Evaluating the Effectiveness of Regulation Schemes in Improving Navigation Condition of Reservoir Channels

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Abstract. Sedimentation has become a world-wide issue for almost all types of dam reservoirs. The impact of sedimentation on navigation is mainly reflected in the obstruction of navigation channels, usually at reservoir ends. The issue can be partially solved by joint water-sediment regulation during the drawdown period, called “sedimentation-reduction (SR) regulation”. It aims to enhance scour at shoals by increasing the outflow of the reservoir and accelerates the water level decline. In general, the more inflow discharge or lower dam water level, the better scouring effects, although the waste of water for hydropower generation also needs to be considered. In this work, we propose a model to evaluate the effectiveness of SR regulation schemes in improving navigation condition of reservoirs channels. The constraints for successful regulation operation are analysed in details. The navigation benefits are estimated by the increment of sediment transport volume, and the power generation impacts are estimated by the loss of effective water head. The model gives optimal starting dam water level and corresponding inflow discharge. The results were compared with actual regulation parameters of the Three Gorge reservoir. This work can provide guidelines for reservoir sediment management.

1. Introduction

Sedimentation has become a world-wide issue for almost all types of dam reservoirs. In order to mitigate the negative impacts of sedimentation, quite a few strategies such as flushing, hydrosuction sediment removal and traditional/environmental dredging, have been carried out to restore reservoir functions such as flood control, power generation, water supply, navigation and ecological conservation. However, how to quantify the effectiveness of these strategies has been less studied. The Reservoir Conservation (RESCON) model, developed by the World Bank [1,2], provides a useful tool for efficient sediment flushing operation at dams. The model aims to maximize the net economic benefits of reservoir operation on the basis of long-term storage conservation. The model gives rough estimates of optimal operation water level and time interval (e.g. years) between regulation events for reservoirs constructed at rivers of high sediment load. However, the RESCON model’s weakness in sediment transport simulation limited its use in evaluating navigation benefits of a short-time regulation event.

Similar to the term “flushing”, there is another terminology, called “drawdown”, which usually refers to the stage when the water level of a reservoir drops from the normal storage level to the flood-limit water level. While a “flushing” regulation generally takes place at high flow rates for short periods of time (i.e., suspended sediment concentration is high), a “drawdown” regulation is conducted during a period of relatively tranquil flow (i.e., suspended sediment concentrations are relatively low, but the time of water emission is longer [3]. In this paper, it is the regulation schemes during the drawdown period rather than the flushing period that will be discussed below.
In river reservoirs, it is common that as the flow discharge at reservoir inlet gradually increases prior to flood season, the flow velocity increases, making the sediment transport process more and more active in navigation channels at reservoir ends [4]. Apart from the inflow discharge, the duration of “active” sediment movement is also related to the water storage level in front of dams, which is vital to the adjustment of reservoir bathymetry. From an engineering point of view, the goal of water-sediment regulation during the drawdown period is to flush the deposited sediment from the “variable backwater area” to the “perennial backwater area” as much as possible, thereby improving the navigation condition of reservoir channels.

For the sake of better flushing (or scouring) effect at reservoir ends, it is usually practical to increase the outflow discharge at dams appropriately, which is called “sedimentation-reduction” (short for SR hereafter) regulation. Although such a strategy is effective in reducing sediment deposition in navigation channels, it also brings about a more rapid decline of water level, which might waste the available potential energy for hydropower generation. Therefore, it is necessary to establish a model to evaluate the benefit variation between different regulation schemes during the drawdown period.

2. The Evaluation Model

In this section, a model was developed to evaluate the loss and gain of benefit of a SR regulation scheme, which is carried out during the drawdown period.

2.1. Preliminary Assessment

Based on practical experience from water-sediment regulation operations in reservoirs, a SR regulation scheme will be effective at least when the following pre-requisites are fulfilled:

- The daily decline of the reservoir water level should not be too large, so as to mitigate the risk of bank slope failure of the reservoir waters.
- The inflow discharge at reservoir inlets needs to be large enough, and the water level in front of the dam needs to be low enough so that the end of the reservoir has a large flow rate and the bed surface is scoured.

