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Determination of Controlled-Release Capacity from Trinity Dam

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Abstract

Recent studies of alternatives for restoring anadromous fisheries on the Trinity River have recommended increased releases from Trinity Dam. To support these recommendations, the river outlet works, powerplant, and auxiliary outlet works at Trinity Dam were analyzed to determine the maximum possible controlled release. This analysis used a mathematical model of the combined operation of the river outlet works and powerplant, which share a common tunnel and penstock system; previously, the capacity of these components had only been analyzed for their separate operation. The model was calibrated using data collected from two field tests. The result of the analysis is a new set of discharge curves for the Trinity Dam outlet works and powerplant system. Curves have been developed for separate operation of the river outlet works and for combined operation of the outlet works and powerplant, using either the low-head or high-head turbine runners.

Introduction

The Trinity River drains a total area of about 3,000 mi^2 in northern California. Before impoundment in the early 1960's by Trinity and Lewiston Dams, the basin contributed nearly one third of the Klamath River's runoff into the Pacific Ocean in an average year (i.e., about 1,250,000 ac-ft of the total 4,000,000 ac-ft). Construction of the dams allowed the majority of the runoff from the Trinity River basin at this point to be stored temporarily and diverted into the Sacramento River basin for use by the Central Valley Project [1]. Since the completion of Trinity Dam in 1962, up to 90 percent of the reservoir's inflow has been exported to the Central Valley. Decline of the fishery became apparent within the first decade of operation [2]. Today, the restoration and improvement of the fisheries and habitats associated with western rivers is a significant water resources management goal.

The Trinity River Flow Evaluation study has considered alternatives for improving the habitat and environment of the Trinity River below Trinity Dam. One recommendation of that study was to increase controlled releases from Trinity Dam to as high as 11,000 ft^3/s at specific times during the year. This raises significant operational issues because it would require combined releases from the various outlet works and the powerplant, a mode of operation not considered by the original designers. The studies described in this paper were performed to determine the maximum

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possible controlled release, considering the performance of both the outlet works and powerplant systems during combined release operations.

Figure 1. — Trinity Dam and Reservoir, Central Valley Project - California.

Trinity Dam is a zoned-earthfill structure completed in 1962, impounding Trinity Reservoir (formerly Clair Engle Lake). It has a structural height of 537.5 ft, a hydraulic height of 440 ft, a crest length of 2,450 ft, crest width of 40 ft, and crest elevation of 2395.0 ft. The reservoir volume is 2,760,900 ac-ft at El. 2388.2 ft, the design maximum water surface; 2,447,700 ac-ft at El. 2370 ft, top of active conservation pool; and 312,700 ac-ft at El. 2145, top of inactive storage. The spillway is an uncontrolled 54-ft diameter morning glory concrete structure with crest elevation 2370.0 ft and a design discharge of 22,400 ft^3/s at water surface elevation 2388 ft. In addition to the uncontrolled spillway, there are three controlled outlet facilities, illustrated in figure 2:

- 7,000 ft^3/s river outlet works controlled by two 84-inch hollow-jet valves
- 140 MW powerplant containing two Francis turbines
- 2,490 ft^3/s auxiliary outlet works controlled by one 84-inch jet-flow gate

The river outlet works system consists of a concrete lined 28-ft diameter tunnel, an intermediate gate structure with a 10×20-ft fixed-wheel gate, and a 16-ft diameter (15′-9″ i.d.) steel penstock with branches to both the powerplant and the outlet works control structures. The outlet works branch is an 11-ft diameter conduit that bifurcates into a pair of 7-ft diameter conduits, each leading to an 84-inch ring-follower gate and an 84-inch hollow-jet valve. The outlet works has a design discharge of 7,000 ft^3/s at El. 2370.0 ft.

