Prado Dam.

Simulated annual maximum elevations plotted as probability exceedance are provided in Figure 6. These results show similar peak elevations for the extreme 500-year events (0.002% exceedance). Results of the 100-year and 200-year events show reduced peak elevations for EFO relative to the WCM and NF alternatives. WCM and NF show peak storage levels above the spillway crest (elevation 543 ft.) for the 200-year event resulting in an uncontrolled release from the spillway, while the FIRO alternatives (EFO and PFO) stay below spillway crest. WCM shows the lowest frequency of flooding the airport (between elevation 514 and 520 ft.), which indicates that FIRO could increase flood risk for the airport. However, EFO and PFO show a reduced frequency when compared to the NF alternative.

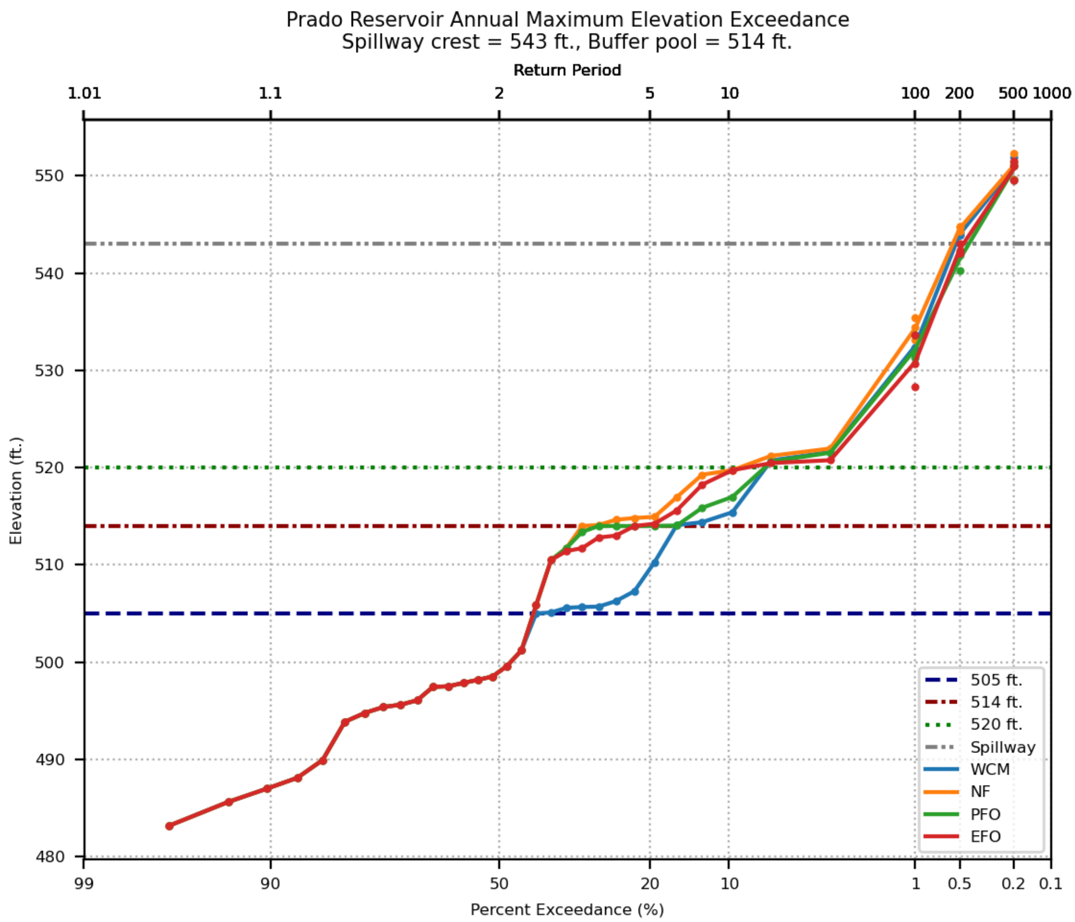

Figure 6. Peak annual water surface elevation of Prado Reservoir plotted as annual exceedance probability.

