
DRAWDOWN MODELLING OF FOUR RESERVOIRS ON THE KLAMATH RIVER TO SUPPORT HYDROELECTRIC FACILITY DECOMMISSIONING

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ABSTRACT

Four hydroelectric facilities on the Klamath River within Oregon and California were successfully decommissioned in 2024. The reservoirs were required to be substantially drawn down during the winter season (January through March), in advance of the dam removals in the subsequent summer low-flow season, to temporally focus the impacts of reservoir sediment release on downstream aquatic resources. Northwest Hydraulic Consultants (NHC), as a sub-consultant to Knight Piesold (KP), developed a U.S. Army Corps of Engineers HEC-RAS hydraulic model to simulate reservoir water levels during the reservoir drawdown and dam removal seasons. The reservoirs were drawn down using existing construction-diversion conduits where feasible, or by the construction of new low-level outlets. Stage-discharge rating curves were developed for each drawdown outlet using computational fluid dynamics (CFD) hydraulic models. Complex operation rules, based on flows and reservoir stage, were used in HEC-RAS to determine simulated outflow from the various dam outlet structures. The primary purpose of the drawdown model was to simulate potential reservoir water surface elevations (WSEs) for the four reservoirs during the drawdown year utilizing a 36-year historic record of varying inflow conditions. These simulations facilitated the evaluation of drawdown outlet alternatives during the design phase, and the scheduling of drawdown operations and dam removal activities during the dam removal year. This paper focuses on drawdown modelling scenarios at the largest dam (Iron Gate), and how this compared to actual conditions observed during the 2024 reservoir drawdown and dam removal activities.

RÉSUMÉ

Quatre centrales hydroélectriques sur la rivière Klamath, dans l'Oregon et en Californie, ont été démantelées avec succès en 2024. Les réservoirs devaient être considérablement vidés pendant la saison hivernale (de janvier à mars), avant les retraits des barrages pendant la saison d'étiage de l'été suivant, afin de concentrer temporairement les impacts de la libération de sédiments du réservoir sur les ressources aquatiques en aval. Northwest Hydraulic Consultants (NHC), en tant que sous-consultant de Knight Piesold (KP), a développé un modèle de rabattement HEC-RAS pour simuler les niveaux d'eau des réservoirs pendant les saisons de rabattement des réservoirs et de démantèlement des barrages en utilisant un enregistrement de 36 ans de conditions d'afflux variables. Les réservoirs ont été abaissés en utilisant des conduites de dérivation de construction existantes lorsque cela était possible, ou par la construction de nouveaux exutoires de bas niveau lorsque cela était nécessaire. Des courbes de débit-niveau ont été développées pour chaque exutoire de rabattement en utilisant des modèles mécaniques des fluides numérique. Des règles de fonctionnement complexes, basées sur les débits et le niveau du réservoir, ont été utilisées dans HEC-RAS pour déterminer l'écoulement simulé des différentes structures d'exutoire des barrages. L'objectif principal du modèle de rabattement était de calculer les élévations de surface d'eau simulées pour les quatre réservoirs pendant l'année de rabattement. Cet article se concentre sur les scénarios de modélisation de rabattement pour une gamme d'événements d'afflux prévus, et sur la manière dont ils se comparent aux conditions réelles lors du rabattement du réservoir et du retrait du barrage en 2024.

1 INTRODUCTION

As part of the Klamath River Renewal Project (KRRP), four hydroelectric facilities (J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate) on the Klamath River within Oregon and California were successfully decommissioned in 2024. The reservoirs were required to be substantially drawn down (drained) during the winter season (January through March), in advance of the dam removals in the subsequent summer low-flow season, to temporally focus the impacts of reservoir sediment release on downstream aquatic resources. At the same time, the reservoirs needed to be drawn down at a rate that limited the potential for instability on the embankment dam slopes and reservoir rims.

Northwest Hydraulic Consultants (NHC), as a sub-consultant to Knight Piésold (KP), developed a one-dimensional (1D) U.S. Army Corps of Engineers Hydraulic Engineering Center River Analysis System (HEC-RAS) (HEC, 2019) numerical model to simulate reservoir water levels during the reservoir drawdowns. The HEC-RAS model simulated dam removal seasons using a 36-year record of varying inflow conditions. The reservoirs were drawn down using existing construction-diversion conduits where feasible, or by the construction of new low-level outlets. Stage-discharge rating curves were developed for each drawdown outlet using computational fluid dynamics (CFD) hydraulic models. Complex operation rules, based on flows, reservoir stage, and timing, were used in HEC-RAS to determine simulated outflow from the various dam outlet structures. The drawdown model is described in this paper and in more detail in NHC (2022).

The primary purpose of the drawdown model was to calculate simulated reservoir water surface elevations (WSEs) for the four reservoirs during the drawdown year. These simulations facilitated the evaluation of drawdown outlet alternatives during the design phase, and the scheduling of drawdown operations and dam removal activities during the dam removal year. Simulated inflows, outflows and reservoir WSEs for all four facilities were estimated for the primary drawdown period in the winter and spring, followed by the post-drawdown period when the dam deconstruction was executed, prior to the final dam breach and establishment of the volitional fish channels. Considering the relative size of the four dams and volume of the respective reservoirs, coupled with the resultant length of the drawdown of each of the reservoirs, the most complex drawdown was associated with Iron Gate Dam. Based on this, the paper will focus on the drawdown modelling and review of the Iron Gate Dam.

2 MODEL DEVELOPMENT

Three separate HEC-RAS models were used to simulate drawdown and operation of the reservoirs during drawdown for J.C. Boyle reservoir, Copco No. 1 and No. 2 reservoirs (the two Copco facilities are combined in one HEC-RAS model), and Iron Gate reservoir. The extent of each model domain and cross-section locations are shown on Figure 1. The outflow from the upstream facilities was used as the inflow into the next downstream reservoir (e.g. outflow from J.C. Boyle model is the inflow into Copco Lake).

HEC-RAS model cross-sections were based on the topo bathymetric data (GMA, 2018) and reach lengths (i.e. the distance between HEC-RAS model cross-sections) were defined to represent, as best possible, a range of storage and conveyance conditions for both high reservoir stage and low-flow immediately after drawdown.

2.1 *Hydraulic Model Inflows, Local Inflows, and Downstream Boundary Assumptions*

The U.S. Bureau of Reclamation (USBR) stores, diverts, and conveys the waters of the Upper Klamath Basin to serve authorized purposes of the Klamath Irrigation Project. Several Biological Opinions have governed the operation of the Irrigation Project since the 1990s. The USBR uses modelling tools to apply current Biological Opinion (BiOp) parameters to historical streamflow and reservoir level records to characterize the flows and levels that would have been experienced had the current BiOp regime been in

place. The latest BiOp applicable at the time of the Klamath River dam removal planning was the 2019 BiOp (USBR, 2018), which the USBR had used to generate 36 years of simulated streamflow records at key Klamath River gaging stations. Daily average 2019 Biological Opinion (BiOp) flows, from October 1980 through September 2016, were provided at the USGS station Klamath River at Keno, Oregon (USGS 11509500), and at the USGS station Klamath River below Iron Gate Dam, California (USGS 11516530) (USBR, 2018).

