Evaluating the performance of a sediment bypass tunnel with integrated operation and surrogate modeling

Frederick N.-F. Chou, Chia-Wen Wu and Ker-Chia Yeh

Abstract

Sediment bypassing entails venting a portion of the inflowing sediment through an upstream outlet to bypass the reservoir and reduce potential deposition. Since this operation is performed primarily during flood conditions, it must satisfy the requirements of ensuring dam safety, mitigating flood and achieving sufficient final storage for perennial water usage. This paper presents an integrated simulation framework to evaluate the performance of an under-planning bypassing tunnel of Shihmen Reservoir in northern Taiwan. This framework quantifies the water supply yield and sedimentation potential of reservoir, by integrating a daily descriptive water allocation model, an hourly flood control operation model and regression models to estimate the sediment concentration of reservoir releases through different outlet works. This tool is used to evaluate the efficacy of proposed desilting strategies on both water supply condition throughout the Tahan River water resources system and the sedimentation potential of the Shihmen Reservoir in northern Taiwan. The trade-off between desilting, flood mitigation and water supply is also evaluated to assist decision makers in drawing a comprehensive reservoir desilting policy and water resources master plan.

Keywords: reservoir desilting, sediment bypassing, flood control operation, water supply

1 Introduction

Recently Taiwanese government has put more emphasis on sediment routing (SR) for reservoir desilting, by constructing sluiceways and tunnels to enhance the venting of density currents and developing upstream bypassing tunnels. The timing to operate such outlets is during floods which the volume of inflow water and sediment peaks. Thus, venting from SR works should conform to the prescribed flood control operation of reservoir to protect dam safety and alleviate downstream flooding damage. Vented sediment usually elevates the turbidity of reservoir releases to exceed the treatable threshold of the downstream public water supply system. Backup clear water sources will be necessary to stabilize water supply during SR. Following a flood, if the reservoir can achieve its desired target storage for water usage, then no impact will be imposed on the year-round water supply due to SR. Otherwise, shortage risk will be increased as part of conservation storage is released to increase sediment bypass.

The interactions among SR, flood control and water supply operations of a multi-purpose reservoir further complicate the performance evaluation of SR scenarios, in addition to the sediment yield of watershed and its movement in the reservoir. This study presents an integrated simulation framework to evaluate the performances of SR scenarios of a multi-purpose reservoir. The framework simulates the daily water supply, hourly flood control operation and SR process of the reservoir. It allows quantifications of water supply yields, flood mitigation performances and reservoir sedimentation potential under different combinations of SR schemes and water supply facilities.

2 Methodology

2.1 Simulation Framework

Three models are integrated in the simulation framework. A descriptive water allocation model simulates daily water supply operations. The simulation is performed according to the historical daily inflow records of the analyzing system. As the model sequentially distributes water supply throughout the water resources system, if the simulated date coincides with the arrival of an historic flood, the hourly simulation model of reservoir flood control operation will be automatically parallelly applied. The flood control operation model begins with the simulated daily initial storage and quantifies the following trajectory of reservoir water surface level (WSL) during the flood as well as the releases of different outlet works based on pre-defined rules of flood control operation. After simulating the operation of reservoir during a flood, regression models are then employed to estimate the sediment concentration from each respective outlet according to the conditions simulated by the flood control operation model. The volume of sediment deposited in the reservoir can then be quantified by calculating the difference between sediment inflow and outflow. Long-term simulation covering all historical flood events allows the integrated model to comprehensively estimate the magnitude of drought-related water shortage, flood mitigation performance and how much sedimentation a given reservoir would experience as a result of user-specified operating strategy and SR scenarios. Figure 1 illustrates the procedure by which this integrated model manages water during ordinary and flood conditions.

