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TWO WAYS TO BENEFIT FROM THE USE OF MATHEMATICAL OPTIMIZATION FOR REVISING RESERVOIR OPERATING RULES – A CASE STUDY OF THE BARGI AND TAWA RESERVOIRS IN NARMADA RIVER BASIN

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ABSTRACT

Mathematical Optimization can introduce significant benefits to reservoir operations in India. One example demonstrated on Tawa reservoir shows the ability to develop and utilize dynamic real-time rule curves based on the current conditions in the field and statistical analyses of previously developed optimal solutions. Another example on Bargi reservoir shows how to improve the existing reservoir operation by combination of optimization algorithms and short-term runoff forecasting models. Both options are demonstrated on case studies conducted on the reservoirs in Narmada River Basin. Optimized operations show a potential to increase monetary benefits by a factor of 4 times in total on Bargi reservoir, where the planned increase of irrigation water supply to the tune of 6.7 times compared to historic operation would result in a reduction of generated hydro power by only 30%. Other large reservoirs in India would benefit from conducting similar analyses.

1. INTRODUCTION

While initially proposed almost half a century ago by Revelle et al. (1969), reservoir rule curves are still a preferred methodology that has dominated reservoir operation world-wide. There are various interpretations of the term “rule curve”, with some authors referring the “reservoir comfort zones” instead of individual curves, or sometimes referring to upper and lower operational limit that is defined as a temporal variable. The differences between these notions will be addressed later in this paper, but in general, a reservoir rule curve will be defined at the outset as “a trajectory of reservoir levels throughout the year that best meets the operational objectives of the reservoir”.

A standard method used to construct reservoir rule curves has relied on the use of simulation models based on the trial-and-error approach. The downside of this approach is that the final outcome often depends more on the skill of the modeler than on the type of simulation model being used. In this context, the most widely used Simulation models in India have been the Mike HYDRO BASIN (Danish Hydraulic Institute, 2021), formerly known as Mike-BASIN, HEC-ResSIM (Hydrological Engineering Center, 2022) and ReSyP (National Institute of Hydrology, 2020). The quality of the rule curves developed using simulation models has not yet been objectively evaluated, and it remains an active area of research.

Optimization models have been used to generate optimal reservoir operation for each simulated year, by using either the historic or stochastic inflow series. A recent review of the types of models used in the water resources sector are provided by Rani and Moreira (2010), while Dobson et al. (2019) provide a comprehensive literature review of the use of optimization models in river basin management with an effort to distinguish planning phase and an operational phase that is based on learning from the results of planning studies. A similar and even a more focused review of such attempts is provided in a recent publication by Macian-Sorribes & Pulido-Velazquez (2020), aimed at analyzing different ways of inferring efficient reservoir operating rules based on the results of modelling. These review papers offer a lot of information related to various attempts to benefit from the use of optimization, without clear guidelines on which approach would likely be the most effective. This paper presents two possibilities for using the results of optimization models. Both possibilities emphasize the use of optimization in the planning phase, from where the results are used to improve reservoir rule curves, and use them in real time either in combination with runoff forecasts or as a basis to construct dynamic rule curves.

2. SINGLE VERSUS MULTIPLE TIME STEP OPTIMIZATION

Most popular optimization-based models such as the MODSIM (Colorado State University, 2022), AQUATOOL (Haro et al, 2012), REALM (Victoria State Government, 2022) or E-water (E-Water.org, 2022) call built-in optimization programs for each time step individually. This may lead to premature emptying of storage in dry years, as shown in Figure 1 below. A rule curve, shown as a broken line in Figure 1, is required in order to prevent this from happening. The curve defines the minimum storage that has to be left in the reservoir at the end of every time step throughout the irrigation season. The principal difficulties associated with rule curves is related to the following:

(a) The current shape of the rule curve is the same of all years, while the best shape depends on the available inflows, starting storge level and water demand management at times when deficits are inevitable; and,

(b) The standard shape of rule curves assumes that the reservoirs were filled during the monsoon season, while this may not happen in every year. In years where the starting storage at the beginning of the dry season has not reached the full supply level, reservoir operators have to resort to alternative rules that are used in combination with various rationing policies to avoid crop failure. In practice, reservoir operations under such circumstances often have to rely on the personal experience and judgement of the operators.