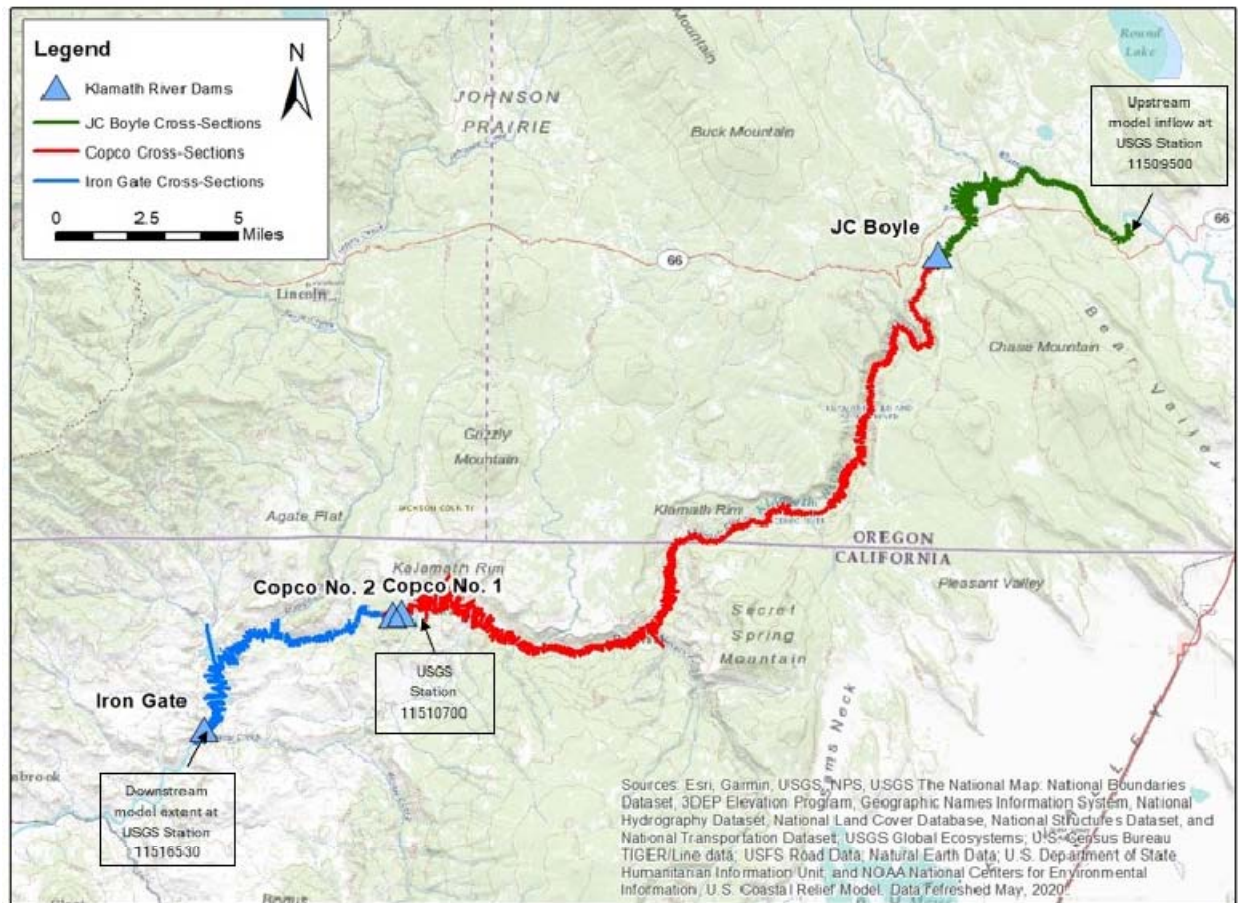


Figure 1. Vicinity Map

The Keno flow was specified as the HEC-RAS model inflow into the riverine reach upstream of the J.C. Boyle reservoir. Figure 2 shows the BiOp flows for years 1981 to 2016 in multiple colours, the monthly average of the BiOp flows record in black, along with the USGS gage data for 2024 for a location at Keno. Local inflow was determined based on the difference between the Keno and Iron Gate BiOp flows. These local inflows were applied to the HEC-RAS model, with each reach of the study area receiving a share of the inflows proportional to the approximate local drainage area within that reach. The time distribution of this local inflow volume was assumed to follow that at Keno. The downstream boundary for each model was assumed as the normal depth of the average downstream slope.

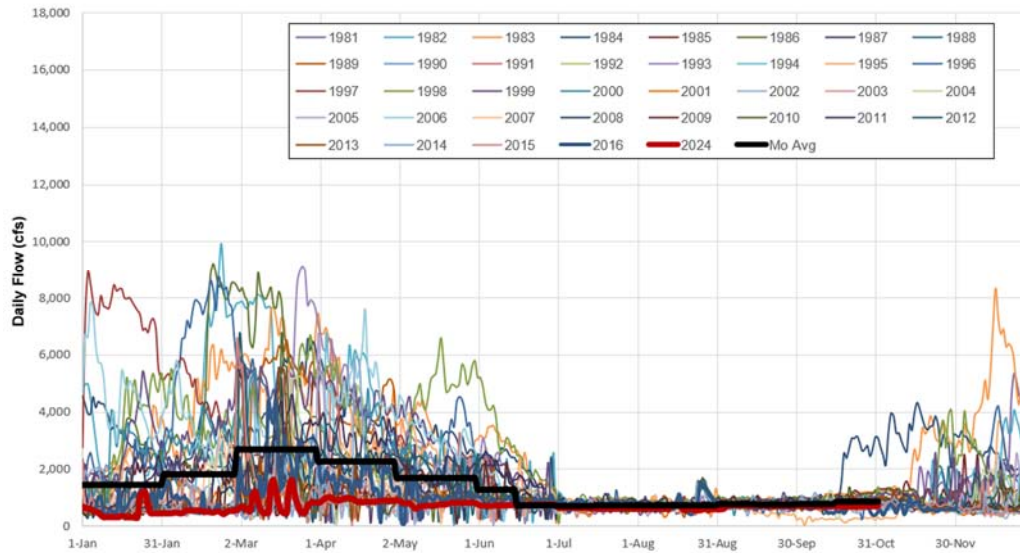


Figure 2. Klamath River at Keno at USGS Gage 11509500 - Actual Flows (2024) and BiOp Flows (1981 to 2016)

2.2 Digital Elevation Model and Structure Elevation Data

Considering the relative size of the four dams and volume of the respective reservoirs, coupled with the resultant length of the drawdown of each of the reservoirs, the most complex drawdown was associated with Iron Gate Dam. Figure 3 shows a profile view of the Iron Gate Dam and reservoir portions of the HEC-RAS model with the elevations of relevant dam features.

