A Multi-Objective Reservoir Optimization Software (MORO) with Sediment Flushing Computation

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Abstract. Sedimentation not only diminishes the benefits of reservoirs, but also leads to the degradation of riverine ecosystems. Reservoir sedimentation appears particularly serious for China with the maximum annual storage loss of 2.3%, resulting from both the hyper-concentration sediment rivers and the rapid increase of large reservoirs. This study proposed multi-objective reservoir optimization software (MORO) with sediment flushing computation based on measured data of sediment concentration, which was applied to a large reservoir and can be generalized to other reservoirs. The results show that within the recommended discharge variation of 4%, the sediment release can be increased by 1.41\times10^6 t as the reduction of per 10^10 kWh in annual power generation. Compared with the original scheme, the sediment release can be increased most by 2.97% at the cost of 0.29% loss of power generation. Moreover, the dual objective in the flood season has been optimized by 6.40% and 3.39%, respectively.

Keywords. MATLAB software, reservoir sedimentation, multi-objective optimization, suspended load

1. Introduction

To solve reservoir sedimentation, various measures have been carried out, mainly including reducing incoming sediment yields from watersheds, mechanical removal, and hydraulic methods. Among these attempts, sediment flushing has been proved to be quite an effective way with low cost in many cases [1]. There have been several numerical models focused on the predicting reservoir sedimentation and sediment concentration during sediment flushing physical reported since 1970s [2, 3], such as HEC-6 developed by US Army Corps of Engineers [4], FLUVIAL-12 model [5], MIKE 11 of Danish Hydraulic Institute (DHI) [6], the International Research and Training Center on Erosion and Sedimentation [7], and Yang & Simões [8]. These models usually contain well-known sediment transport equations sourcing from different researchers. A large amount of empirical formulas inevitably occur in these models.
Complicated mechanism leads to a large amount of empirical formulas in sediment calculations, and thus simulation-based models are usually adopted for reservoir sedimentations instead of optimizing the sediment flushing during its operation. Moreover, the confliction between flushing sediment and other reservoir operational objectives such as water supply also limits the consideration of sedimentation in reservoir optimizations. Reservoir operators usually undertake the flushing operation by experience rather than a definite operation rule [9]. Accurate calculation of sediment transportation appears the bottleneck constraint, which should not be with the today’s upgraded monitoring technology.

This study proposed multi-objective reservoir optimization software (MORO) with sediment flushing computation based on measured data of sediment concentration. There are four modules in the system, the curve fitting of vertical distribution of flow velocity, the curve fitting of vertical distribution of suspended load, the calculation of sediment flushing, and the multi-objective optimization module. Two objectives are considered in this study for reservoir operation: maximizing annual power generation, and maximizing sediment flushing. The reservoir releases are taken as the decision variables, determining both the power generation and the sediment flushing. The vertical distributions of flow velocity and suspended load are fit with actual measured data. The amount of flushed load is then calculated with different reservoir release. Non-dominated Sort Genetic Algorithm (NSGA-II) is used for optimization, and the Pareto Front is finally figured out. For uses, they only need to provide several measured data, and the optimal trade-off between power generation and sediment flushing, as well as the corresponding reservoir release scenarios can be obtained.

2. Methodology

2.1. Bi-level Optimization Model

Object 1: Maximizing annual power generation

Power generation is an important function for most reservoirs. The hydropower station’s regulating capacity is used to generate maximal hydropower by considering the operational constraints and power load of the system. The objective function can be expressed as equation (1) [10]:

$$\max E(\tilde{Q}) = \max \sum_{t=1}^{T} KQ^tH^t\Delta t$$  \hspace{1cm} (1)

where $E$ is the total annual power generation; $K$ is the comprehensive output coefficient, which is set as 8.5 in this study; $\Delta t$ is the time step; $Q^t$ is the total discharge of the hydropower station in period $t$; $H^t$ is the water head of the hydropower station; $\tilde{Q} = (Q^1, Q^2, ..., Q^T)$ is the turbine discharge sequences at different time periods.

Object 2: Maximizing reservoir sediment transportation

Sedimentation determines the service life of a reservoir. To maximize the reservoir capacity, the sediment needs to be discharged as much as possible. Because the vast majority of the sediment comes in the flood season, the average sediment concentration in the non-flood season was used. In contrast, sediment transportation is specified by the sediment concentration and flow rate during the flood season. The objective of maximizing reservoir sediment transportation can be expressed as equation (2):
\[
\text{max } S = \text{max}(S_1 + S_2) = \text{max} \sum_{t=1}^{T}(QF^t S_{v,1}^t + Q^t S_{v,2}^t) \Delta t 
\]

where \( S \) is the amount of sediment delivery (in kg); \( QF \) is the flood discharge (in \( \text{m}^3/\text{s} \)); \( S_{v,1}^t \) is the temporal average sediment concentration at the spillway in the flood season (in kg/m\(^3\)), and \( S_{v,2}^t \) is the average sediment concentration flow through the turbine (in kg/m\(^3\)).