2.2 Estimation of sediment concentrations of reservoir releases from different outlets

This study adopts regression models to estimate the release concentrations of different reservoir outlet works. Regression modeling focuses on finding the mapping between release concentrations with other related factors, rather than numerically solving the governing equations of sediment movement. Sufficient field measurements of inflow and released sediment concentration should be available for model establishment. Thus, the established model should provide acceptable accuracy with much less computation burden. In this paper, reservoir WSL, inflow discharge, inflow sediment concentration and outflow discharge are selected as independent variables, where the dependent variable is the sediment concentration of release. Logarithmic transformation of variables and backward time shifting of the independent variables are introduced to elevate the estimation accuracy. The general regression equation is shown below:

$$
\begin{aligned}
L(\overline{C}^{O}_{i,t+1}) = &-a_i \cdot L(H_t) + b_i \cdot L(\overline{I}_{t-l_i+1}) + c_i \cdot L(\overline{C}^{I}_{t-l_i+1}) \\
&- d_i \cdot L(\overline{O}_{i,t+1}) - e_i \cdot L\left(\sum_{j=t-m}^{t-1} \overline{O}^{B}_{j+1}\right) \\
&+ f_i \cdot L\left(\sum_{j=t-l_i-m}^{t-l_i-1} \overline{I}_{j+1}\right) + g_i \cdot L\left(\sum_{j=t-l_i-m}^{t-l_i-1} \overline{C}^{I}_{j+1}\right) + h_i
\end{aligned} \qquad [1]
$$

where, $\overline{C}^{O}_{i,t+1}$ is the average sediment concentration of the release from the i-th outlet during hour t to t+1, H_t is the reservoir WSL at hour t, $\overline{I}_{t+1}$ is the average inflow discharge between hour t to t+1, $\overline{C}^{I}_{t+1}$ is the average sediment concentration of reservoir inflow during hour t to t+1, $\overline{O}_{i,t+1}$ is the average release discharge from the i-th outlet during hour t to t+1, $\overline{O}^{B}_{t+1}$ is the total release discharge from the bottom outlets during hour t to t+1, a_i, b_i, c_i, d_i, e_i, f_i, g_i and h_i are non-negative regressive coefficients for the release concentration of the i-th outlet, m represents the duration during which accumulative previous inflowing and releasing discharges of water and sediments will significantly influence current release concentration, l_i is the time shift number of the i-th outlet and L denotes the natural logarithm function.