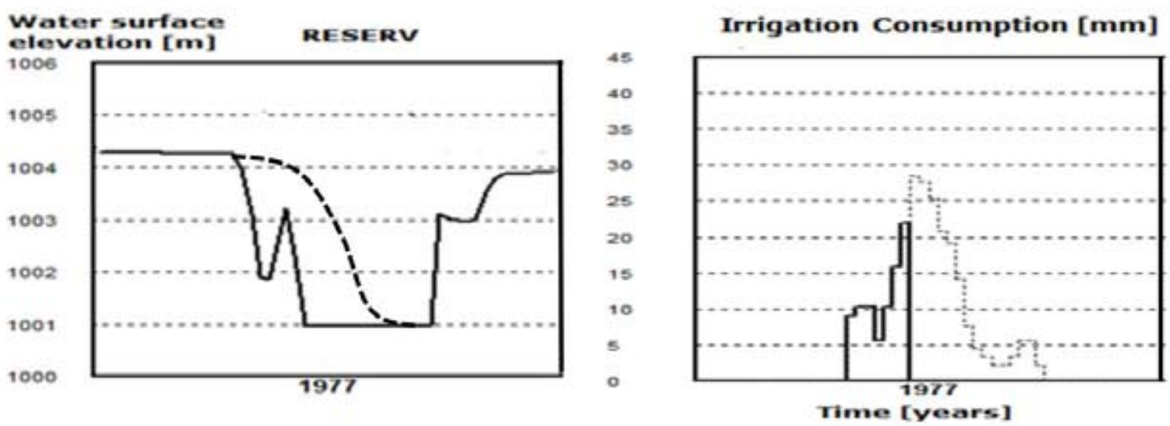

Fig. 1 : The Rule Curve Concept

To resolve issues (a) and (b), it is necessary to develop a combined approach at strengthened development of river basin plans as well as a methodology to apply such plans in real time operation. A good plan starts by developing a series of optimal solutions over the long historic (or stochastic) inflow data series, based on the known approach that utilizes dynamic networks, where consecutive time steps are solved simultaneously over a longer time horizon, as shown in Figure 2 below.

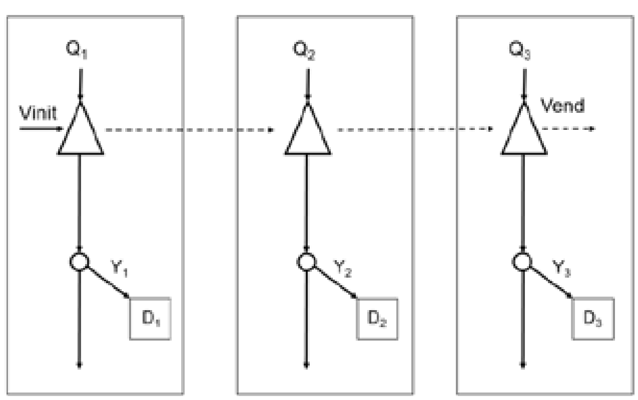

Fig. 2 : Example of Multiple Time Step Solution Setup for three consecutive time steps