2.2. Economic Formulation

2.2.1 Cost of a SR Regulation

In general, the cost of a SR regulation is estimated by the difference of hydropower generation benefits between a SR regulation and a corresponding reference regulation. The hydropower output N can be calculated by:

\[ N = 9.81 \gamma Q H \]  

(1)

where \( N \) is turbine output, (kW); \( \gamma \) is the power generation efficiency; \( Q \) is the outflow discharge at dams (m³/s); \( H \) is the water head at dams during a regulation event, which can be deduced from

\[ H = \eta - \eta_0 \]  

(2)

where \( \eta \) and \( \eta_0 \) respectively denote dam operation and tail water levels, (m). With the assumption that the operation water level declines linearly, the total amount of generated electric power in a regulation event can be estimated by:

\[ E = \int N \cdot dt = \int 9.81 \gamma Q H(t) \cdot dt = 9.81 \gamma Q \cdot \left[ 0.5(\eta_s + \eta_e) - \eta_0 \right] T \]  

(3)

where \( E \) is the amount of generated hydropower, (kWh); \( \eta_s \) and \( \eta_e \) respectively denote the starting and ending operation water levels of a regulation event, (m); \( T \) is the duration of the event. It is noted that the above formulation is suitable for both SR and reference regulations. The difference lies in the duration of regulation when the operation water level drops from \( \eta_s \) to \( \eta_e \), which are respectively denoted as \( T_1 \) for reference and \( T_2 \) for SR regulations.

Hence, the difference of hydropower generation benefits can be expressed as:
\[ B_e = p(E_2 - E_1) = 9.81 \gamma \left\{ \frac{Q_e}{0.5(\eta_e - \eta_0)} \cdot T_e + Q_0 \cdot (\eta_e - \eta_0) \cdot (T_e - T_1) \right\} - Q_1 \cdot \left[ 0.5(\eta_e + \eta_0) - \eta_0 \right] \cdot T_1 \]  

where \( B_e \) is the loss of hydropower generation compared to a reference regulation event, \( \gamma \), \( p \) is the unit price of electricity, \( ¥/(kW \cdot h) \). The subscripts “2” and “1” denote the SR and a reference regulation, respectively.

### 2.2.2 Benefit of a SR Regulation

Since a SR regulation has an equivalent function as an operation of maintenance dredging, its benefit can be therefore estimated by the widely-used “alternative engineering method”. In the terminology of dredging engineering, the sediment volume that “hinders” navigation refers to the amount of sediment that causes insufficient space for navigation is channels, which lowered the navigation grade of the channel.

It should be noted that the amount of sediment that hinders navigation is only a part of the total amount of sediment deposition in the river section, which excludes the sediment deposited on the bank or other parts of the navigation channel that does not affect navigation. Hence, the gain of navigation benefit can be formulated as:

\[ B_n = q \cdot \sum \alpha_i \Delta V_i \]  

where \( B_n \) is the navigation benefit (¥); \( \Delta V_i \) denotes the scoured sediment volume of the \( i \)th reservoir unit (m\(^3\)); \( \alpha_i \) is a parameter defined as the percentage of scour sediment volume of the \( i \)th reservoir unit that hinders navigation, with value within 0 ~ 1; \( q \) is the average dredging cost per unit volume (¥/m\(^3\)). It should be noted that the sediment transport process can be modelled by a one-dimensional unsteady flow and sediment model.

### 2.3. Optimization Framework

In summary, the calculation procedure of the evaluation model follows the flow chart below (Figure 1).

**Figure 1.** Flow chart of performed analysis for determination of economic appraisal of a SR regulation.
3. Model Application
In order to verify the applicability of the model proposed here, the regulation scheme of the Three Gorges Reservoir during the drawdown period is investigated by taking the inflow discharge \( Q_0 \) at reservoir inlets, and daily water level decline amplitude \( \Delta A \) as control variables. The objective is to maximize the total benefit in terms of hydropower generation and navigation.

On the one hand, according to previous research on sediment transport characteristics in the “variable backwater area” of the Three Gorges Reservoir, it is necessary for the inflow discharge \( Q_0 \) being greater than 5000m\(^3\)/s at the reservoir inlet, i.e. Cuntan hydrological station, so as to mobilize bedload sediment at the Chongqing reach [5]. On the other hand, the daily water level decline amplitude \( \Delta A \) should not exceed 0.6m, so as to meet the bank stability requirement of the Three Gorges Reservoir.

According to the intra-year flow discharge distribution collected at Cuntan station, the regulation during the drawdown period is expected to be carried out in May, when \( Q_0 \) falls within the range 7000 m\(^3\)/s \( \sim \) 12000 m\(^3\)/s. Some published data show that when the water level in front the dam \( \eta \) equals to 157m, variation of the operation water level has little influence on sediment transport regime in Chongqing reach. If \( \eta \) increases to around 160m \( \sim \) 162m, the regime changes, which means the backwater area of the reservoir covers most of the river sections in Chongqing reach. When \( \eta \) further increases to 165m, variation of \( \eta \) has a great impact on sediment transport regime in Chongqing reach.

