An efficient and economic desilting strategy for reservoir sustainable development under the extreme flooding threat

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\textbf{ABSTRACT}

The severe sediment disaster has already been observed locally and worldwide, and the serious disaster scale must frequently happen in the future due to climate change. Hence, developing a proper reservoir desilting strategy is an urgent issue to ensure that the water resources can be sustainable development worldwide. This study aims to investigate the release efficiency of the bypass tunnel in the reservoir. Firstly, a 2D numerical model was adapted to reproduce the most severe sedimentation disaster due to Typhoon Aere and obtain a reliable result compared with the measured data. Then, the concept of climate change was embedded to understand the release capability of the bypass tunnel under slight to worst scenarios. Finally, the bypass tunnel is demonstrated to be effective in releasing sediment during typhoon periods and prolong the reservoir lifespan. In conclusion, this study proposes a proper solution to reservoir sedimentation during extreme flooding event. The optimization of water resources and economic benefits can help reservoir management achieve the goal of sustainable development. The presented research can be promoted in the worldwide reservoir to face the possibly severe sediment disaster under the threat of climate change.

\textbf{Key words:} bypass tunnel, desilting strategy, extreme flood, reservoir lifespan, reservoir sustainable development

\textbf{HIGHLIGHTS}

- Proper solution to the reservoir sedimentation during extreme flooding event.
- Optimization of water resources and economic benefit.
- Achievement of the reservoir sustainable development.
INTRODUCTION

The sustainable development of the water resource is a critical point for the continuation of human civilization. However, drought and flood are frequently happening due to climate change in recent periods. Although the construction of the reservoir is increasing worldwide (Wisser et al. 2013; Wang et al. 2021), the storage capacity is still losing due to the continuously increased sediment yield of the catchment. For instance, the negative situation was observed that the annual deposition rate of the worldwide reservoir was reached 1%, and continually increasing (Wisser et al. 2013). As a result, reservoir sedimentation has been an existing problem after several operations in the reservoir worldwide (Kondolf et al. 2014).

The reservoir sedimentation issue needs to be settled worldwide and in local regions, especially an island located in East Asia, Taiwan, because a more significant deposition rate has been occurring in the recent two decades (Chen et al. 2016). According to the statistical, the design storage capacity of all Taiwan reservoirs was 2.7 billion m³. After several decades, the current storage capacity is calculated as 1.9 billion m³ due to the steep morphology and severe flood discharge (Yu 2016). Moreover, the ranked the 3rd Shimen Reservoir in Taiwan is lost 0.1 billion m³, and the current 0.2 billion m³ storage capacity is estimated to decrease continually in the future (Huang et al. 2019). Therefore, developing a more effective desilting strategy become the primary topic for the reservoir management (Wang et al. 2018).

The reservoir management should develop long-term benefits, which can be achieved by dividing into three feasible stages. In the first stage, catchment restoration has been a concerning topic in the few decades. The reduced percentage of the produced material is insufficient to slow down the reservoir deposition rate. In addition, the check dam might be the other solution to resist the sediment flow into the reservoir. However, the regret result is often presented that the dramatic inflow discharge always carries huge sediment. Most of the check dams are filled up with sediment by several severe typhoons due to climate change (Ulfiana et al. 2020). Then, the sediment removing approach needs to be conducted, such as the mechanism trucking and soil dredging. However, the current removal efficiency was considered lower than the expectation because the lost storage capacity still increases (Annandale et al. 2016). Lastly, hydraulic sluicing is considered the better method to release more inflow sediment to the downstream river to relieve the deposition problem (Idrees et al. 2021). Hydraulic sluicing has many operating approaches, and suitable methods are the use of existing sluice gates or a newly constructed bypass tunnel during the flooding period in Taiwan. However, the release efficiency of the existed outlets has a limitation because the outflow discharge of the current outlets is fixed, and difficult to release the whole inflow material
Chamoun et al. (2016). If the extreme typhoon occurs more frequently, a bypass tunnel is an efficient method to release the upstream sediment that can maintain the reservoir storage capacity effectively.