The powerplant houses two 70 MW generators that were uprated from the original equipment (50 MW generators) in 1984. Water is supplied to the Francis-type turbines through two 11-ft diameter penstocks with 158-inch butterfly valves as guard valves for the turbines. Designers anticipated significant variation of water levels in the reservoir, and thus the turbines are equipped with both low-head and high-head turbine runners that can be interchanged on a seasonal basis. The low-head runners operate in the range of 222 to 394 ft of head, and the high-head runners operate in the range of 277 to 483 ft of head. Rated discharge from the low-head runners is 2,300 ft^3/s for each turbine, and rated discharge from the high-head runners is 2,050 ft^3/s for each turbine.

The auxiliary outlet works consists of a box intake structure, a 7-ft diameter concrete conduit, a gate chamber housing an 84-inch ring-follower gate and an 84-inch jet-flow gate, and an 8-ft oval shaped tunnel that slopes parabolically down to and exits freely into the spillway tunnel. The design discharge of the auxiliary outlet works is 2,490 ft^3/s at El. 2370.0 ft.

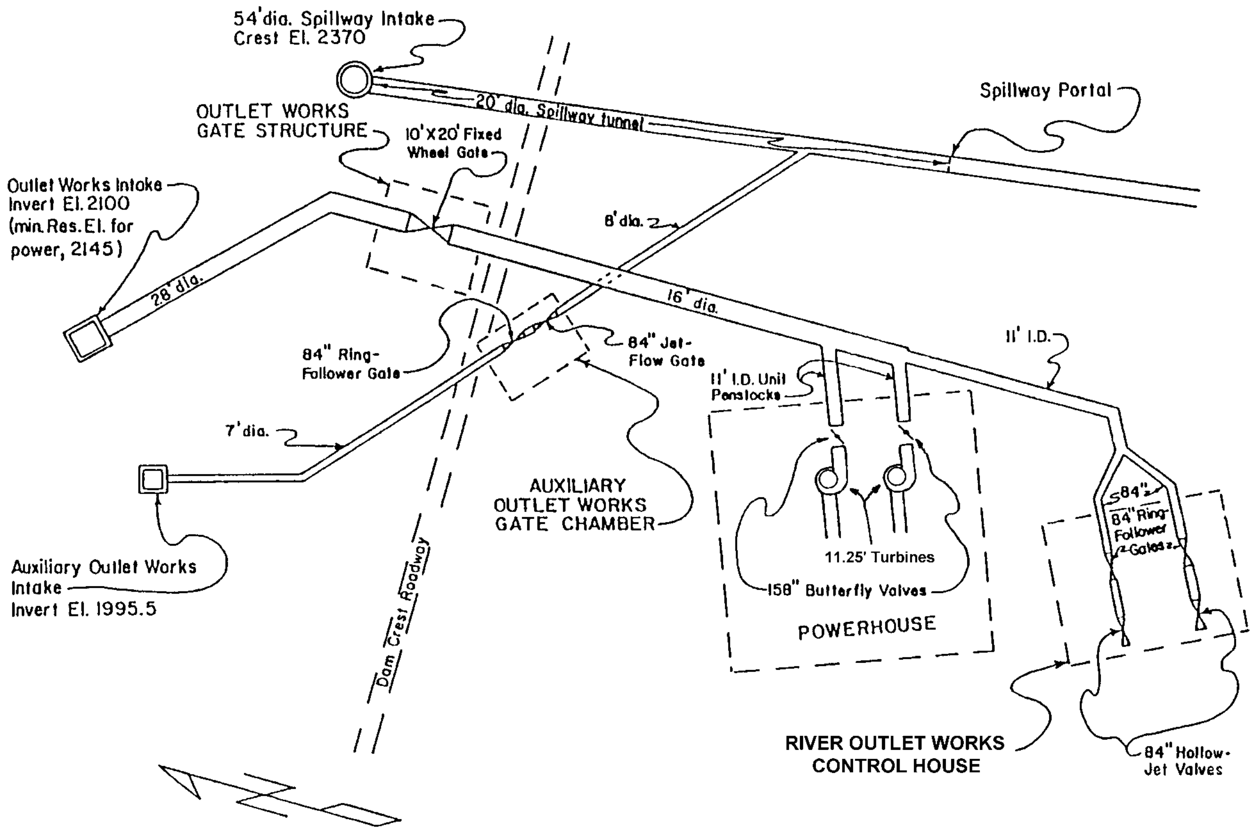

Figure 2. — Schematic diagram of spillways and controlled-outlet facilities at Trinity Dam.