According to a numerical study of sediment transport in a 3-day regulation event [6], under the condition of same inflow discharge \( Q_0 \), the lower the water level, the greater volume of sediment erosion \( \Delta V \). Under the condition of same water level \( \eta \), the greater the inflow discharge \( Q_0 \), the greater volume of sediment erosion \( \Delta V \). However, with the same increment of outflow discharge (i.e. the same daily water level decline amplitude), the volume of sediment erosion \( \Delta V \) does not vary monotonically with the inflow discharge \( Q_0 \). Hence, the variation of navigation benefit is not obvious. It is concluded that the optimal starting water level is 162m and the volume of sediment erosion for both reference and SR regulation schemes are listed in Table 1. Substituting these data into the evaluation model established in section 2, the power generation \( (B_p) \), navigation \( (B_n) \), and total benefit \( (B_t) \) of different regulation schemes can be calculated, as shown in the table.

### Table 1. Power generation \( (B_p) \), navigation \( (B_n) \) and total benefit \( (B_t) \) of different regulation schemes.

| Regulation scheme | Reference | SR |
|-------------------|-----------|----|
| \( Q_0 \) (m\(^3\)/s) | 7000 | 9000 | 12000 | 15000 | 7000 | 9000 | 12000 | 15000 |
| \( Q \) (m\(^3\)/s) | 7500 | 9500 | 12500 | 15500 | 12000 | 14000 | 17000 | 20000 |
| \( \Delta \eta \) (m) | 0.04 | 0.04 | 0.04 | 0.04 | 0.4 | 0.4 | 0.4 | 0.4 |
| \( T \) (d) | 30 | 30 | 30 | 30 | 3 | 3 | 3 | 3 |
| \( E \) (×10\(^4\)kw·h) | 539.91 | 683.88 | 899.85 | 1115.82 | 416.74 | 525.52 | 688.70 | 851.88 |
| \( B_p \) (×10\(^4\)¥) | 134.98 | 170.97 | 224.96 | 278.95 | 104.19 | 131.38 | 172.18 | 212.97 |
| \( \Delta V \) (m\(^3\)) | 11.9 | 13.6 | 18.4 | 22.8 | 12.5 | 14.2 | 18.9 | 23.3 |
| \( B_n \) (×10\(^4\)¥) | 714 | 816 | 1104 | 1368 | 750 | 852 | 1134 | 1398 |
| \( B_t \) (×10\(^4\)¥) | 848.98 | 986.97 | 1328.96 | 1646.95 | 854.19 | 983.38 | 1306.18 | 1610.97 |

For the water level in front of the dam maintained at 162m, the benefit of the SR regulation schemes as well the reference regulation schemes in scenarios of different inflow flows are calculated. The results show that, with a daily 0.4m decline of the operation water level, which corresponds to an excessive outflow discharge of 5000m\(^3\)/s, the scenario of inflow discharge \( Q_0 = 7000m^3/s \) leads to the greatest benefit of all. Under such condition, the SR regulation scheme generates about \( 36.0 \times 10^4 ¥ \) more navigation benefit than the reference regulation, although it loses about \( 30.8 \times 10^4 ¥ \) of hydropower generation benefit. Compared to the reference scheme, the total benefit of SR scheme is increased by about \( 5.0 \times 10^4 ¥ \).
According to published data [6], from May 7th to 18th in 2012, the Three Gorges Reservoir implemented the first SR regulation test, which lasted for a total of 12 days. During the test period, the average flow of the Cuntan station was 6850 m$^3$/s, and the water level in front of the dam $\eta$ dropped from 161.97 m to 156.76 m, and the average daily decline in water level was 0.43 m. It shows that the model’s output of optimal inflow discharge $Q_0 = 7000$ m$^3$/s, is generally in agreement with the actual value, 6850 m$^3$/s, which indicates the reliability of the model proposed here.

4. Concluding Remarks
In this paper, a simple evaluation model is developed that takes hydropower generation benefit and navigation benefit into consideration for reservoir regulations conducted during the drawdown period. Compared to other models for reservoir management (e.g. RESCON), the model’s ability in simulating sediment transport makes it possible to account for navigation benefit of a short-time regulation event.

Using the newly proposed model, the optimized regulation scheme during the drawdown period of the Three Gorges Reservoir was evaluated. The model gives an optimal inflow discharge $Q_0 = 7000$ m$^3$/s under the condition that the starting operation water level $\eta = 162$ m, which is consistent with the actual regulation scheme carried out in the year 2012 in the Three Gorges Reservoir.

The model has several limitations, such as the simplification of the reservoir geometry, a relatively rough cost estimate of an entire dredging process, and little consideration on the water-supply and flood control benefits, which will be improved in the future.

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