There is no doubt that reservoir desilting is a critical issue of reservoir management to keep the water resources sustainable development. This study proposes a suitable strategy that could be widely applied not only in a local reservoir but also worldwide reservoirs. This research aims to investigate the hydraulic sluicing efficiency in the Shimen Reservoir. Not only the existing sluice gates but also a designed bypass tunnel (Amuping Bypass Tunnel, ABT) is considered to study the practicable of sustainable reservoir development. A two-dimensional numerical model, SRH2D, was adopted, and the result of the physical model was applied to calibrate and validate this numerical model. A typical extreme flood event, Typhoon Aere, caused a most serious sedimentation disaster after the construction of the reservoir, and this study focuses on it to figure out a better solution to prevent the same scale sedimentation attack and cause more severe deposition. As a result, this study can well reflect the time series and average sediment flux of the hydraulic model result. In addition, the near-decade typhoon events are also considered to evaluate the bypass tunnel. The positive trend was indicated that the release efficiency is significantly improved by operating the bypass tunnel. The most important is that this study conducts the estimated lifespan of the Shimen Reservoir and benefit evaluation of the ABT. The relevant outcome proves that this study proposes a proper solution to reservoir sedimentation during extreme flooding. In addition, the management of water resources and economic benefits also develop to obtain a better evaluation. A positive trend is indicated that the goal of the reservoir sustainable development can be achieved. The proposed strategy can be promoted in the worldwide reservoir under the climate change threaten. To significantly highlight the procedure of the proposed research, the data-information-knowledge-wisdom (DIKW) framework indicating the application of the collected data, the adaptive strategy, numerical outcome, and the benefit evaluation, as shown in Figure 1. The more detailed content is described as follows.

Figure 1 | Flowchart of the DIKW framework.
STUDY BACKGROUND

Shimen Reservoir

The Shimen Reservoir is a multi-objective reservoir including flood control, domestic supply, agriculture irrigation, and power generation. The designed storage capacity of the Shimen Reservoir was 309 million m³ and ranked second in Northern Taiwan (Figure 2). The main purpose of Shimen Reservoir is the water supply, and the total amount is 0.8 million m³/day. In addition, the power generation reaches 230 million kWh/year. However, it suffered from the existed disadvantage, deposition, in Taiwan reservoirs, the sedimentation had affected the water quality and storage capacity after its first operation.

The Shimen Reservoir has operated water storage on 15 May 1963. However, an unexpected dramatic flood event, Typhoon Gloria, attacked Shimen Reservoir and yielded numerous amounts of sediment, and deposited 19.47 million m³.
on the reservoir bed. Nevertheless, Typhoon Gloria was not a contingency; in 1969, Typhoon Elsie attacked the Shimen Reservoir and caused a 5.03 million m^3 deposition. Additionally, Typhoon Bess, Betty, Billie, Nelson, Herb occurred in 1971, 1972, 1976, 1985, and 1996 carried a huge amount of sediment, and settled down 24.66 million m^3 sediment in the Shimen Reservoir finally.

Typhoon Aere occurred and recorded the most dramatic sedimentation disaster in the Shimen Reservoir of North Taiwan on 23 and 26 August 2004. In these 3 days, the extreme flood disaster caused 15 people to pass away, 399 people injured, and 60 million US Dollars lost. The statistics showed that the cumulative rainfall reached 967 mm, almost 1/2 average rainfall of Taiwan. It packed 700 million m^3 fluid to attack the Shimen Reservoir, and the peak observed discharge was 8,594 m^3/s, the 2nd high in the Shimen Reservoir (Lin 2005). Finally, sedimentation caused a significant loss in the storage capacity of the Shimen Reservoir. According to the historical record, the measured deposition was recorded at 27.88 million m^3 (Chang et al. 2008). Compared to the historical typhoon event, the deposition amount was 1.5 times more than Typhoon Gloria approximately, and more than the total amount of those major events from 1969 to 1996. In addition, the total storage capacity decreased by 9%, and the remaining capacity was 73% after the Aere event, and the destroy scale of Typhoon Aere has noted the most severe sedimentation event until now in Shimen Reservoir (Lin et al. 2011). The muddy lake of the Shimen Reservoir after Typhoon Aere is shown in Figure 2.

The destroy scale of Typhoon Aere had been raised everyone's attention. The extraordinary sedimentation and flood events have occurred frequently and dramatically due to the 1999 Chi-chi Earthquake (Lee et al. 2002) and climate change. Several extreme flood events were observed in Taiwan reservoirs (Schleiss et al. 2016), especially the first worst event after Chi-chi Earthquake, 2004 Typhoon Aere in Northern Taiwan. Hence, the extreme rainfall caused by climate change might not be an exceptional case but a usual flood event in the future. To well-responded to the water security issue has attracted more attention worldwide.