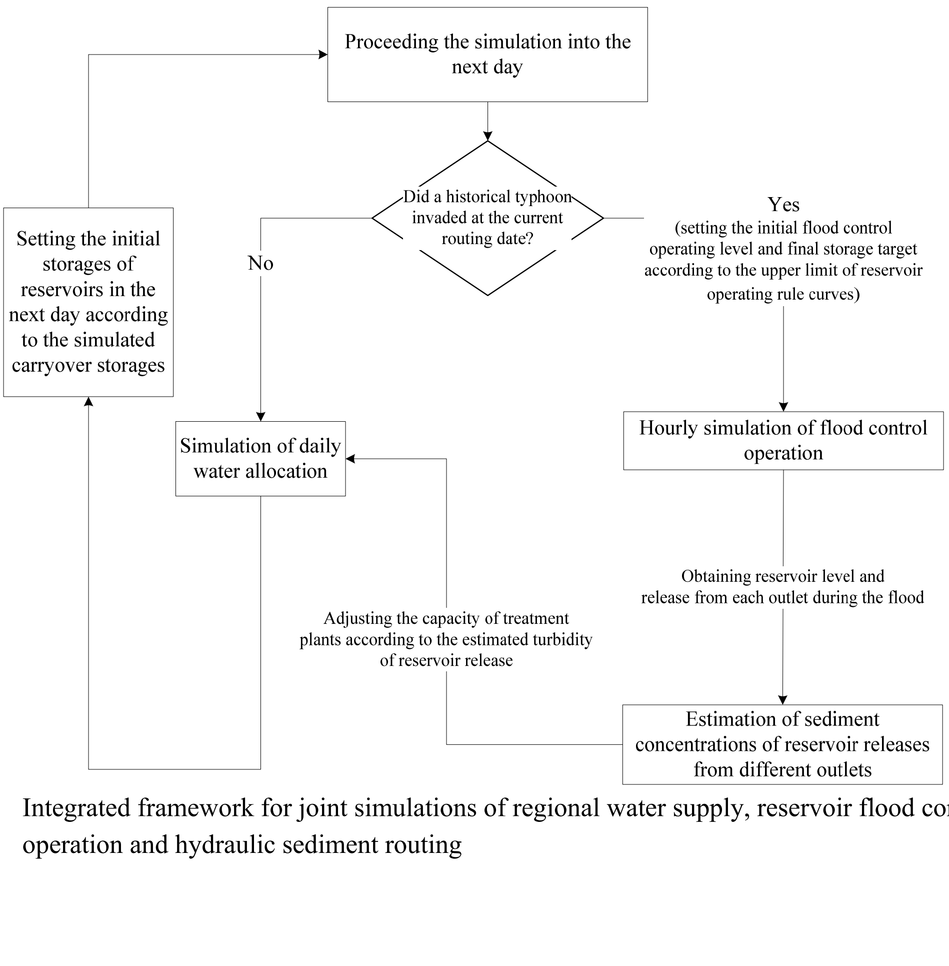


Fig. 1: Integrated framework for joint simulations of regional water supply, reservoir flood control operation and hydraulic sediment routing

3 Case study

3.1 Shihmen Reservoir and Tahan River Water Resources System

The present study demonstrates the application of the integrated framework by applying it to the Shihmen Reservoir on the Tahan River of northern Taiwan. Figure 2 depicts proposed water resources facilities with dotted links and nodes to show their relative locations with respect to the existing elements of the Tahan River water resources system. The off-stream Chongchung Regulation Pond, located downstream of the Shihmen Reservoir and currently under construction, will hold a design capacity of 6.90 million m^3. This pond is designed to serve the dedicated purpose of supplying clear raw water to the Pan-Hsin and Taoyuan districts during floods, when turbidity levels of reservoir release exceed what treatment plants equipment can handle. Figure 3 identifies the respective invert elevations of major outlets of the Shihmen Reservoir.