The same system shown in rectangular section is connected to itself in consecutive time steps via the reservoir carry-over storage arcs, such that the ending storage for the previous time step represents the starting storage for the subsequent time step. The optimization problem is not posed as a water management problem over space and time. In instances where maximization of the benefit function is used, this translates into the following objective function:

$$Max \sum_{i=1}^{n} \sum_{t=1}^{m} Y_{i,t} P_i \qquad ...(1)$$

Where $Y_{i,t}$ is the amount of water provided and Pi is the pricing factor applicable to the unit of supply to each stakeholder. Typical constraints will involve the mass balance at each node, inclusion of net evaporation and upper limits on flows in various channels. We add one more important constraint which is associated with sharing deficits evenly over the entire irrigation season:

$$\frac{Y_t}{D_t} = \frac{Y_{t+1}}{D_{t+1}} \qquad for\ t{=}0{,}n{-}1 \qquad ...(2)$$

With the inclusion of this constraint, the model will simultaneously provide a perfect rule curve for each year as part of its solution, along with the minimum required water demand hedging if this is necessary in dry years. Consumptive use deficits expressed as a fraction of the total demand will be evenly distributed over the entire irrigation season in each year. Such solutions provide a wealth of information for statistical analyses or machine learning algorithms. They can be used to help generate dynamic rule curves, or they can be used to improve the existing operating rules and test them under the assumption of forecasting horizons of limited lengths, as demonstrated below, and as previously demonstrated on a Damodar Valley Corporation study by Ilich and Basistha (2021). The same WEB.BM model used in that study was used to obtain the optimization results analyzed in this study. The WEB.BM enables the use of Linear Programming optimization for river basin planning studies and for real time operation (assuming forecasted runoff is available from third party sources), by incorporating both reservoir and hydrologic channel routing as constraints to optimization (Ilich, 2022).

3. THE UPPER NARMADA RIVER BASIN

The examples presented in this paper are based on the recently generated historical natural flows into Bargi and Tawa reservoirs, which are the major reservoirs located in the upper portion of the Narmada River Basin. Their main purpose is irrigation supply, and both reservoirs have not yet reached the full diversion capacity that was planned for the ultimate utilization. Tawa reservoir has a small hydro power plant on its left canal, while there is a hydro power plant of 90 MW capacity on the outflow to downstream river from Bargi reservoir. The modeling schematic of the Upper Narmada Basin is shown in Figure 3.

Fig. 3 : Upper Narmada Basin Modeling Schematic

3.1 Construction of Dynamic Rule Curves on Tawa Reservoir

Tawa reservoir was built in 1974. It collects average annual runoff of 3750 MCM that mainly occurs during the 4 monsoon months from a catchment area of 5983 km^2. This runoff is balanced with a live storage is 2300 MCM so as to manage the ultimate irrigation target demand of 2600 MCM supplied via two large irrigation canals. Historical reservoir inflows were generated on a 10-daily basis by using the historic outflows, storage levels and estimates of net evaporation. The historical natural inflows developed in this fashion were used as input into a stochastic hydrologic model that generated 1000 years of synthetic inflows which are statistically indistinguishable from the historic series on all relevant statistics such as the mean, variance, annual auto-correlation and auto-correlation of 10-daily flows for all significant lags (Ilich, 2009).

Optimal solutions were developed by using the WEB.BM (Ilich, 2022) model for each of the 1000 synthetic inflow series assuming perfect forecast over one hydrological year. The ending storage from the previous year was used as a starting storage for the subsequent year. In dry years, deficits were distributed evenly by complying with equation (2). An example of simulated storage levels and water use for several consecutive years are shown in Figures 4 and 5.