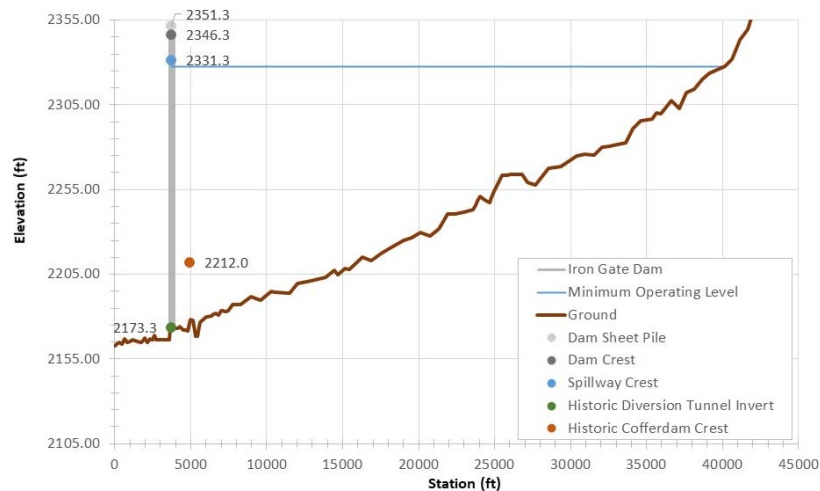


Figure 3. Profile of the dam and reservoir portion of Iron Gate HEC-RAS hydraulic model.

2.3 Hydraulic Model Calibration, Validation, and Sensitivity Analyses

The model was validated to show that it can replicate observed reservoir stage. In a reservoir water balance, inflow plus change in reservoir storage equals outflow, and if these values are correct, then a well calibrated hydraulic model should replicate observed stage. Reservoir storage is a function of volume, and therefore the representation of the three main reservoirs within HEC-RAS (calculated up to the dam or spillway crest based on cross-section shape and the specified reach length between cross-sections) were compared to that of the topobathymetric data from approximately the spillway crest to, at or near the historic cofferdam. In

addition to storage, all inflows and outflows must be known or estimated to complete a water balance for the reservoirs. Gaged reservoir inflow and outflow data are available, however the local inflow between these points is also necessary to complete the water balance and evaluate the models' capability to replicate observed stage. As described in Section 2.1, local inflows were roughly determined to create an observed match between the simulated and observed stage within a portion of the normal operating pool range. Figure 4 shows the simulated stage with the estimated local inflow for a yearlong simulation for Iron Gate reservoir.

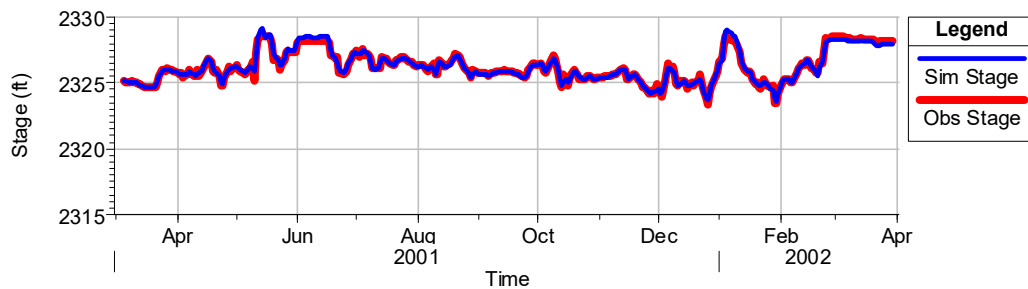


Figure 4. Iron Gate Reservoir Simulation Replicating Observed Stage with Estimated Ungaged Flow

The hydraulic model was calibrated to existing data for the riverine portions of the study area and also validated to show that it accurately simulates reservoir stage conditions within the range of normal pool operations. Figure 5 shows the different simulations run with Manning's roughness values of 0.04, 0.05, 0.06, and 0.07 to test model sensitivity for Iron Gate. The local rating curve data from the USGS gage was input as an observed time series. Manning's n was calibrated based on the USGS gaging station within the study reach, and the values of $n = 0.05$ and $n = 0.06$ were selected for the main channel and overbanks, respectively, to match the best fit lines in Figure 5.

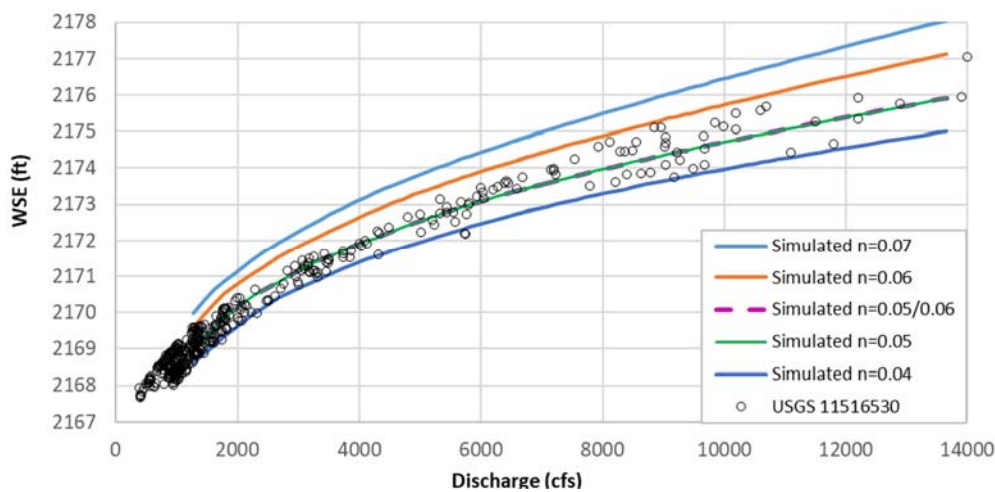


Figure 5. Simulated Stage Discharge Curves for a Range of Manning's n Values compared to Measured Values at a USGS Station 11516530 Downstream of the Iron Gate Reservoir

2.4 Sensitivity Analyses

Several sensitivity analyses were conducted to understand how adjustments to model parameters would affect the simulated results. When results show a high variability to modifying a specific model parameter, then additional attention should be made in selecting an appropriate value for that parameter. Sensitivity

analyses evaluated varying Manning's n through the riverine portions of the hydraulic model, and through the reservoirs, both with and without dams in place (the latter investigating sensitivity to the simulated drawdown condition). In addition, the sensitivity analyses included evaluating varying the computational time step, and the effect of varying the output time step on downstream model results (where the upstream model output is used for input into the downstream model). None of these had a significant effect on models results, with difference in water surface of typically less than a foot and time difference of less than an hour.

3 HYDRAULIC MODELLING OF DAM STRUCTURE OPERATIONS DURING DRAWDOWN AND POST-DRAWDOWN AT IRON GATE

CFD methods were used to determine rating curves for the outlet structures at all four dams, and then the HEC-RAS rules were used to dictate when a specific outlet structure is active based on the specified drawdown operating criteria. For the simulations, all reservoirs were assumed lowered to their minimum operating levels and starting at that level when simulated drawdown began (assumed on January 1 of each drawdown year).

“Rules” are used in the hydraulic modelling to specify outflow from the dams through the various outlet structures. The Rules set up in HEC-RAS facilitated modelling of the complexity in the prescribed operating rules for the drawdown, with specific water levels and timing applied for each BiOp flow scenario. It was planned that the drawdown of the Iron Gate reservoir would utilize the spillway, power intake using hydraulic turbine or by-pass (Howell-Bunger valve), and existing diversion tunnel reopened for use as the primary low-level drawdown outlet. The flow through the existing diversion tunnel was planned to be controlled by the existing upper gate, opened to the fully open position and not varied over time. The drawdown operations specified in the HEC-RAS model for Iron Gate are as follows:

- The initial WSE is at the minimum operating level (El. 2327.3 feet, 709.4 m).
- Drawdown is initiated on January 1 by fully opening the existing upper gate in the diversion tunnel (57 inches, 1.4 m), and by opening the power intake and the bypass valve.