The density current flow often generated during the typhoon period in the Shimen Reservoir (Lin et al. 2015). The serious deposition problem is due to the lack of bottom discharge capacity to release the hyper-concentrated flow to the downstream river. Therefore, the purpose of this study is to formulate the desilication strategy. One of the hydraulic sluicing methods, the bypass tunnel, is defined as a proper alternative strategy to resolve the sedimentation issue.

**Current sluice gates**

The original construction of the Shimen Reservoir could be divided into six major parts: The total length of the reservoir is 16.5 km, in which the catchment area is 766 km^2. The normal water level is 245 m, and the present effective water storage capacity is 208 million m^3.

The Shimen dam is a rolling rock structure, and all the sluice gates are around the dam face. The spillway (SP) consists of six gate overflow weirs with a length of 100 m, and the peak outflow discharge is 11,400 m^3/s. Two diversion tunnels (DT) were established in 1984, and the total discharge amount is 2,400 m^3/s. Both the spillway and the diversion tunnel can be used to reduce the water level before the arrival of typhoon events. These outlets can increase reservoir storage capacity to maintain dam safety. Shimen Main Canal (SC) is the main entrance located at the upper left bank of the dam. The elevation centerline is 195.55 m, and the canal scheme is a concrete structure with a diameter of 2.5 m and a length of about 300 m. The purpose of this canal is to convey domestic and industrial water to the downstream area. Power Plant Intake (PI) has two generator sets, each with a capacity of 45,000 Watts. The elevation centerline is 173 m. Bottom Outlet (BO) is near to PI and operated in 201. It is able to play a role in the early typhoon season to release the flooding fluid.

In this research, SP, DT, SC, PI, and BO were considered in the simulation, which happened after 2011. The relative location of the above facilities at the Shimen Reservoir is shown in Figure 3.

**METHODOLOGY**

**Numerical governing equation**

A 2D layer-averaged density current flow model, SRH2D, based on the finite-volume method, is presented to solve the equations (Lai et al. 2015). The related governing equation is presented below.

\[
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = e_w UD
\]
where $h$ is the current thickness; $t$ is the time; $x$ and $y$ are the $x$- and $y$-direction in Cartesian coordinates; $u$ and $v$ are the layer-averaged velocity in the $x$- and $y$-directions; $U_D$ is the average velocity defined as $\sqrt{u^2 + v^2}$; $e_w$ is the dimensionless entrainment coefficient, as defined in (2).

$$e_w = \frac{0.075}{\sqrt{1 + 718R_i^{2.4}}}$$  \hspace{1cm} (2)

$$R_i = \frac{ghRC_t}{U_D^2}$$  \hspace{1cm} (3)

where $R_i$ is the bulk Richardson number, the relationship between $R_i$ and $F_i$ is $R_i = 1/F_i^2$; $g$ is the acceleration of gravity; $C_t$ is the total suspended sediment concentration defined as $\sum_k C_k$; $C_k$ is the layer-averaged volumetric concentration of the $k$th sediment size class.

The momentum is presented in Equations (4) and (5).

$$\frac{\partial hu}{\partial t} + \frac{\partial huu}{\partial x} + \frac{\partial huv}{\partial y} = \frac{\partial hT_{xx}}{\partial x} + \frac{\partial hT_{xy}}{\partial y} - (RgC_t)h \frac{\partial Z}{\partial x} - \frac{Rg}{2} \frac{h^2}{\partial C_t}{\partial x} - (1 + r_w) \frac{\tau_x}{\rho}$$  \hspace{1cm} (4)

$$\frac{\partial hv}{\partial t} + \frac{\partial huv}{\partial x} + \frac{\partial hvv}{\partial y} = \frac{\partial hT_{xy}}{\partial x} + \frac{\partial hT_{yy}}{\partial y} - (RgC_t)h \frac{\partial Z}{\partial y} - \frac{Rg}{2} \frac{h^2}{\partial C_t}{\partial y} - (1 + r_w) \frac{\tau_y}{\rho}$$  \hspace{1cm} (5)