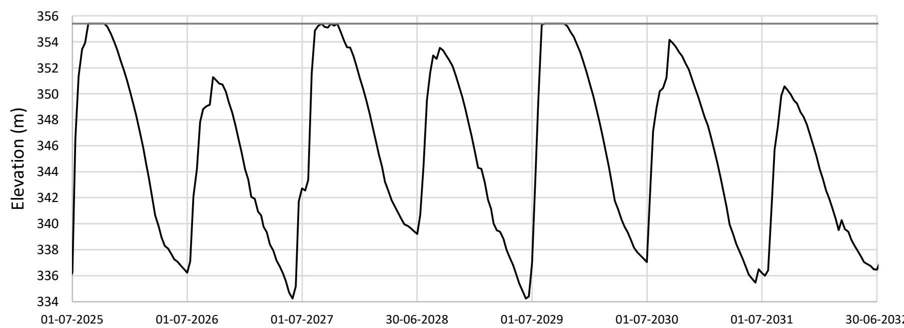

Fig. 4 : Example of Simulated Storage Levels on Tawa Reservoir

The above levels should be understood as the "perfect rule curves" derived by the optimization model assuming full foreknowledge of incoming flows in the current year and the starting storage level inherited from the previous year. The above simulated levels correspond to the supply levels that may experience a varying degree of deficits (Figure 5) that comply with the constraint in equation (2).

It is obvious from Figure 4 that a standard rule curve is applicable for dry season operation in years when the reservoir is filled (e.g., hypothetical years 2025-26, 2029-30 since the hydrological year begins on July 1st), but its guidance is not applicable for other starting levels that are seen in years when the complete filling of storage has not been achieved. Each of those years is associated with some level of deficits, implying that the basin managers must manage both storage and water demands simultaneously. It should be mentioned that these results were obtained with the assumed minimum environmental flow of 10 m3/s to be maintained at all times. This is an improvement to the current operation that has no minimum outflows, thus causing environmental concern during dry seasons.

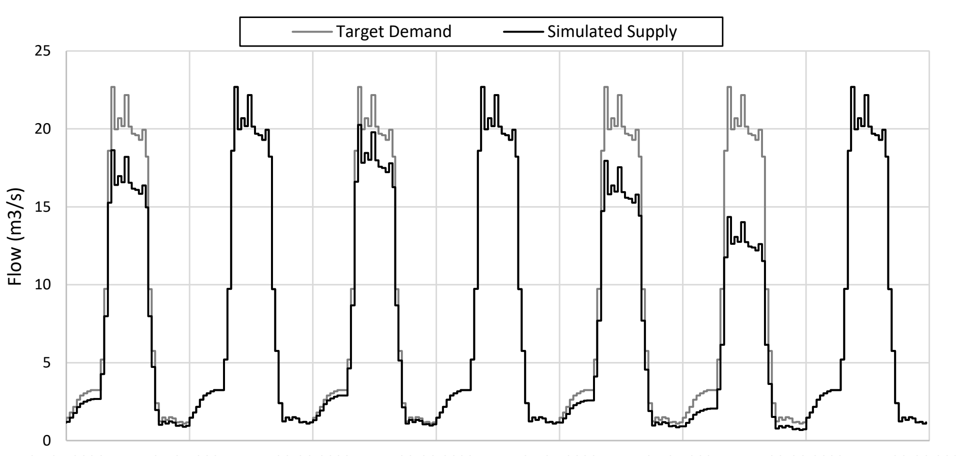

Fig. 5 : Achieved Water Supply to Tawa Right Canal

Once optimal solutions have been developed for 1000 synthetic years, derivation of dynamic rule curves proceeds in the following manner:

(a) Pick a time interval within the year and a selected starting storage level;

(b) Select a subset of solutions (from the entire database of 1000 years) such that their simulated starting levels are within a small range (e.g., +/— 0.2 m) from the starting storage at the time interval selected in step a);

(c) Conduct statistical analyses of simulated sub-set of storage levels selected in step (b) to find the selected the median, 10 percentile and 90 percentile elevations, thus defining a family of reservoir trajectories that starts from the selected time step and progresses for a chosen horizon of up to 2-3 months ahead. As an example, Figure 6 shows the 10 solutions (out of 1000) that have the closest elevation to 345 m at the end of February 20th of each simulated year. The color of each line depicts a trajectory of storage levels for each of the selected years.