The rating curves used in the HEC-RAS model for the Iron Gate facility are shown on Figure 6. The rating curve was developed using CFD by NHC (2020) and KP (2021) following a tunnel survey completed by Yurok Tribe between November 17 and November 20, 2020.

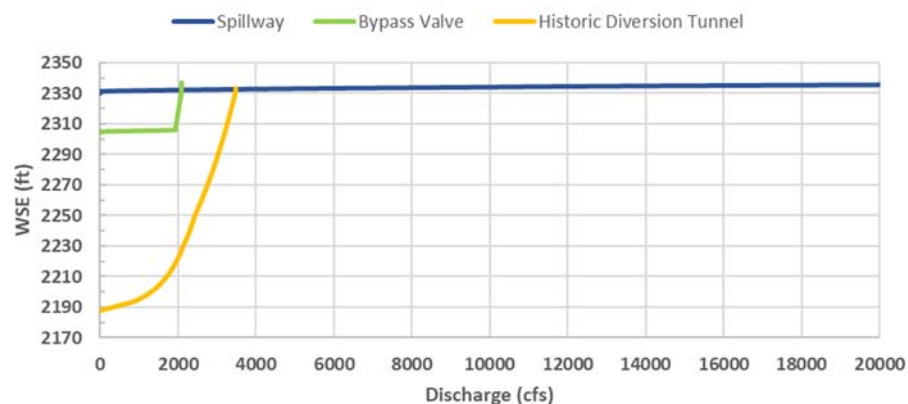


Figure 6. Stage versus flow relationships at Iron Gate Dam for simulating outflow at the dam.

4.1 Simulated Reservoir Drawdown at Iron Gate Using Historical Flows

The simulation results highlight key elevation and time triggers for the hydraulic operational controls of the reservoirs for a variety of hydrologic conditions. All 36 simulation periods (1981 through 2016) were evaluated for each reservoir to ensure the efficacy and functionality of the proposed drawdown operations. Drawdown plots for selected Iron Gate simulations are provided in Figure 7 through Figure 9. The 1997 simulation shows extended activation of the bypass valve due to high headwater conditions, and the 2005 simulation provides an example of dramatic stage increases due to spring runoff events.

A stage and flow profile plot for the full 1997 simulation is provided in Figure 7. A finer resolution profile showing the minimum operating levels and initial hydraulic controls is provided in Figure 8. As shown in Figure 7 and Figure 8, the simulation begins at the minimum operating level of El. 2327.3 feet (709.4 m). The bypass valve and HDT are open on January 1 and the gate in the HDT will not be used to regulate flow. Due to high inflows, the bypass valve is utilized until March 17 (Figure 7), when the WSE drops below El. 2305 feet (702.6 m). This is in contrast to the 2005 simulation (Figure 9), where the WSE dropped below the bypass valve invert on January 6.

One notable result in the Iron Gate figures is the significant increase in stage seen in spring due to large inflows from Copco No. 2 and adjacent tributaries, as occurred in 2005 with a stage increase from 2200 to 2300 feet (670 m to 701 m) (Figure 9). In general, stage increases were between 40 to 100 feet (12 to 30 m) in the reservoir during these inflows, with the larger increases in the drier years. Outflow from Iron Gate was hydraulically controlled by the regulating gate, which has a capacity of approximately 4000 cfs (113 m³/s) with the reservoir at the spillway crest elevation, providing some attenuation of large inflows within the Iron Gate reservoir.

The 36 years of modelled reservoir levels are presented in Figure 10 (ensemble plot of 36 hydrographs) and Figure 11 (time series of non-exceedance percentiles). The magnitude, duration, and rate of change of these reservoir water level fluctuations were assessed with regards to environmental implications (reservoir sediment flushing), dam slope stability (during periods of more rapid drawdown), and construction activity logistics (access into the drawn down reservoir for preparation of dam removal activities). Modelled years with more rapid initial drawdown were assessed as favourable for sediment flushing but represented the critical case for dam slope stability.

Modelled years in which the reservoir refilled and drained one or more times after the initial drawdown represented a challenge for preparatory construction activities. Overall, the range of modelled reservoir water levels during the 36 model years indicated that:

- The environmental sediment flushing objective would be achieved under most inflow scenarios
- The dam slopes would maintain an acceptable factor of safety under the most rapid drawdown scenario
- Accessibility of the drawn down reservoir for preparatory construction activities was likely under most inflow scenarios, but should be limited to activities that could accept being flooded temporarily.