In the above equations, $T_{xx}$, $T_{xy}$, $T_{yy}$ are the dispersion terms defined as (6); $R = \rho_D/\rho_w - 1$ is the submerged specific gravity of sediment in the turbidity current; $\rho_D$ is the density of sediment; $\rho_w$ is the density of ambient water; $Z$ is the current top elevation; $r_w$ is the friction between upper ambient water and the bottom turbidity current; $\rho$ is the mixture density; $\tau_x$ and

Figure 3 | Location of the current facilities, and ABT at the Shimen Reservoir. (Image © 2019 DigitalGlobe, Google Earth; Water Resources Agency, MOEA.)
\( \tau \) are the bed shear stresses in the \( x \)- and \( y \)-directions:

\[
\begin{align*}
T_{xx} &= 2(v + v_t) \frac{\partial u}{\partial x} \\
T_{xy} &= (v + v_t) \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \\
T_{yy} &= 2(v + v_t) \frac{\partial v}{\partial y}
\end{align*}
\]  

Equation (6) was calculated with the Boussinesq formulation, where \( v \) is the kinematic viscosity of water; \( v_t \) is the turbulent eddy viscosity. In addition, a turbulence model, also known as a depth-averaged parabolic model, was used to calculate the turbulent eddy viscosity. The equation of the parabolic model is shown in Equation (7).

\[
v_t = C_P V_c h
\]  

In the above equations, \( C_P \) is a constant and ranges from 0.05 to 1.00; \( V_c \) is the bed frictional velocity.

In Equations (4) and (5), the friction velocity components, for instance, \( u_* \) and \( v_* \), are shear velocities in the \( x \)-direction and \( y \)-direction. These terms could be written as Equations (8) and (9).

\[
\begin{align*}
u_*^2 &= C_f u^2 + v^2 \\
v_*^2 &= C_f v^2 + v^2
\end{align*}
\]  

In the equations above, \( C_f \) is the drag coefficient, which may be considered as the total drag friction including both the drag friction of the bed and that of the interface. In addition, \( C_f \) is a critical parameter and needs to be calibrated.

Equations (10) and (11) are the non-equilibrium sediment transport equation in the water column and the bed elevation change equation at the bed surface, respectively. They are based on the mass conservation law and represented as follows:

\[
\begin{align*}
\frac{\partial h C_k}{\partial t} + \frac{\partial h u C_k}{\partial x} + \frac{\partial h v C_k}{\partial y} &= v_h (p_k E_k - C_{bk}) \\
(1 - \gamma) \frac{\partial Z_b}{\partial t} &= -\sum_k v_h (p_k E_k - C_{bk})
\end{align*}
\]  

In the above formula, the right-hand side includes both the erosion and deposition terms, in which \( v_h \) is the fall velocity of the \( k \)th sediment size class; \( p_k \) is the volume fraction of the \( k \)th sediment size class; \( E_k \) is the erosion rate potential; \( C_{bk} \) is the near-bed concentration of the \( k \)th size class; \( \gamma \) is the porosity of bed sediment; and \( Z_b \) is the bed elevation.

The layer-averaged concentration is used to calculate the near-bed concentration \( (C_{bk}) \). The relationship between \( C_{bk} \) and the shape factor of sediment particle \( (r_{ok}) \) is \( C_{bk} = r_{ok} C_k \), and the shape factor is computed by:

\[
r_{ok} = 1.64 + 0.4 \left( \frac{d_k}{d_{gm}} \right)^{1.64} \quad \text{ln} \left( d_{gm} \right) = \frac{\sum C_k \ln \left( d_k \right)}{\sum C_k}
\]  

where \( d_k \) is the diameter of sediment size \( k \); \( d_{gm} \) is the geometric mean diameter.
Finally, the topic of this paper revolves around the release amount of sediment from the existed sluice gates and the bypass tunnel. The mentioned terms can be defined by Equations (13) and (14).

\[
\begin{align*}
S_{RSP} &= Q_{SP} \cdot SC_{SP} \\
S_{RDT} &= Q_{DT} \cdot SC_{DT} \\
S_{RSC} &= Q_{SC} \cdot SC_{SC} \\
S_{RPI} &= Q_{PI} \cdot SC_{PI} \\
S_{RBO} &= Q_{BO} \cdot SC_{BO}
\end{align*}
\]  

(13)

\[
\sum_{t=1}^{n} S_{Rt} = \left( S_{RSP} + S_{RDT} + S_{RSC} + S_{RPI} \right) \cdot t
\]

(14)

where \(Q_{SP}, Q_{DT}, Q_{SC}, Q_{PI},\) and \(Q_{BO}\) is the outflow discharge from SP, DT, SC, PI, and BO (m\(^3\)/s); \(SC_{SP}, SC_{DT}, SC_{SC}, SC_{PI},\) and \(SC_{BO}\) is the sediment concentration from corresponding outlets; \(S_{RSP}, S_{RDT}, S_{RSC}, S_{RPI},\) and \(S_{RBO}\) is the sediment flux from corresponding outlets, \(S_{IIF}\) is the total amount of inflow sediment (m\(^3\)) \(S_{Rt}\) is the cumulative release amount (m\(^3\)).