(d) Probability density functions are plotted for the end of the 6th and the 8th 10-daily time period. These functions are generated for the end of each period, and the storage levels are plotted for selected probability of occurrence for these periods. This will generate for example a median comfort zone (water levels between 40 and 60 percentile), and a wider range (between 10 and 90 percentile) of anticipated water levels that can serve as guide curves given the starting storage level in combination with the anticipated hydrological conditions, which will be available as a result of the current NHP projects such as the Extended Hydrologic Prediction (EHP) project managed by the Central Water Commission that includes the Narmada River Basin forecasts. The amount of water demand hedging (reduction) can also be analyzed in a similar way and included in the forecast based on the analyses of the range of deficits encountered in the selected solutions.

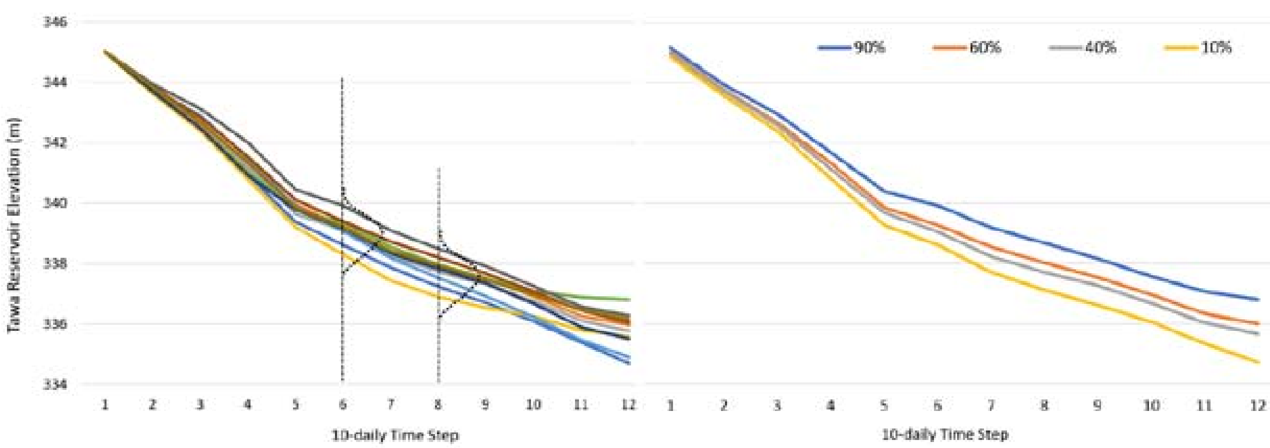

Fig. 5 : Derivation of Dynamic Rule Curves for Low Flow Season

Dynamic rule curve created in the above manner have some good properties: (a) they are easy to follow, since they always start from the current storage level; (b) they can be updated after every 10-daily (or weekly) period by updating the storage level and the starting time step; and, (c) they can be combined with the hydrologic forecasts (assuming they are available) to select the appropriate trajectory which may be above or below the median range in combination with the right amount of demand hedging.

3.2 Improvement of Bargi Reservoir Rule Curves

The WEB.BM model was run on a 47 years of weekly natural flow data that were obtained from the most recent development on the EHP project. Weekly data provide a slightly better resolution than 10-daily, since they split the annual hydrograph into 52 points instead of 36. Similar approach shown in Figure 5 is based on statistical analyses of the MTO solutions but over the entire hydrologic year (i.e., all 52 weekly time steps). This approach was applied to create alternative reservoir operating zones, and these zones were used in combination with the short horizon MTO solutions which are based on relying on runoff forecasts of up to 4 weeks.