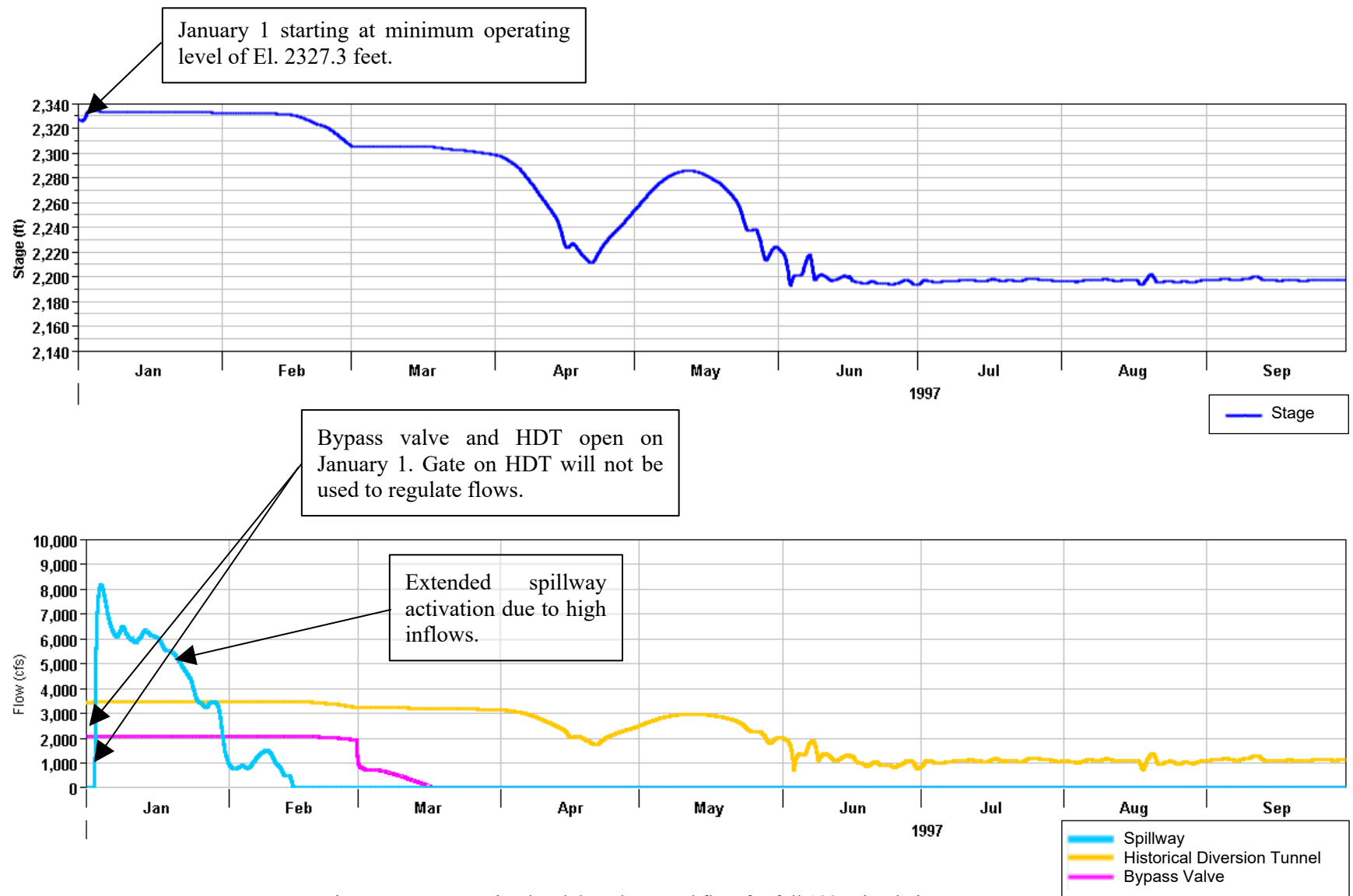


Figure 7. Iron Gate simulated drawdown and flow for full 1997 simulation.

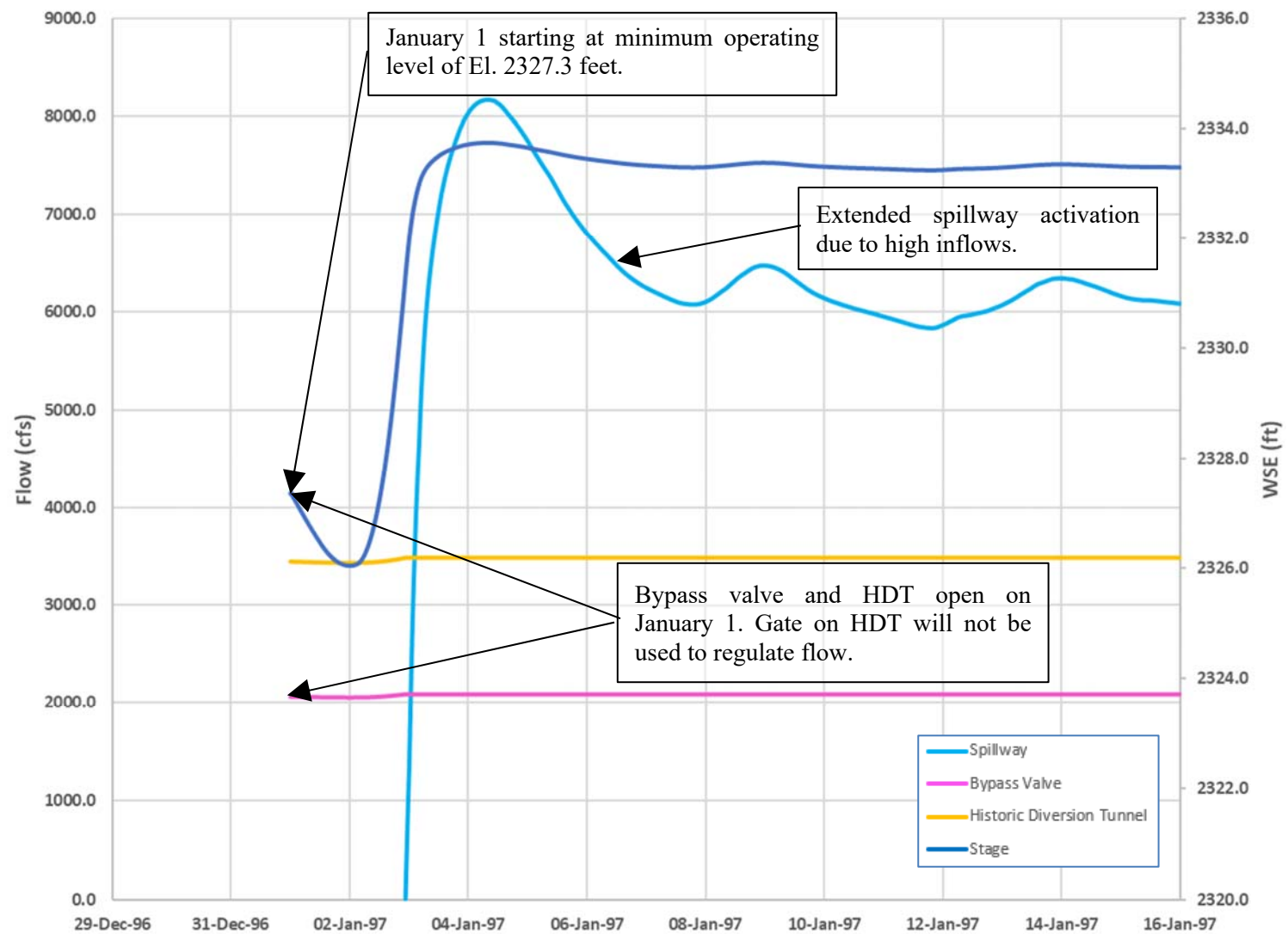


Figure 8. Iron Gate Project simulated drawdown and flow for spillway, HDT, and bypass valve for 1997 simulation.