**Numerical set-up**

A robust numerical model needs to carry out a parameter sensitivity analysis to ensure the practical in the field site. Lai et al. (2015) determined that some parameter settings, including turbulence model, the gravity of sediment, sediment particle size, sediment transport capacity equation, and water temperature, could be applied in the physical model and field reservoir. In addition, some critical parameters, such as drag coefficient, time step, mesh resolution, and time step, should be calibrated to obtain the well-simulated result. Huang et al. (2019) calibrated the above three major parameters and improved the numerical result in Shimen Reservoir. This study recalibrated the above parameters and figured out a reasonable range of drag coefficient, time step, and the number of simulated grids is between 0.002–0.06, 0.2–1.5 (sec), and 4,156–19,987. The final drag coefficient, time step, and the number of simulated grids are 0.02, 0.5 (sec), and 10,230, respectively. The mentioned parameter setting is shown in Table 1.

**Boundary condition**

In accordance with the research aim, this study collected information on the inflow and the overflow materials of the Shimen Reservoir during the 2004 Typhoon Aere. The field data included discharge and sediment from the watershed, overflow water release, and released sediment from the reservoir outlet for the Typhoon Aere. These data represent the conditions used in the numerical model. In addition, the numerical output can be calibrated and verified by this data.

The 2004 Typhoon Aere could be seen as a second serious flood event in the historical statistical. The total inflow discharge during Typhoon Aere was 700.93 million m\(^3\), the amount of outflow discharge was 688.15 million m\(^3\), and the release rate was 98.29%. In addition, the release flood of SP was 79.89%, that of the Diversion Tunnel was 14.50%, that of PI was 3.48%, that of SC was 0.31%, and that of the BO was 0.11%. Both the SP, DT, PI, and BO released 686.01 million m\(^3\), and equal to total outflow discharge approximately.

**Table 1 | Parameter setting list**

| Parameter                                      | Value                        |
|------------------------------------------------|------------------------------|
| Turbulence model                                | Parabolic                    |
| Gravity of sediment (ton/m\(^3\))               | 2.7                          |
| Sediment particle size (mm)                      | 0.5                          |
| Sediment transport capacity equation            | Englund-Hansen               |
| Water temperature (°C)                          | 24                           |
| Drag coefficient                                | 0.002–0.06 (0.02)            |
| Time step (sec)                                 | 0.2–1.5                     |
| Simulated grids                                 | 4,156–19,987                 |
The primary function of the ABT is to release sediment and avoid all the density current fluid flows to the dam face. In addition, it can improve the flood control capacity to respond to the scenario of extreme hydrological events that occur in the future due to climate change. The entrance of ABT is located at Section No. 19 (Amuping) in the Shimen Reservoir, and the outlet is situated between Section Nos. 86 and 87 of the Dahan River. The relative location of the bypass tunnel is shown in Figure 3.

The Typhoon Aere in 2004 was chosen as the study case, and Figure 4 shows the simulation region, which total simulation mesh consisting of 10,230 nodes. The inflow boundary is located at Section No. 32 (Lofu), and the outflow boundaries are situated in the dam face, including the SP, DT, SC, PI, and Bypass Tunnel.

Figure 4 | Simulation (a) grids; (b) bed elevation.
Besides, this study adopted different return-period events and long-term typhoon events to be the application cases to figure out the release ability of the ABT. Furthermore, the reservoir benefit can be evaluated by the above cases. The above simulation cases are listed in Table 2. Firstly, the signal event, Typhoon Aere was adopted to be the calibrated case. The result of a down-scale physical model could be compared to the numerical result and calibrated the applicability of SRH2D. The above description is shown in ‘Calibration’. Then, the comparison of ABT operation could be further verified the simulated ability of the numerical model. In addition, different return-period cases could be considered to predict the release ability of the ABT and the current sluice gates. The above content is shown in ‘Verification’. Finally, this study collected the measured data of the historical typhoon events to predict the release efficiency of the Shimen Reservoir by operating the ABT. The related description is presented in ‘Application’.