Original Designs and Operations

Flood control and irrigation were the primary objectives of the original design. Recreational, fishery, and environmental releases were not recognized at that time as significant planning goals. Planned releases at Trinity are made through the powerplant, the river outlet works, the auxiliary outlet works, and the uncontrolled morning glory spillway, but not necessarily in combination with one another. Each possible outlet serves specific operational purposes, e.g., power production, reservoir evacuation during an emergency, and protection of the dam during flood events. The outlet works in particular were likely sized to meet reservoir evacuation criteria, and were analyzed for separate operation because operability of the powerplant could not be assumed during an emergency requiring evacuation of the reservoir. Similarly, the powerplant was designed for separate operation, since combined operation of the powerplant and the river outlet works would lead to reduced power output due to additional headloss in the penstocks.

Due to the large volume of storage behind the dam and the need to keep the reservoir low at certain times of year to meet flood control objectives, the spillway only operates during large floods, and normal day-to-day flows are released through the power outlets. The original plan for operation of the reservoir is to use the powerplant to the greatest extent possible, optimizing the power production through the use of the low-head and high-head runners. If additional releases are needed, the auxiliary outlet works is added to the powerplant flows. This allows for most efficient operation of the powerplant, since the auxiliary outlet works is an entirely separate system whose operation does not reduce the effective head on the turbines. If still more release capacity is needed, the powerplant is shut down and the river outlet works are operated. Finally, if flows are needed in excess of the capacity of the river outlets, the auxiliary outlet works could also be operated.

None of these original operational modes will produce the 11,000 ft^3/s release that is desirable for habitat improvement. To achieve this release capacity, simultaneous operation of all three outlet systems would be required. Directly summing the capacities of the three outlet systems suggests that such a flow is possible, but doing so neglects the fact that the combined operation of the river outlet works and the powerplant will lead to increased headloss in the penstock system, thereby reducing the effective head and the associated discharge for both the turbines and the hollow-jet valves. The increased headlosses may be dramatic, since headloss is generally proportional to the square of the velocity. If the total discharge is increased from 7,000 ft^3/s to 11,000 ft^3/s, headlosses through those components carrying the combined flow would increase by a factor of about 2.5.

A quick examination of the conduit system also suggests that the reduction of discharge capacity during combined operation may be dramatic, since the combined area of the three 11-ft diameter penstocks (one for each turbine and one for the pair of hollow-jet valves) is nearly 50 percent greater than the area of the 15′-9″ penstock. This suggests that when both turbines and hollow-jet valves are operating, there may be dramatic headlosses in the 15′-9″ penstock, leading to a so-called shift of control from the turbines and valves to the upstream conduit. Net head on the turbines and hollow-jet valves would be dramatically reduced, thereby reducing their discharge capacity at a given reservoir condition when compared to current operations.

Mathematical Model

A direct test to determine the combined release capacity of the Trinity Dam outlet works and powerplant system was not feasible due to the fact that there is no direct and accurate method for independently measuring the flow of the Trinity River immediately below the dam. The discharge from Trinity Dam almost immediately enters the backwater pool created by Lewiston Dam, located about 7 miles downstream. Lewiston Reservoir acts as an afterbay to Trinity Dam, attenuating peak power releases and serving to divert flows through the Clear Creek Tunnel into Whiskeytown Lake in the Shasta River drainage. Possible methods for conducting such a test would be to operate the Trinity outlets for a sufficient time to establish a steady state condition in Lewiston Reservoir and then measure the outflows from Lewiston, or to attempt to account for the transient behavior of Lewiston Reservoir, its releases, and the river channel between Trinity and Lewiston. Each of these alternatives presented significant logistical problems related to scheduling and conducting a test, collecting necessary data, and analyzing the data.