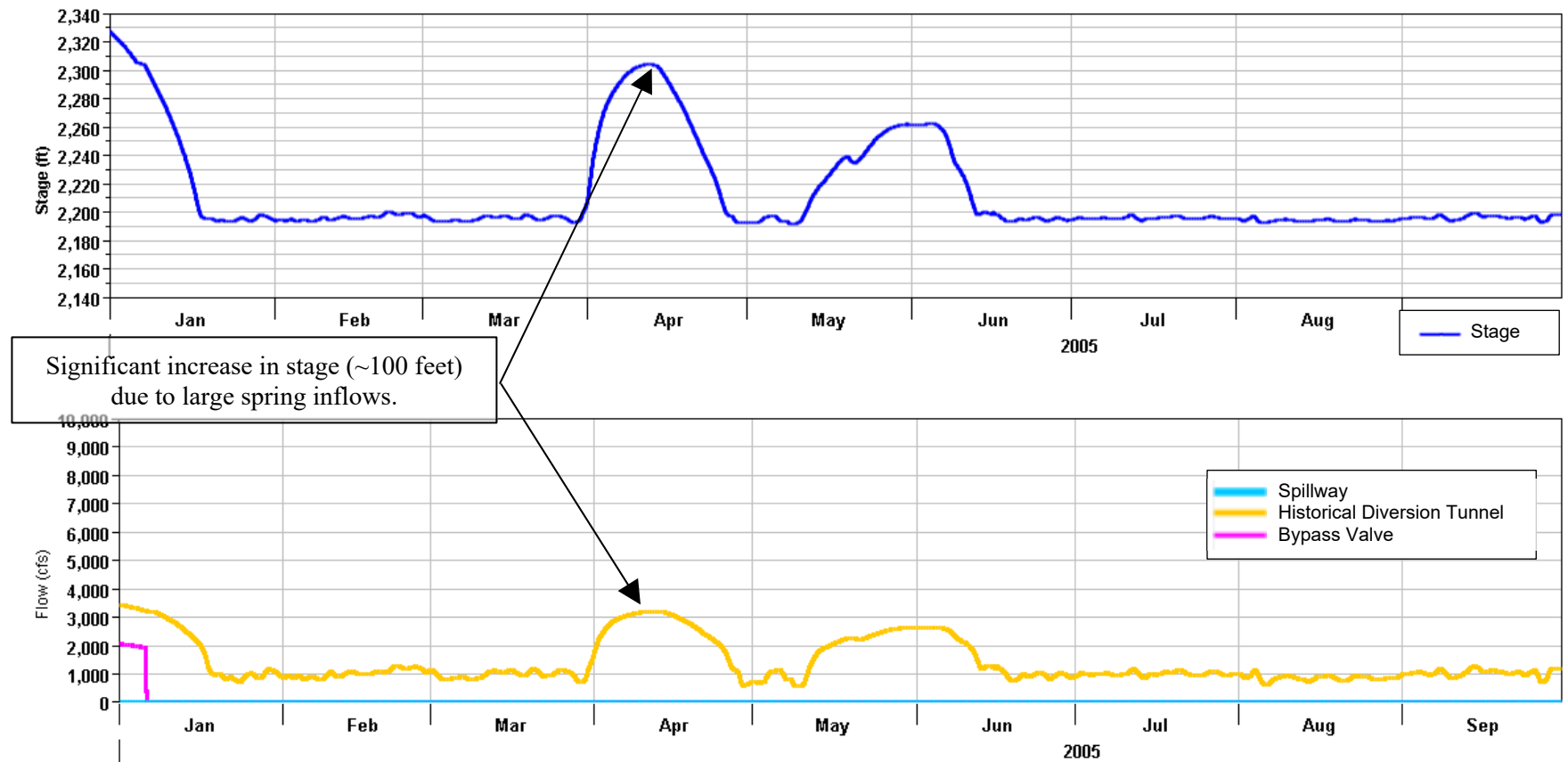


Figure 9. Iron Gate simulated drawdown and flow for full 2005 simulation.

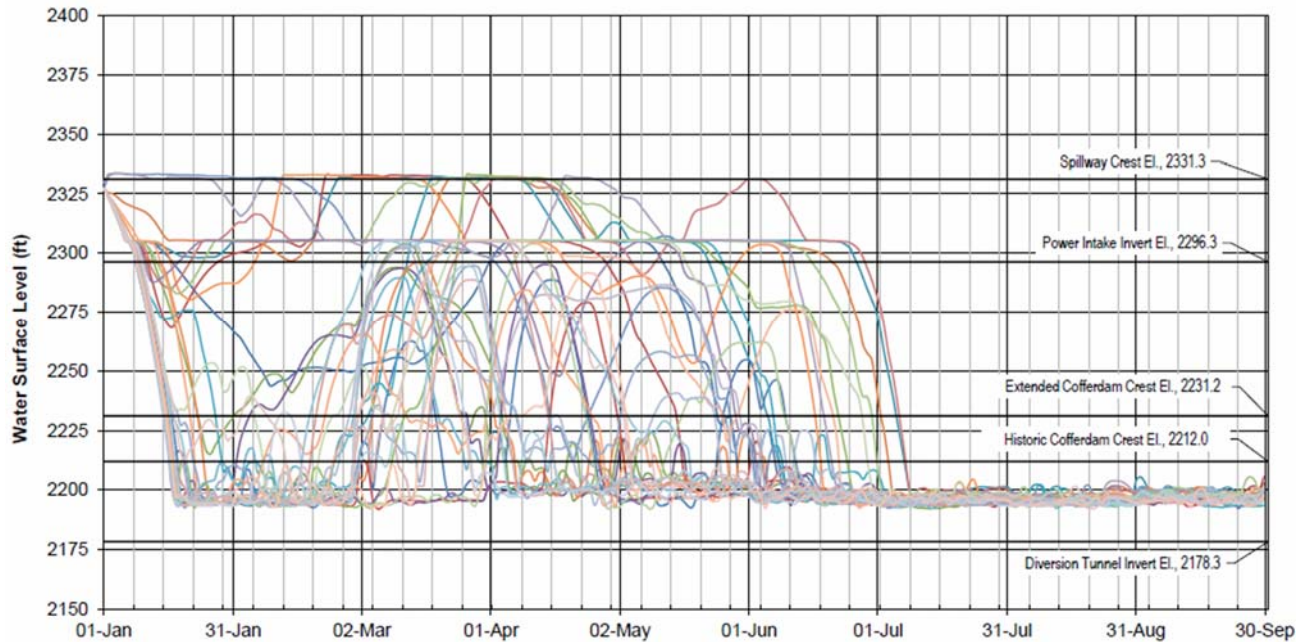


Figure 10. Iron Gate Reservoir Drawdown – Simulated Water Surface Levels Ensemble Plot

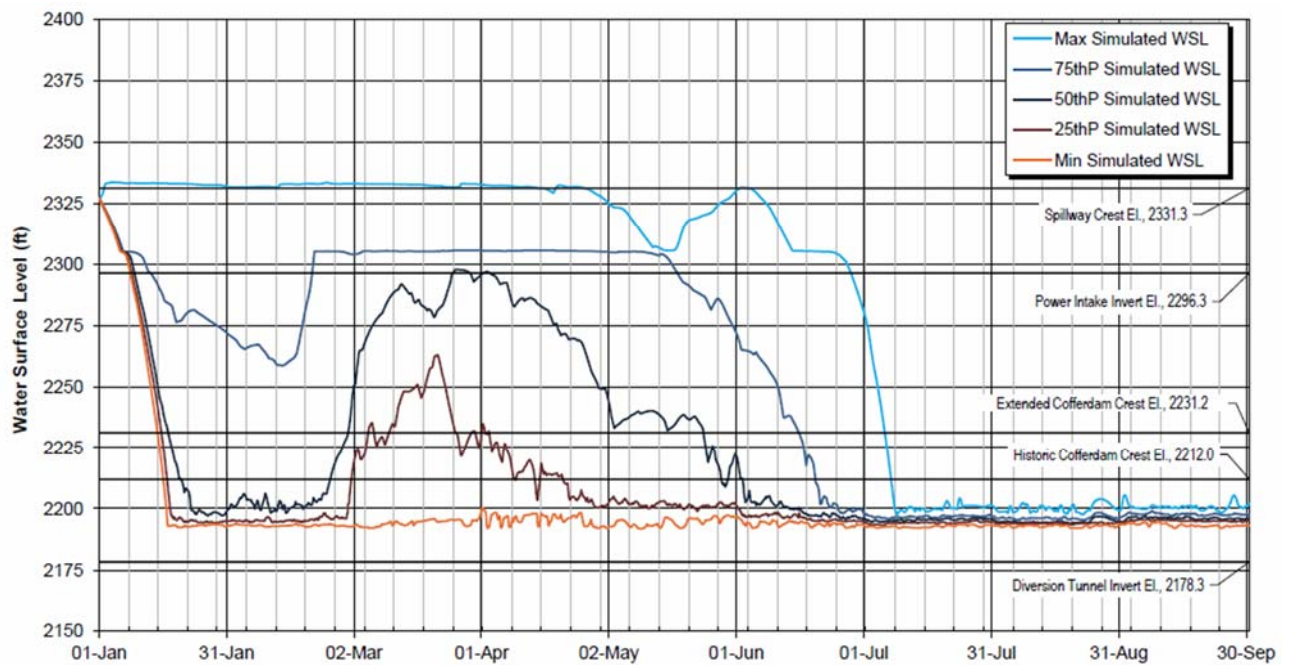


Figure 11. Iron Gate Reservoir Drawdown – Simulated Water Surface Levels Non-Exceedance Percentiles