**NUMERICAL VALIDATION**

The accuracy of the density current model will compare with a down-scale physical model for Shimen Reservoir (Wu 2015). The main purpose of Wu (2015) is to use a 1/100 physical model to investigate the sedimentation process and release efficiency of each sluice gate during Typhoon Aere. In addition, the flow field, vertical concentration, and reservoir deposition measurements were used to calibrate this physical model. Therefore, the comparison of the measured data and simulation result can be the validation case to check the simulated ability of the adopted numerical model.

Firstly, the numerical model should verify the quantity of the sediment flux of each sluice gate during the flood period. Secondly, the sediment release efficiency of the bypass tunnel has to grasp and further investigate the application in different scenarios. Last but not least, the estimated benefit was mentioned to understand the practicality of the ABT. The evaluated lifespan and remain function of the Shimen Reservoir will be the reference of the updated management policy.

**Calibration: reproduction of Typhoon Aere**

The comparison of the spillway, diversion tunnel, power plant intake between measurement and simulation are presented in Figure 5(a). The spillway shows the highest sediment flux, and the diversion tunnel and the power plant intake ranked second and third.

In the first, the variation of the sediment flux needs to be compared and evaluated the model capability. The simulated flux of SP has presented an upward trend from 23rd to 28th hour, which is the same as the measurement. Then, the downward trend was observed from 29th to 32nd, and the simulation showed the match process. DT was operated during 23rd and 33rd

| Classification          | Event    | ABT | Calibration | Verification | Application | Peak  |
|-------------------------|----------|-----|-------------|--------------|-------------|-------|
| Single event            | Aere     | X   | V           |              |             | 8,594 |
| Single event            | Aere     | o   | V           |              |             | 8,594 |
| Return-period event     | 2-year   | o   |             | V            |             | 2,511 |
|                         | 5-year   | o   |             | V            |             | 4,188 |
|                         | 10-year  | o   |             | V            |             | 5,327 |
|                         | 20-year  | o   |             | V            |             | 6,431 |
|                         | 50-year  | o   |             | V            |             | 7,855 |
|                         | 100-year | o   |             | V            |             | 8,920 |
|                         | 200-year | o   |             | V            |             | 9,975 |
| Long-term event         | Fongwong | o   |             | V            |             | 2,039 |
|                         | Sinlaku  | o   |             | V            |             | 3,447 |
|                         | Jangmi   | o   |             | V            |             | 3,292 |
|                         | Morakot  | o   |             | V            |             | 1,837 |
|                         | Saola    | o   |             | V            |             | 5,588 |
|                         | Soulik   | o   |             | V            |             | 5,457 |
|                         | Trami    | o   |             | V            |             | 2,412 |
|                         | Soudelor | o   |             | V            |             | 5,634 |
|                         | Dujuan   | o   |             | V            |             | 3,802 |
|                         | Megi     | o   |             | V            |             | 4,267 |

Peak: peak discharge; unit: m³/s.
hour; the major release duration was noted from 24th to 32nd hour that of the flux values were between 11.7 and 15.4 m$^3$/s. Comparing to the simulation, the minimum and maximum simulated flux were 11.0 and 15.9, respectively, and the measured and simulated results possessed highly related patterns and values. The power plant intake operated after the 10th hour and shut down in the 65th hour, and the measurement and simulation showed the matching trend in the operation period. Because the measured data could sometimes disturb the instrument or personal error slightly, the average sediment flux can fairly evaluate the difference between measured data and simulated results. The details of each outlet are shown in Figure 5(b), and the numerical model simulates relative values with the measurement. The maximum error value is noted in 3.5 for the spillway. In other words, the percent deviation is only 9.9%, and it is an acceptable error range.

As a result, the simulation presents a robust capability to match the measured data. The numerical model can grasp the trend of the sediment flux by time series. Furthermore, the measured data demonstrated the simulated result of three different

![Figure 5](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2022.353/1002768/jwc2022353.pdf)
sluice gates, and the difference was quite close. This model reveals a reasonable temporal and spatial in the reservoir sedimentation during the typhoon period. Therefore, it is considered to apply in the next scenario to investigate the release efficiency of the ABT.