When the sediment flux upward and downward reaches a dynamic equilibrium state, the turbulent diffusion process of the sediment is uniform and constant, and the 2D diffusion equation can be written as

\[
\frac{\partial S}{\partial t} + \frac{\partial S}{\partial z} = 0
\]

where \( Z = \frac{\alpha}{kD_z} \) is called the suspension index, the value of which determines the uniformity of the sediment distribution along the vertical direction. The suspended load was distributed more uniformly with a smaller \( Z \).

Taking reservoir discharge as the decision variable, the operational constraints mainly include the constraints of the water level and discharge. Other state equations include the water balance equation, the water level–storage capacity relationship, and the reservoir’s tailwater level–outflow relationship. The Non-dominated sorting genetic algorithm (NSGA-II) is adopted to solve the multi-objective optimization problem above.

2.2. Software Platform of MORO

The MORO software introduced in this study is coded in MATLAB, and its main interface is shown in Figure 1. The MORO contains two modules: (1) the reservoir sediment transportation calculation module and (2) the multi-objective optimization module. The reservoir sediment transportation module includes three sub-modules: (1) vertical distribution calculation of the suspended load, as indicated by (1) in Figure 1; (2) vertical flow velocity calculation in front of the dam, as indicated by (2) in Figure 1; (3) sediment transport rate calculation, as indicated by (3) in Figure 1. The multi-objective optimization module includes two sub-modules: (1) multi-objective optimization, as indicated by (4) in Figure 1; and (2) post-processing and display, as indicated by (5) in Figure 1. The corresponding pictures are shown in Figure 1, part (6).

Figure 2 shows the flowchart of the implementation of the multi-objective optimization model.

3. Results and Discussion

The proposed software is applied on a large-scale reservoir in China, and Figure 3 shows the evolution process of the Pareto front in an iteration. Green scattered points represent the value of the objective function corresponding to the initial population. Blue data points represent the objective function corresponding to the non-dominated solutions after 20 iterations. Similarly, red, pink, cyan, and black represent the Pareto front after 40, 60, 80, and 100 iterations, respectively.
Figure 1. Main interface of software MORO.

Figure 2. Flowchart of the multi-objective optimization model.

Figure 3. Evolution of the Pareto front. Green scattered points refer to objective function value of the initial population. Blue, red, pink, cyan, and black represent 20, 40, 60, 80, and 100 iterations of the Pareto front.
Figure 4 shows the monthly reservoir discharge throughout an entire year corresponding to the maximal power output (i.e., max $E$) and maximal sediment discharge (i.e., max $S$). The discharge sequence corresponding to max $E$ is represented by a solid green line with triangles, and that of max $S$ uses a solid brown line labelled by circles. Moreover, the actual reservoir discharge is represented by the dashed line with grey squares.

![Figure 4. Reservoir discharge sequence corresponding to the maximum power generation and the maximum sediment discharge.](image)

Table 1 shows the Pareto front of the 100th generation, indicating the maximal annual power generation and the corresponding annual sediment transportation, as well as the maximal annual sediment transportation and the corresponding power generation.

<table>
<thead>
<tr>
<th>$\delta$ (m$^3$/s)</th>
<th>Maximum power output ($10^7$ kW)</th>
<th>Corresponding sediment discharge ($10^8$ t)</th>
<th>Maximum sediment discharge ($10^8$ t)</th>
<th>Corresponding power output ($10^7$ kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.7077</td>
<td>0.1002</td>
<td>0.1002</td>
<td>7.7077</td>
</tr>
<tr>
<td>200</td>
<td>7.9070</td>
<td>0.1008</td>
<td>0.1038</td>
<td>7.6343</td>
</tr>
<tr>
<td>Rate</td>
<td>+2.59%</td>
<td>+0.62%</td>
<td>+3.58%</td>
<td>-0.95%</td>
</tr>
</tbody>
</table>

4. Conclusion

In this study, a software platform was developed to balance the trade-off between power generation and sediment discharge of reservoirs. The main functions of software are as follows: (1) calculating the vertical distribution of the suspended load, (2) fitting the vertical distribution flow velocity, (3) calculating the sediment transport rate of the reservoir, (4) optimizing a multi-objective model that simultaneously considers power generation and sediment discharge, and (5) post-processing and displaying reservoir operational schemes.
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