As a result, the decision was made to take a primarily analytical approach and develop a mathematical model of the Trinity Dam outlet works and powerplant system, similar to that likely used for the computation of the original design discharge curves, but including the effects of combined operation. A simplified field test was also used to calibrate the model. The mathematical model was applied only to the river outlet and powerplant system. The auxiliary outlet works capacity was assumed to be that shown on the original design drawings, although an analytical study by Buyalski [3] in connection with physical model tests of the auxiliary outlet jet-flow gate suggests that the auxiliary outlet capacity may be about 400 ft^3/s larger than that indicated on the original design drawings.

Several alternative methods for performing the analysis were considered, including the use of in-house and commercial software packages for outlet works and pipe network analysis, but none were fully capable of modeling the complexity of the Trinity Dam system, primarily due to the fact that turbine performance could not be modeled properly. As a result, a custom model of the system was developed using a spreadsheet that accounts for headlosses, boundary conditions, and operating characteristics of the various conduits, valves, turbines, and associated features of the system.

In general, the performance of most outlet works components can be modeled using an equation of the form $H_L=K_L(V^2/2g)$ in which H_L is the headloss caused by the component, K_L is a loss coefficient for the component, V is a reference velocity associated with the component, and g is the acceleration of gravity. Loss coefficients are typically constant over reasonable ranges of operating conditions, although they can sometimes vary as velocity changes. The performance of terminal components, such as the turbines and the hollow-jet valves in the river outlet works are generally analyzed using equations that relate the discharge to the net head available across the component, such as $Q=C_dA(2gH)^{1/2}$, in which Q is the discharge, C_d is a discharge coefficient, A is the area of opening, and H is the net head across the component. This net head is computed by starting with the total reservoir head and then subtracting the headlosses caused by the intermediate components. Sources of headloss in the Trinity outlet system include intake trashracks, entrance transitions, bends and elbows, pipe friction, expansions and contractions, the butterfly valves, the fixed-wheel and ring-follower guard gates, and the hollow-jet control valves.

The calculation of discharge capacity for any given reservoir level is an iterative process, since headlosses for specific components cannot be computed until the discharge is known, and discharges through the control structures (turbines and valves) vary as total system headloss changes. The computation procedure is to assume a discharge, compute corresponding headlosses, and then compute a revised discharge. In the spreadsheet model the calculations generally converge very rapidly. Calculations take place along three flow paths: the river outlet penstock leading to the two symmetric hollow-jet valves, and the two penstocks leading to the turbines in the powerplant. The turbine penstocks are not identical and connect to the river outlet penstock at different locations, and thus each must be analyzed individually. At the junction points within the system, heads must be equal and flow rates into and out of the junctions must be balanced.

The mathematical model was created using recommended values from the literature of loss coefficients and friction factors for the various conduits and other components of the system. Performance characteristics of the turbines and hollow-jet valves were available from original design drawings of the facilities and the dam's Standard Operating Procedures [4]. Once the mathematical model was validated to ensure its proper operation (i.e., conservation of head, conservation of flow, etc.), it was necessary to test the model at specific flow conditions to determine whether there was a need for adjustment of the assumed loss coefficients, friction factors, etc. It was expected that some adjustment would be required, since the range of recommended values for loss coefficients and friction factors is often quite large, depending on a number of factors such as the age and internal surface condition of conduits, geometric details of bends and other transition structures, and divisions of flow at elbows and bifurcations.

The first test of the model was to attempt to recreate the discharge curves for the river outlet works system, assuming no flow through the powerplant. For this mode of operation the model predicted significantly higher discharges than those indicated on the original design drawings. This result was not unexpected, since the original design discharge curves were probably computed using assumptions that led to a conservatively low prediction of the outlet capacity. Also, there was anecdotal evidence of past releases greater than the stated discharge capacity of the river outlets. For the purposes of this study, the objective was to determine the most likely maximum capacity of the outlets, so it was desirable to perform field tests that would help to tune the model to produce the most accurate estimates of actual release capacity.