**Verification: sediment flux efficiency of ABT**

As shown in the above description, sufficient accuracy is shown in the simulated result, which reasonably estimates the sediment flux at each sluice gate. In this study, estimating the released amounts of sediment from the ABT is another primary focus. Figure 6(a) shows the release efficiency and amount of the simulated and measured outcome. The simulated results corresponded well with the measured data by the release rate, which value is 16.6 and 18.3, respectively. Besides, the release amounts are 1.60 and 1.76 million m$^3$. If Typhoon Aere occurs again, the ABT can show the practical release ability.

This study adopted different return-period events, including 2-, 5-, 10-, 20-, 50-, 100-, 200-year return period cases to be the investigation setting. Figure 6(b) shows the release and deposit amount of different return-period cases. The bypass tunnel is set wide open means it is operated to release density current flow as much as possible. The release amount from current sluice

![Figure 6](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2022.353/1002768/jwc2022353.pdf)

**Figure 6 |** (a) Comparison of release efficiency and amount at ABT; (b) release and deposit amount of 2- to 200-year return period cases.
gates is 1.19 of 2-year, 2.79 of 5-year, 4.15 of 10-year, 5.68 of 20-year, 7.91 of 50-year, 9.77 of 100-year, and 11.76 million m$^3$ of 200-year, respectively. The deposited sediment amount of each return period is 2.23 of 2-year, 5.20 of 5-year, 7.75 of 10-year, 10.59 of 20-year, 14.76 of 50-year, 18.22 of 100-year, and 21.93 million m$^3$ of 200-year, respectively. Shortly, the ABT can join to operate and release 0.6 of 2-year, 1.4 of 5-year, 2.08 of 10-year, 2.85 of 20-year, 3.97 of 50-year, 4.90 of 100-year, and 5.89 million m$^3$ of 200-year, respectively. It will help keep the adequate storage capacity and prolong the remaining lifespan of the Shimen Reservoir.

**Application: sediment flux efficiency of long-term scenario**

This research collected the related measured data during near-decade typhoon periods (Table 1). The selected typhoon events included Typhoon Fongwong (2008), Sinlaku (2008), Jangmi (2008), Morakot (2009), Saola (2012), Soulik (2013), Trami (2013), Soudelor (2015), Dujuan (2015), and Megi (2016).

Figure 7 compares the release efficiency of the original design (without bypass tunnel) and with bypass tunnel. A significant trend is indicated that the bypass tunnel contributes to the positive sediment release efficiency in every typhoon event. The current outlets show the poor efficiency in past typhoon events, which were between 12.79 and 28.48%. The primary reason is that the current reservoir outlets have insufficient ability to release the inflow material. The current outlets can release sediment smoothly during the rising and recession limb but not during the crest segment. In addition, the huge amount of sediment is often carried by the inflow discharge during the crest segment and be trapped in the reservoir due to the poor release ability. The above situation can be improved by operating the bypass tunnel, and the total release efficiency can be upgraded significantly from 12.79 to 28.48% to 24.23 and 93.93%. To sum up, the operation of the bypass tunnel presents a highly efficient and beneficial to slow down the reservoir deposition trend.

**BENEFIT EVALUATION**

**Service life of the reservoir**

ABT has already shown sufficient sediment release efficiency in the simulated result. The Shimen Reservoir is ensured to prolong lifespan after the construction is done and conduct to operate. Herein, the prediction of the lifespan of the Shimen Reservoir is an interesting topic by comparing with the traditional method before the construction of the ABT is complete. Figure 8 shows the diagram of the capacity inflow ratio and trap rate. The solid line and the hollow dot represent Huang et al. (2018) and the measured data of the Shimen Reservoir, respectively. Based on the information, Brune’s investigation can reasonably apply to the Shimen Reservoir. The information worth to be discussed is that the trap rate in Shimen Reservoir

![Figure 7](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2022.353/1002768/jwc2022353.pdf) | Comparison of the release efficiency without and with bypass tunnel.
is 30 to 50% in the current years. While the trap rate reaches 0, this reservoir can trap the sediment no more, and the sediment passes through the reservoir, such as the open channel flow pattern. In the meanwhile, the reservoir is announced dead, which means it is filled up with sediment.