4.2 Follow Up Analyses with Staggered Drawdown Initiation Dates

Additional analyses were conducted in the weeks leading up to the initiation of reservoir drawdown in January 2024. The smallest dam, Copco No. 2, had been removed in the summer of 2023. NHC was asked to model drawdown of the other three reservoirs, using staggered start dates that would provide an

initial lowering of Iron Gate reservoir prior to the initiation of drawdown from the next largest reservoir, Copco No. 1.

The analyses utilized the same one-dimensional HEC-RAS models that were previously developed to simulate drawdown and operation of the J.C. Boyle reservoir, Copco No. 1 and No. 2 reservoirs and Iron Gate reservoir, however, with staggered drawdown rules applied for the dams. Model domains, cross-sections, and datums were unchanged from the original analysis, except for the removal of Copco No. 2 from the model to maintain consistency with current field conditions.

Rather than using the 36 years of BiOp streamflow records, USBR's anticipated outflows from Keno Dam in the upcoming drawdown period and estimated net local tributary flows downstream of Keno Dam, were provided to NHC. These local inflows were applied to the HEC-RAS model, with each reach of the study area receiving a share of the inflows proportional to the approximate local drainage area within that reach. Based on this method, which matches the distribution of local inflow in the prior hydraulic modelling work, the difference between Keno and Iron Gate gaged flows were applied as follows; 20 percent to the J.C. Boyle Dam reach, 30 percent to the Copco reach, and 40 percent to the Iron Gate Dam reach. The remaining 10 percent of the local inflow enters downstream of Iron Gate Dam. NHC was provided with operating procedures for a staggered drawdown of the three reservoirs starting on January 4 for Iron Gate, January 8 for J.C. Boyle, and January 16 for Copco No. 1.

The hydraulic model results were validated by comparing the simulated stage output results to previous simulations for consistency with stage and flow. Simulated flow and stage hydrographs for each reservoir were provided to the design team. The ongoing collaboration between the design team and the contractors enabled the evaluation of scenarios in the weeks leading up to project implementation which represented scenarios that were closer to the planned implementation with staggered drawdown of each reservoir. The actual staggering of drawdown initiation in January 2024 was the same in terms of ordering of the drawdown of the reservoirs; however, with Iron Gate initiated on January 9, then J.C. Boyle on January 16, and then Copco No. 1 on January 23.

5 ACTUAL METEOROLOGICAL, FLOW, AND DRAWDOWN CONDITIONS DURING PROJECT IMPLEMENTATION

The drawdown of Iron Gate reservoir was conducted over 33 days, from January 9, 2024 to February 11, 2024. The drawdown of J.C. Boyle occurred from January 16 to January 17, 2024, and the drawdown for Copco No. 1 took four days from January 23, 2024 to January 27, 2024. The following sections outline a review of the actual meteorological conditions during the time of the drawdown and the operating conditions and resultant flow conditions during the drawdown.

5.1 A Review of the Meteorological Conditions

A review of meteorological data for Klamath Falls Airport Station shows that precipitation during the drawdown period (shown with the black line) was within the typical range for the region, as shown in Figure 12. In addition, a review of the snow water equivalent (SWE) data for the Upper Klamath Basin, as documented by Natural Resources Conservation Service (NRCS), is shown in Figure 13. The black line in Figure 13 denotes that SWE was close to the median for the region during the drawdown period in 2024.

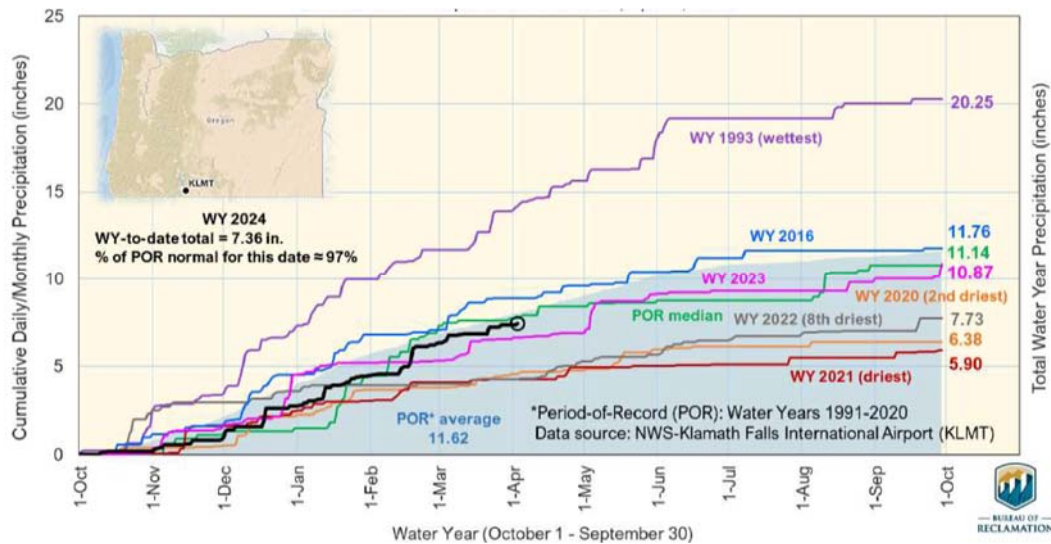


Figure 12. Klamath Falls Airport Meteorological Station - Precipitation

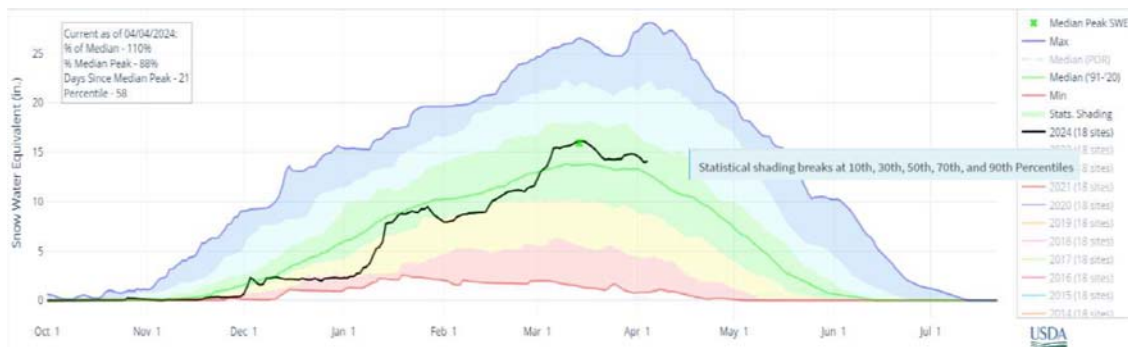


Figure 13. Upper Klamath Basin SWE (NRCS, 2024)

5.2 Klamath River Daily Flow Conditions

Figure 14 shows the BiOp flows for years 1981 to 2016 in multiple colours, the monthly average of the BiOp flows record in black, along with the USGS gage data for 2024 for a location below Iron Gate Dam. Although the meteorological data indicated that winter of 2024 was not a dry period for the region, Figure 14 shows that flow in Klamath River during the drawdowns was generally below the monthly average of the BiOp flows. A review of conditions shows that USBR was able to effectively manage upstream basin conditions to limit flow released downstream to essentially the minimum environmental flow requirements for the duration of the drawdown of the reservoirs.

