Optimized Reservoir Refill

Tom Chisholm, Civil Engineer, U. S. Army Corps of Engineers Northwestern Division, Portland, OR tom.a.chishom@usace.army.mil

Introduction

Refilling reservoirs in regions with seasonally varying water supply can be one of the most challenging aspects of reservoir operation planning. Refill operations aim to strike a balance between storing sufficient water to meet demand for water during ensuing periods of lower water supply while maintaining sufficient space in reservoirs to prevent flooding caused by high inflow events occurring when projects approach full. The operational challenge becomes finding the optimum balance between these two competing objectives. The following describes attempts to use mathematical optimization to find this optimum balance.

Application

To address uncertainty in future water supply, regulators use multiple scenarios, called ensemble stream flow predictions (ESP). Hydroregulation models regulate ESP traces. Historically, a regulator calculated a refill operation using engineering procedures and judgment for the median ESP trace. The resulting operation was then tested using the full suite of ESP traces. The optimization approach described herein allows automatic calculation of an optimum refill operation for each ESP trace. These optimum operations are then statistically analyzed to determine operational directives provided to dam operators. The optimization approach results in more repeatable results obtained with less regulator effort. The procedure may be implemented repeatedly as revised ESP traces become available.

The optimization procedure starts by running a constraint driven reservoir regulation model with pre-computed refill percentages. The implementation described herein used the Reservoir System Simulation (HEC-ResSim) model (HEC 2013). The HEC-ResSim flow at the potential flooding location is extracted from HEC-ResSim as a sum of discharge from the dam being analyzed and discharge from other sources. The discharge from the dam being analyzed is then optimized using the Frontline Systems Analytic Solver (Frontline Systems 2018) on an ESP trace by ESP trace basis resulting in a cumulative distribution plot of optimum project elevations. Frontline Systems developed the solver that comes with Microsoft Excel and Analytic Solver is similar but more capable.

Test System

Numerical experiments investigated optimization based operation of a reservoir system. Analyses use an artificial system of two dams one upstream of the other. Both dams have a capacity of 600 kaf. Inflow to the reservoir system occurs into the upstream reservoir, between the reservoirs, and downstream of the lower reservoir. Inflows use daily flow from ESP data produced by the Northwest River Forecast Center in Portland, OR and issued 7 January 2019 (https://www.nwrfc.noaa.gov/misc/downloads/). Using data beginning 6 months after forecast date minimizes impacts of current conditions on ESP traces. Analyses use the portion of ESP projections extending from 1 July 2019 to 30 June 2020. Data from three northwest river systems provided inflow traces. These included the Slocan River near Crescent Valley, BC (SLCQ2W 123229000) modeled as flowing into the upper reservoir (upstream reservoir inflow), the Yakima River near Parker, WA (PARWW 125050003) modeled as the incremental flowing into the lower reservoir (between reservoir inflow), and the Grande Ronde River at Troy, ID (TRYO3W 133330000) modeled as the incremental below the lower reservoir (downstream of lower reservoir inflow). Much of the upstream reservoir inflow comes from high elevation so it occurs during the early summer freshet. Between reservoir inflow and downstream of lower reservoir inflow come from more southerly areas so their freshets occur earlier and their runoff is more evenly distributed throughout the year. The Yakima River has the largest annual average runoff of 3942 kaf and the Grand Ronde has the least with 2190 kaf. The Slocan is slightly larger than the Grande Ronde with 2438 kaf.

Analysis

Flood management attempts to minimize peak flow for a flood season. The obvious objective of optimization is thus to minimize maximum discharge of the season. In practice minimizing peak flood implies maintaining constant flow during a flood season. Two measures of constant flow are 1) sums of absolute values of daily flows minus average flows and 2) sums of squares of flows. These were tested on a one reservoir system with the reservoir fed by the Yakima River traces and Grande Ronde River traces serving as incremental flow downstream of the reservoir.

Specifying peak flow in the objective function implies that flow on only one date specifies the objective function, although the date can vary as the optimizer searches for the optimum solution. This can lead to unrealistic solutions in time periods that are not flow peaks. Therefore, using max flow as the objective functions leads to undesirable solutions.

Specifying even flow effectively minimizes peak flow. The absolute value of the flow minus the average flow evenly weights all deviations from average. However, it results in a function with a discontinuous derivative, which adversely impacts efficiency of gradient solvers. Squaring flow or the difference between flow and average flow yields a value that increases quadratically as flow increases. Therefore, their sum over a time period is minimized by even flows. Both appear best suited for optimization based minimization of peak flows.

Optimization software frequently limits problem sizes, providing an incentive to simplify problems. One simplification for the test system would be to optimize reservoir operations one at a time. Thus a comparison was done of 1) optimizing the upstream reservoir then the downstream reservoir 2) optimizing the downstream reservoir then the upstream reservoirs and 3) optimizing both concurrently. These approaches were compared for a high water trace (1973-1974) and a low water trace (1972-1973). All scenarios optimized to produce virtually identical maximum flows. Not surprisingly, if the reservoirs are optimized separately the solution flexes the first reservoir optimized more aggressively then the second. In larger water conditions, operations are more similar because flexibility in both reservoirs is used to the maximum extent possible. In smaller water years the first reservoir optimized is flexed as much as possible and the second reservoir is only flexed as much as necessary to achieve objectives. Optimizing both reservoirs concurrently produces more balance between reservoirs. Optimizing reservoirs separately results in a numerically simpler problem and appears to produce acceptable results if the analyst is aware of this behavior. Optimizing concurrently in most cases appears to be the desired approach.

If an optimizer is not available or the analyst does not wish to use one this section describes a simplified approach that uses a root finding algorithm such as bisection. Remembering that minimizing peak flow for a period is achieved by releasing constant flow throughout the period one can divide the sum of inflows and change in reservoir storage for the period by the length of time to obtain a discharge for the entire period. In most cases this operation is physically infeasible: to support it the reservoir must draft below empty or fill beyond full or water must flow upstream into the reservoir. However, modeled reservoir elevation is readily constrained to ensure physical reasonableness. In this case the reservoir releases the desired average flow except when it can't. The problem becomes adjusting the desired discharge to minimize the sum of the squares of the discharge. This problem has one free parameter, the desired discharge, and one value to minimize, the sum of the squares of the discharge. Numerically it is an easy problem to solve. The result is not as optimal as that produced by a solver. In a test example the objective function found using the simplified example was 14% larger than the optimized solution. However, in one example of 70 traces it reduced solution time from over an hour to less than 5 minutes.

Conclusion

Modeling reservoir operations using the constraint driven HEC-ResSim but applying a solver to determination of reservoir refill operation appears to offer promise. Minimizing squares of project discharge is computationally more robust than other tested approaches. Alternate numerical approaches including individually optimizing reservoirs and using a root finding based approach yield less desirable but useful solutions.

References

Frontline Systems. 2018. "Frontline Solvers Reference Guide", Incline Village, NV.

HEC (Hydrologic Engineering Center). 2013. "HEC-ResSim Reservoir System Simulation, User's Manual". Davis, CA.