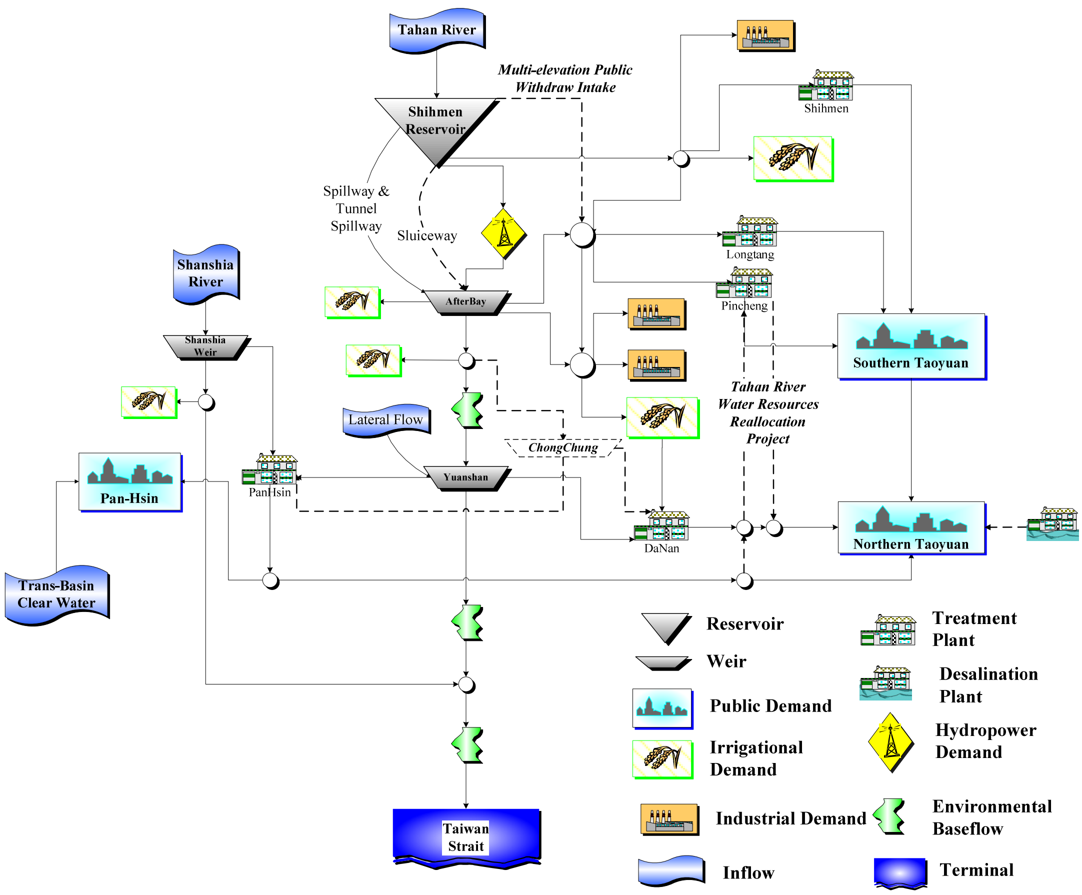


Fig. 2: Network structure of the Tahan River water resources system

3.2 Reservoir desilting alternatives

Following the critical Typhoon Aere in 2004, the "Shihmen Reservoir and Catchment Management Project" was proposed in 2006 to mitigate the sedimentation of this reservoir. Currently, this project carries mechanical excavation upstream of the reservoir on removing 0.40 million m^3 of sediment annually. This capacity is expected to be maintained in the future. The dredging operation in the area close to the dam aims to remove an annual sediment volume of 0.50 million m^3. One of the two penstocks of HPO was reconstructed as a sluiceway with a maximum discharge of 300 m^3/s. Four scenarios of sediment routing tunnels were proposed as illustrated by Figure 4 and three among them, entitled as Tunnels A, C and D respectively, were considered as economically feasible. This paper focuses on Tunnel A, which entails constructing a bypass tunnel upstream of the reservoir to directly divert floodwater and sediments into the downstream river channel with a maximum discharge as 1600 m^3/s.

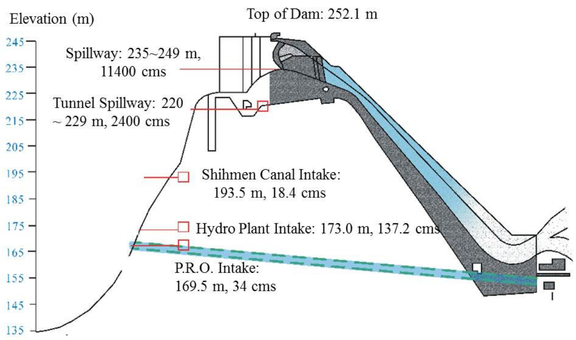


Fig. 3: Major outlets of the Shihmen Reservoir

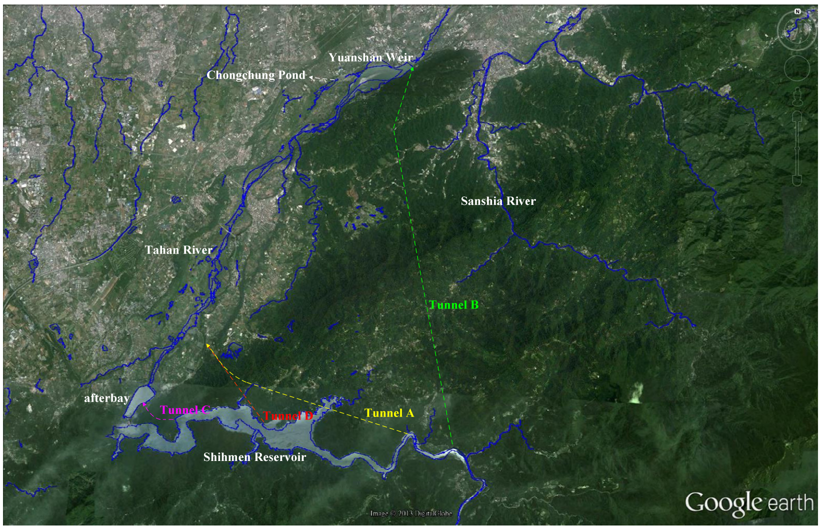


Fig. 4: Locations of sediment routing tunnels

3.3 Regression models for estimating release concentration

The field measurements of sediment concentration of reservoir inflow and outflow of each existing outlet during five typhoons from 2008 to 2010 provide a basis for establishing the regression model of release concentration. These events are Typhoons Fungwong, Sinlaku and Jangmi in 2008, Morakot in 2009 and Fanapy in 2010, with inflow peaks as 2040, 3447, 3292, 1838 and 1056 m^3/s respectively. The model tests conducted by the Water Resources Planning Institute (WRPI) of WRA supplement data for the establishment of regression models for the under-planning SR tunnels (Water Resources Planning Institute 2011). A physical model of 1/100 scale of the Shihmen Reservoir constructed by WRPI was experimented for cases with only the existing outlet works, with the addition of bypass Tunnel A. All the experiments simulated the inflow process of Typhoon Aere in 2004.