WEB.BM has three solution modes: Single Time Step Optimization (STO), Multiple Time Step Optimization (MTO), and a combined mode of where MTO solution is applied only over a short-term horizon designated as the STO-n mode, where n is the number of time steps in the forecasting horizon. In this context, a weekly simulation is conducted using the simultaneous optimal solution for 4 weeks, while the only adopted solution is the decision on reservoir releases for the first out of four weeks. This improves a weekly flow allocation since the model assumed foreknowledge of the runoff in the subsequent three weeks. The assumption of runoff forecast availability over the 4-week period is based on the existing target of the EHP project which has a goal to provide runoff forecast of up to 4 weeks ahead. This causes the model to conduct reservoir drawdowns prior to incoming floods, such that the flows bypassing the turbines are minimized, while also adopting allocations with equal deficit sharing forecasts over the next 4 weeks. Figure 6 shows a comparison of the historic Bargi reservoir elevations and the results of the STO-3 simulation for the current (1365 MCM) and the ultimate (3388.5 MCM) levels of water use, which are significantly higher than the mean historical water use over the 2000-2017 period (506 MCM).

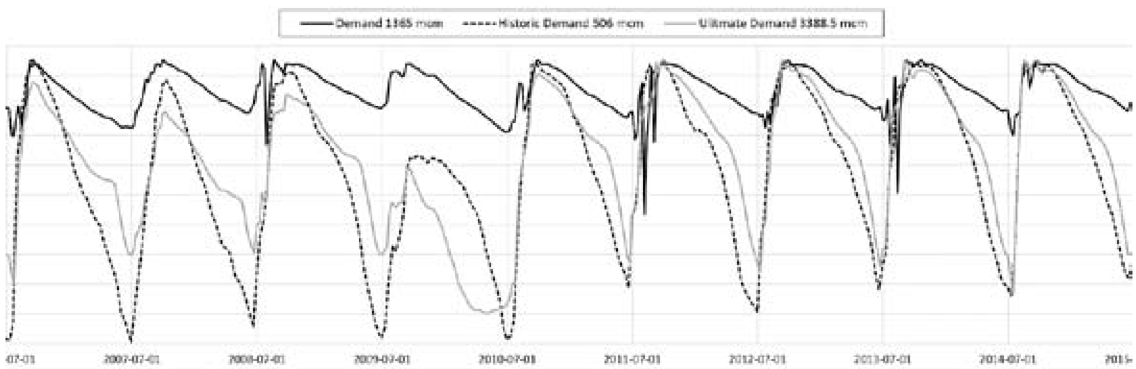

Fig. 6 : Comparison of Historical and Simulated Bargi Reservoir Levels (m)

Table 1 : Mean Annual Economic Benefits of Improved Reservoir Operation

Scenario	Mean Annual output		Monetary Benefits in millions of Rupees		
	Irrigation (MCM)	Power (GWh/MU)	Irrigation	Electricity	Total Value
1 (Historical)	506.0	379	1518	1326.5	2845
2 (Current)	1365.0	299	4095	1046.5	5142
3 (Ultimate)	3388.5	271	10166	948.5	11114

It should be noted that although the average historic water use over the 2000-2017 period was only 506 mcm, the reservoir has been drawn down significantly to a level between 406 and 408 m almost every year (dashed line in Figure 6), while there seems to be little justification for this, as attested by the simulated levels in Scenario 2 which provides 1365 MCM on average to irrigation blocks, while managing to maintain the Bargi reservoir storage at much higher levels. The higher than historical levels are seen even in the case of the ultimate water demand scenario which is 6.7 times higher than the historical. Assumed monetization in Table 1 is 3 million Rupees per 1 MCM of Irrigation water supply and 3.5 million Rupees per 1 GWh of generated electricity, considered as the average figures in India.

4. CONCLUSIONS AND RECOMMENDATIONS

This paper demonstrates a potential for significant improvements in reservoir operation as a result of using MTO solution procedure. Dynamic rule curves are presented as an option for low flow season management, while the monsoon season requires both an optimization model with modified operating rules and a runoff forecasting model. The results presented in this paper are optimistic in terms of the runoff forecasts, since they assume perfect runoff forecasts for 4 weeks ahead.

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