As a result, two field tests were performed, and assumed loss coefficients in the model were adjusted based on the results of the tests. Once the adjustments were made, the model was used to compute combined discharges through the river outlet works and powerplant during simultaneous operation. These release capacities were used to create a set of revised discharge curves for the outlet facilities (fig. 3). The discharge curves show only the maximum release capacities, i.e., turbines operating a full-gate and hollow-jet valves fully open. Intermediate discharges can be obtained by throttling the hollow-jet valves or operating the powerplant at reduced gate settings. The mathematical model could be used to analyze details of these flow conditions as well.

Field Testing

It was desirable to confirm the combined turbine and outlet works discharge to the extent possible with field tests, since the revised values would affect operational modifications at the dam. The tests took place in August 1998, and were designed to produce data that could be used to calibrate the mathematical model. The data collected included reservoir and tailwater levels, powerplant output, pressures at the two turbines in the powerplant, and pressure and valve-position data at the hollow-jet valves. Discharges through the hollow-jet valves were determined as a function of valve opening and the measured pressure at the valve using original design drawing 416-D-1084, and the discharge through the powerplant was determined as a function of net head on the turbines from tables in the Standard Operating Procedures and from turbine performance curves on file at Reclamation's Technical Service Center in Denver. Discharges were not measured independently.

During tests in which the powerplant was operating, the pressure measurements at the turbines were used to compute the net head on the turbines, and discharges could then be determined from tables or the turbine performance curves. Pressure measurements at the turbines were also valuable for the tests in which the powerplant was not operating, because they indicated the division of headlosses upstream and downstream from the junctions of the turbine and outlet works penstocks. Pressure measurements at the turbines and at the hollow-jet valves were made using permanently installed gages that had been calibrated against a dead-weight tester.

Two tests covering three flow conditions were used to calibrate the model. On August 4, 1998, the river outlet works was operated at 60 percent and 100 percent valve openings (both valves at same opening in each case), with the powerplant operating at speed-no-load (minimal discharge), and the reservoir at elevation 2365.6 ft. On August 6, 1998, the outlet works and powerplant were operated simultaneously with both hollow-jet valves 100 percent open and both turbines operating at near full-gate conditions. The high-head runners were installed in both turbines, and the reservoir was at elevation 2364.95 ft. The overflow spillway and auxiliary outlet works were not operating during any of the tests.

The general procedure for each of the tests was to establish the desired flow conditions, then wait 5 minutes before beginning to record data for a 25 minute test period. The stabilization period allowed for dissipation of transients and gave time for the interior surfaces of the conduits to be swept clean of any debris or buildup that might temporarily increase friction losses at the start of the test. The various guard gates in the system (fixed-wheel gate, ring-follower gates, butterfly valves) were all fully open during the tests.

In an effort to minimize downstream turbidity, the test procedures were designed to minimize the volume of water released into Lewiston Reservoir. Lewiston Lake turbidity levels were monitored prior to and during the tests at the request of the North Coast Region of the State Water Quality Control Board. Turbidity levels did increase more than 20 percent during the first test on August 4, but both tests were allowed to be completed as scheduled.

Overall, the tests confirmed the higher discharge capacities being predicted by the mathematical model. Some fine-tuning of loss coefficients and friction factors was required to obtain a good fit to the test data, but the resulting model parameters were well within reasonable bounds. Of course, it was not possible to perfectly tune the model to match all of the test results. Some possible reasons include variation of loss coefficients during combined flow operations, random errors in pressure measurements and other test data, potential for bias in pressure measurements due to imperfect pressure taps and piezometer connections, and uncertainty in discharge determinations. The model was calibrated to most closely fit the test results from the 60 percent operation of the outlet works, since the lower flowrate during this test minimizes the magnitude of some of the potential errors. This causes the model to underpredict the observed pressure at the outlet works valves during the tests at 100 percent valve opening, and thus the corresponding discharge is also underpredicted. The differences between the releases predicted by the calibrated mathematical model and the estimated discharges during the field tests range from +1.6 percent to -4.6 percent.