The measurements from the historical typhoons and the experimental cases are used to develop the models for estimating release concentration of existing outlets. For the experiment with Tunnel A, a portion of the inflow discharge and sediments are diverted upstream to bypass the reservoir. The un-diverted flow and sediments are used to represent the inflow and sediment concentration in the regression models for the outlet works near the dam if Tunnel A is in presence. Figure 5 depicts the simulated hydrograph of sediment concentration and accumulated volume of vented sediments for different outlet works.

3.4 Results of integrated simulation of current system

The water supply simulation is carried out with historical daily inflows to the Shihmen Reservoir and the Sanshia Weir from 1963 to 2010. The water supply yield (WSY) of the Tahan River system is estimated according to the simulated results.

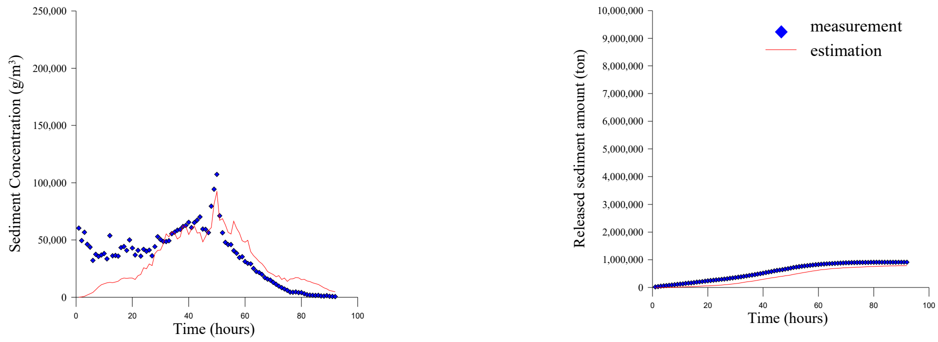
Flood operation simulation of Shihmen Reservoir uses hourly inflow records of 59 flood events during the simulating time horizon. The flood control operation rules of Shihmen Reservoir optimized by Chou and Wu (2015) are used to determine the hourly reservoir release during floods. The release priorities of outlet works are ordered as following: PRO and HPO, sluiceway, Tunnels A, tunnel spillways, and finally the main spillway. The operation of flood control and SR ends when the reservoir WSL is regulated to the upper limit of operating rule curves. Then the simulation is switched to the daily water allocation routing.

For the evaluation of current system status, available outlet works of Shihmen Reservoir for flood control operation include spillway, tunnel spillway, sluiceway, HPO and PRO.

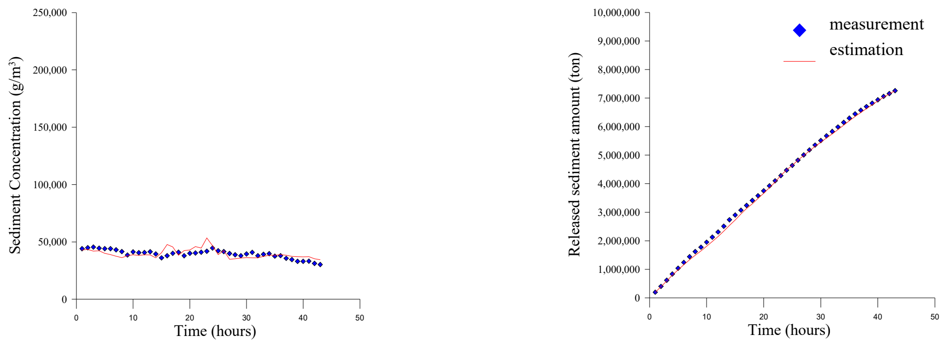
By considering scenarios with and without the newly constructed sluiceway, the simulated results are tabulated in Table 1. The results reveal that:

1. The simulated WSY, 2.20 million m^3/day, is adequate for the current public demand of 2.17 million m^3/day. It validates the functions of PH-Phase I to effectively reduce the public water shortage risk in this area.