The duration, in days per water year, that simulated water surface elevation exceeds the airport (elevation 514 ft.) is provided in Figure 7. This figure shows that the FIRO alternatives (EFO and PFO) show increased duration and frequency of flooding the airport relative to WCM, however both FIRO alternatives show reduced frequency relative to the NF alternative.

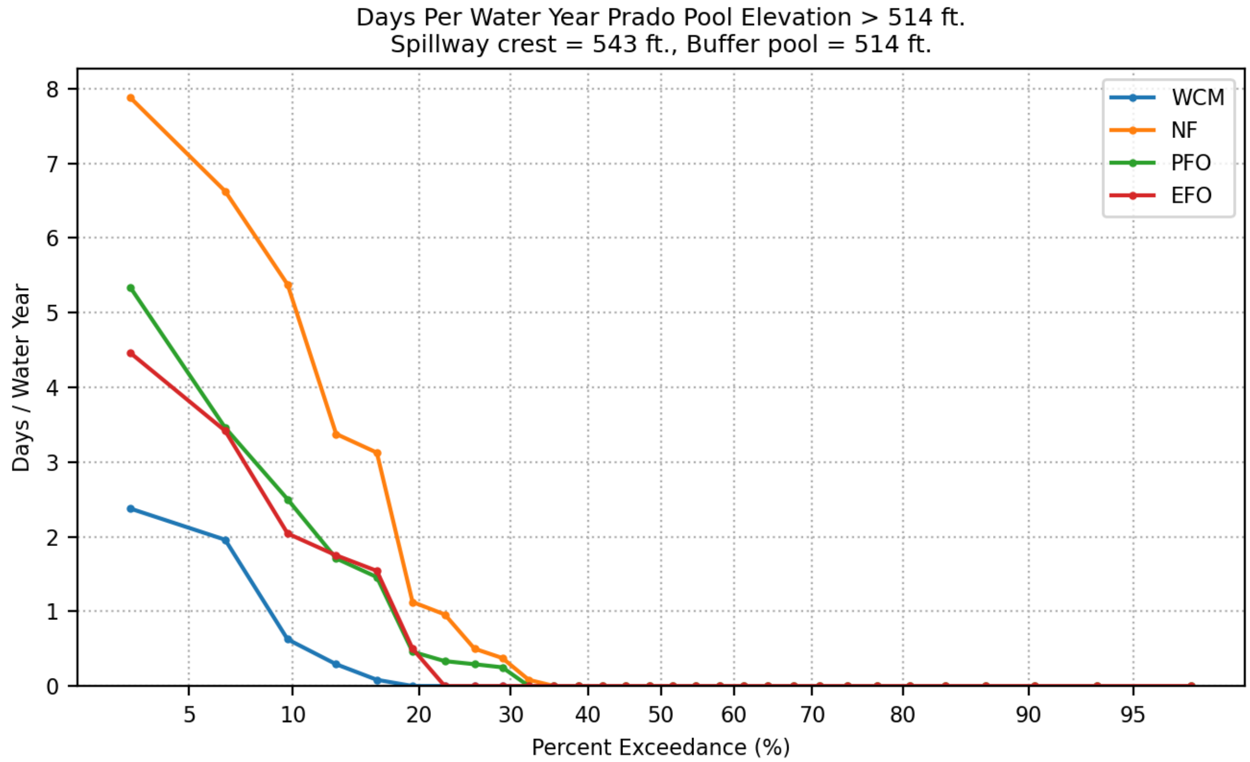

Figure 7. Days per water year that Prado Reservoir water surface is greater than 514 ft. (airport elevation).

Findings

The expanded buffer pool to 514 ft. (40,500 ac-ft) assumed with the FIRO alternatives (EFO and PFO) and the "No Forecast" (NF) alternative show improved water supply through increased diversions for groundwater recharge at downstream facilities owned and operated by OCWD. The FIRO alternatives do not show increased peak annual water surface elevations for the 100, 200 and 500-year return periods relative to the WCM alternative, indicating no increase in flood risk for extreme events. The EFO alternative shows increased flood frequency and duration of the airport (elevation 514 ft.) relative to the WCM alternative. The NF alternative shows the highest flood frequency and duration of the airport and also shows the highest pool elevations for the 200-year scaled events, indicating that increasing the buffer pool to 514 ft. without FIRO would increase flood risk.

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