Results

The calibrated model predicts a maximum controlled-flow release of 13,750 ft^3/s at reservoir water surface elevation 2370 ft (crest of the uncontrolled spillway), which includes flows through the river outlet works, the powerplant (using the high-head runners), and the auxiliary outlet works. A set of revised controlled-release discharge curves is shown in figure 3. The figure shows the maximum controlled-release capacity under three different scenarios:

1) **River outlet works operating without powerplant** - This curve shows the discharge at 100 percent opening of the two hollow-jet valves, and indicates about 18 percent greater discharge

than that shown on the original design drawings. This increased discharge capacity was verified by the field test performed August 4, 1998.

2) **River outlet works in combination with powerplant (high-head runners) -** This curve shows the combined discharge when the hollow-jet valves are operating at 100 percent opening and with one or both turbines at full-gate, with the high-head runners installed. Due to increased headlosses in the shared outlet/powerplant penstock system during simultaneous operation, at reservoir elevations below 2262 ft there will be insufficient head to operate the powerplant in the design net head range for the high-head runners. Between elevation 2262 ft and 2290 ft, there is only sufficient net head to operate one turbine; bringing a second unit online would reduce the net head below 277 ft. Unit 1 should be operated in this case, since it has the most upstream connection to the outlet works penstock, and thus the most available head. It should be noted that these restrictions on turbine operation can be relaxed if the river outlets are partially throttled, since this would reduce total headloss and increase the net head on the turbines. The mathematical model could be applied to such scenarios, although specific cases were not analyzed for this study.

3) **River outlet works in combination with powerplant (low-head runners)** - This case is similar to (2). For reservoir elevations below 2213 ft, there will be insufficient head to operate the turbines within the design head range for the low-head runners. From elevation 2213 ft to 2241 ft, there is only sufficient head to operate one turbine. Again, unit 1 should be operated in this case. For reservoir elevations at or above 2298 ft, the simultaneous operation of the outlet works and powerplant produces enough additional head loss that the low-head runners can still be used and will operate within their design net head range. However, the low-head runners are unlikely to be installed in the powerplant under these conditions, since they would operate at heads higher than their design range if the outlet works were not also operating. Thus, this portion of the discharge curve is shown as a dashed line. Note that the greatest release capacity is obtained by using the low-head runners in this range. Again, it should also be noted that there would be additional flexibility in turbine operations if the river outlet works were operated at partial capacity.

Cavitation potential in the outlet works system was not analyzed. The increased discharge and reduced pressures caused by combined operations of the outlet works and powerplants do have the potential to create cavitating flow conditions. If prolonged combined operations of the river outlet works and powerplant occur in the future, special attention should be given to any elevated noise levels that might indicate ongoing cavitation, and the outlet works system should be inspected for cavitation damage following those operations.

Conclusions

Modifying operations of existing facilities to meet new project objectives often raises many difficult issues and requires detailed analysis to ensure that new operating scenarios are compatible with capabilities of the facility. The intent and objectives of the original designers should be carefully considered when examining such changes in operations. The model described in this paper and the process used to develop and calibrate it demonstrate this for the specific case of increasing releases from Trinity Dam. Similar models could be applied to other dams at which controlled-release operations are being modified to meet new project objectives.

References

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3) Buyalski, Clark P., Trinity Dam Auxiliary Outlet Works-Hydraulic Laboratory Model Results, Report PAP-483, Water Resources Research Laboratory, U.S. Bureau of Reclamation, Denver, Colorado, 1985.

4) Standard Operating Procedures for Trinity Dam, U.S. Bureau of Reclamation, Denver, Colorado.