2. The average hydraulically vented sediment volume from the reservoir is 1.19 million m^3 per year with the sluiceway, and the corresponding annual desilted volume (ADV) is 1.97 million m^3 per year. Simulation results show that the sluiceway increases desilting by 0.48 million m^3 per year.



(a) Hydro-plant outlet during Typhoon Sinlaku



(b) Bypassing Tunnel A during Typhoon Aere

Fig. 5: The concentration and accumulative volume of vented sediments of different outltes

Table 1: The simulation results for scenarios of the current status

WSY to public demands (million m^3/day)	Outlet works for flood operation	Expected flood peak reduction ratio, EPR	Annual deposited volume, ADV (million m^3/year)
2.20	Current system I : Spillway, tunnel spillway, HPO, PRO	0.828	2.45
	Current system II: Current system I + sluiceway	0.836	1.97

3.5 Simulation results of target year 2021

Table 2 shows that reservoir volume decreases by 1.97 million m^3 per year due to long-term sediment deposition. Total reservoir capacity would drop from 212.73 million m^3 in 2010 to 193.14 million m^3 at target year of 2021 at this rate. Application of the empirical area-reduction method (Morris and Fan 1998) yields projected results of the reservoir height-area-volume relationship for the estimated condition at 2021.

Proposed water supply projects including PH Phase-II, Chongchung Regulation Pond and one seawater desalination plant are considered in the year 2021. Flood operation simulation incorporates the joint operation of proposed future tunnel A with existing outlet works. The simulated performance indices for year 2021 are illustrated in Table 2. The results reveal that:

1. The simulated WSY is 2.30 million m^3/day, which is less than the expected growing demand of 2.37 million m^3/day in 2021. This unveils the need to develop effective desilting schemes of Shihmen Reservoir to sustain its capacity and satisfy future demand in this area.
2. Comparing to the current system with sluiceway, operation with the bypass Tunnel A removes additional 0.77 million m^3 of sediment per year.
3. The simulated EPR of the Shihmen Reservoir in target year 2021 drops significantly from the current status. This is due to the heavier water supply burden in the target year, which consumes more conservation storage and leads to a lower initial reservoir WSL prior to the arrival of a flood.

Table 2: The simulation results for scenarios of year 2021

WSY to public demands (million m^3/day)	Operational outlet works for flood control operation and SR	Expected flood peak reduction ratio, EPR	Annual deposited volume, ADV (million m^3/year)
2.30	Current system II + bypass Tunnel A	0.769	1.19

4 Conclusions

This paper proposed a simulation framework to evaluate the performance of sediment routing measures for reservoirs. The framework integrates long-term water supply simulation, short-term reservoir flood control operation, and estimation of outflow sediment concentration. It facilitates evaluation of the water supply situation of Tahan River water resources system and the sedimentation potential of Shihmen Reservoir in northern Taiwan, based on a variety of water resources facilities and desilting measures in both the current status and future target year.

The major uncertainty in the proposed method is from the estimation of sediment concentration of reservoir releases. The empirical regression equations are established based on historic typhoons and hydraulic model test with peak discharges between 1056 and 8594 m^3/s and reservoir levels between 239.60 and 245.80 El. m. It is assumed that these models are also valid for floods with peak inflows and reservoir operating levels outside the ranges of calibration events. Ideally, the validity of regression models will be improved in the future, because more calibration events will be continuously generated by measuring sediment concentrations of reservoir inflows and outflows during floods. With sufficient number of data available, nonlinear regression or artificial intelligence methods may also be applied to improve the estimation accuracy.

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Authors

Frederick N.-F. Chou (corresponding Author)
Chia-Wen Wu
Department of Hydraulic and Ocean Engineering, National Cheng-Kung University, Taiwan,
Email: hyd4691@mail.ncku.edu.tw

Ker-Chia Yeh
Department of Civil Engineering, National Chiao-Tung University, Taiwan,
Email: kcyeh@mail.nctu.edu.tw