5.3 Operating Conditions During Drawdown

The effective management of flow released by USBR from the Upper Klamath Basin accelerated the drawdown process of the reservoirs, which was beneficial in a number of ways, but represented a critical condition for stability of the Iron Gate Dam slopes. In response to this, modified drawdown operations were implemented at Iron Gate Dam to initially constrain the drawdown rate with partial openings of the diversion tunnel gate before fully opening it to achieve complete drawdown.

As described in Section 4, modelling analyses conducted during the design phase assumed that the Iron Gate diversion tunnel gate would be fully open at 57 inches (1.4 m) during the drawdown.

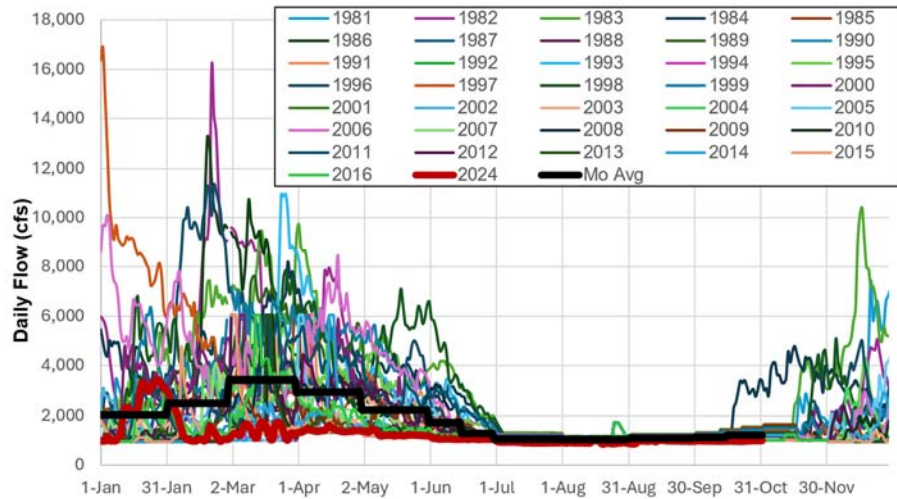


Figure 14. Klamath River Below Iron Gate Dam at USGS Gage 11516530 - Actual Flows (2024) and BiOp Flows (1981 to 2016)

However, in reality, the gate was incrementally opened as follows:

- starting on January 9 at 12 inches (0.3 m) open,
- then 30 inches (0.8 m) to 26 inches (0.7 m) open on January 11 to January 17,
- then 29 inches (0.7 m) on January 17,
- then fully opened (57 inches, 1.4 m) on January 19 (before the Copco No. 1 drawdown inflow initiated on January 23) and until drawdown was complete on February 11.

The resulting water surface levels in Iron Gate reservoir from January through March 2024, are shown in Figure 15. Drawdown rates were constrained during the initial period of drawdown in Iron Gate reservoir (January 9 to 19), then increased after January 19, with the exception of rising levels associated with the inflows from Copco No. 1 reservoir for a few days after January 23. The main period of continuous drawdown occurred from January 27 to February 11, during which the rate of drawdown approximately matches the modelled drawdown in low inflow model years.

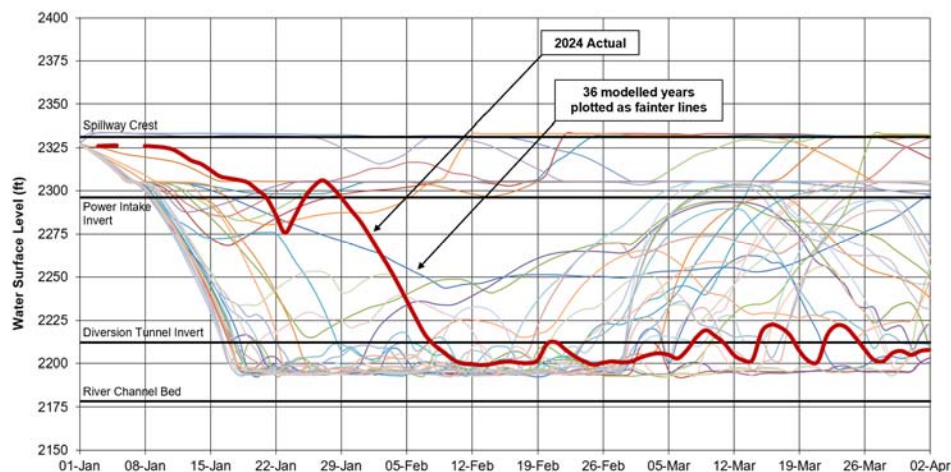


Figure 15. Iron Gate Reservoir Water Levels – Actual 2024 Drawdown and 36 Years of Modelled Conditions

Overall, the actual 2024 drawdown operation was successful. Daily topographic surveys and visual inspections throughout the drawdown period did not detect any dam slope instabilities. The reservoir was fully drawn down within the prescribed winter season, thereby achieving the sediment flushing objective. The reservoir remained in a drawn down state through the remainder of the winter and spring, which facilitated preparatory construction activities. Lowering of the dam crest below the spillway crest elevation commenced in mid-May once the USBR was able to provide certainty on flow releases throughout the summer season, and the magnitude of downstream tributary peak inflows was determined to be acceptably low. The difference in the operation of the drawdown tunnel (with varying the opening of the gate as opposed to a consistent fully open gate) resulted in the drawdown conditions deviating from the model results. However, all the modelling work provided the basis for effective decision making and planning in the field during the active drawdown by enveloping the possible drawdown conditions.

6 CONCLUSIONS

This paper focuses on the development of drawdown modelling scenarios for a range of predicted inflow conditions, and how this compared to actual conditions observed during the 2024 reservoir drawdown and dam removal activities. Specifically, the paper focused on the drawdown conditions for the most downstream dam, Iron Gate, given its dam and reservoir sizes, and required duration for drawdown. Operation rules, based on flows, reservoir stage, and timing, were used in HEC-RAS to determine simulated outflow from the various dam outlet structures. This facilitated the simulation of complex drawdown scenarios to provide the team information to support the design of the outlet structures and plan the timing of the initiation of the drawdown of each reservoir. The meteorological conditions experienced in the region during the drawdown were typical for the region, however, effective management in the upper basin by USBR resulted in lower than average discharges in the Klamath River. The analyses show that the numerical modelling conducted in the design phase of the project effectively enveloped conditions that were experienced during the actual drawdown activities. Ongoing communication of results was fundamental to coordination with the Contractor, Owner, and regulatory agencies.

7 REFERENCES

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