Conversion Factors

1 ft = 0.3048 m
1 ft^3/s = 0.0283 m^3/s
1 inch = 2.54 cm
1 ac-ft = 1233 m^3
1 mi^2 = 2.59 km^2

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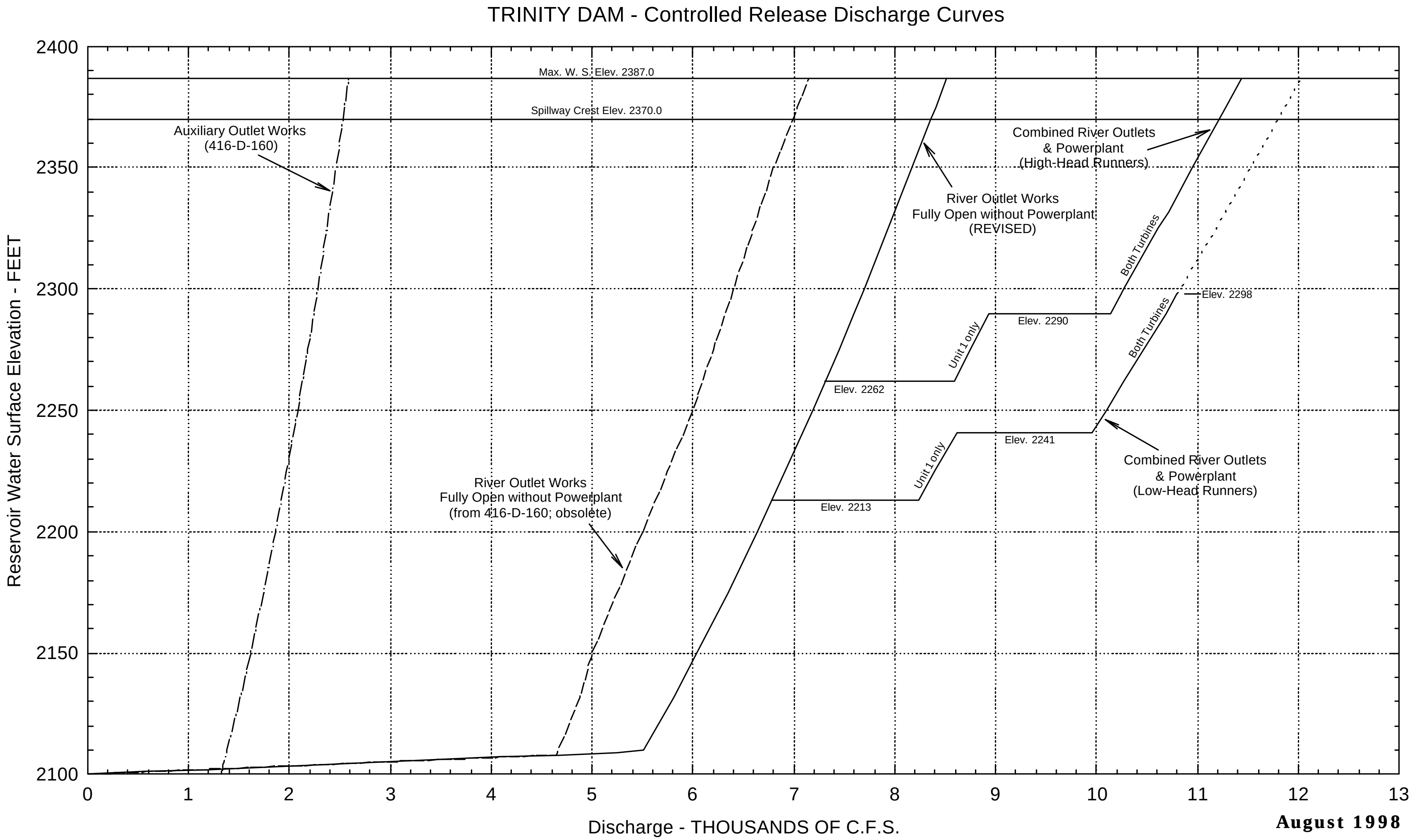

Figure 2. — Discharge curves indicating maximum separate and combined releases from Trinity Dam outlet works and powerplant.