This research adopts three different scenarios, worst, medium, and slight, situation to predict the lifespan of the Shimen Reservoir. Herein, the worst scenario means Typhoon Aere attacks Taiwan once per year; the medium scenario means the 10-year return-period event occurs once per year; the slight scenario means the return cycle of the long-term event is once per decade.

Figure 9 shows the prediction of the reservoir lifespan in the worst, medium, and slight scenarios. The red, blue, and green solid lines mean the worst, medium, and slight situation, and without the operation of ABT and the red, blue, and green dot
lines mean the worst, medium, and slight situation, and with the operation of ABT. Undoubtedly, the worst scenario will destroy the reservoir soon. The remaining lifespan left 19 by using ABT to release the sediment because the bypass tunnel is challenging to deal with the dramatic inflow sediment. It just prolongs the service time for 4 years. The medium scenario presents a positive result because the ABT presents a well-effective sediment release ability. It can prolong the reservoir lifespan by 15 years. Lastly, the slight scenario indicates that the reservoir service life is longer than the other two scenarios whatever the bypass tunnel operates or not.

**Optimization of water resources**

Figure 10 shows the release proportion of each sluice gate during different typhoon events. Two significant results can be indicated in Figure 10. First, the release efficiency of ABT is better than other sluice gates, and the sum of other outlets is even lower than ABT during several typhoon events, such as Typhoon Jangmi, Morakot, Saola, Trami, Soudelor, Dujuan, and Megi. The prime reason is that ABT is located relative upstream of the reservoir, and it can release sediment earlier to prevent the density current flow to the front of the dam and produce the muddy lake. Then, ABT presents the highest release amount in all sluice gates compared to every typhoon event. The total release amount is 160,738, 1,900,694, 638,578, 686,695, 1,020,693, 1,558,235, 725,209, 760,186, 547,031, and 553,658 during Typhoon Fongwong, Sinlaku, Jangmi, Morakot, Saola, Soulik, Trami, Soudelor, Dujuan, and Megi, and the release amount from ABT is 75,875, 842,550, 413,618, 524,319, 598,821, 621,467, 440,442, 501,018, 558,523, and 369,188 m³. The above results indicate that the operation of the ABT can highly improve the release efficiency and slow down the reservoir deposition rate.

Therefore, the reservoir storage capacity can be used to compare the applicability of ABT. A significant result can be indicated that the ABT can help the reservoir release more sediment and maintain the storage capacity. For instance, the storage capacity of slight scenario with and without ABT is 13.6 and 11.5 million m³, respectively, after 50 years. It means the ABT can deal with the inflow sediment during the flood event and increase the storage ability meanwhile.

**Improvement of economic benefit**

The benefits evaluation is the other essential issue in this study. The construction cost of the bypass tunnel and revenue by saving storage capacity has to investigate the cost-effectiveness, and the above information is shown in Table 3. Firstly, the build-up time of the ABT was set up for 7 years, and the construction cost is 147.25 million USD. This study assumes a 3% discount rate, and the total discount cost is calculated at 4.42 million USD. Then, the total can be decided to be 151.47 million USD. After the ABT is done, the sediment release amount and the saving storage capacity can be the income. This study assumes that the average inflow sediment amount is 2.29 million m³, and the released sediment is 0.53 million m³ by reference to the simulation. Based on the above result, the income can be divided into two parts, hydropower and mechanism dredging. In the first part, the revenue of the hydropower and water sold is 0.01 and 0.03 USD/m³, and the total cost is 0.02 million USD per year. Secondly, 18 USD/m³ have to pay for dredging, and the total cost is 9.54 million USD for the slight scenario, and 37.44 million USD for the medium scenario every year. Besides, the maintenance fee is 1.05 million USD per year. According to the above calculation, the cost-recovery period is 18 years for the slight scenario; the cost-recovery period is 5 years for the medium scenario. In other words, the ABT can keep the storage capacity of the Shimen Reservoir and produce the benefit after 2059 and 2026 for the slight and medium scenarios.

The above description is the expected benefit, and there are several hidden benefits unable to calculate that can be discussed as below. Firstly, the ABT can operate during the flood period, and the released sediment is equal to the increased storage capacity. It can improve the reservoir desilitation ability and protect the lives and property of downstream people. Secondly, the released sediment can replenish the sand source in the downstream river of the reservoir, and it can reduce the river and coast scouring situation. Finally, the bypass tunnel is one kind of hydraulic flushing type. The best operation timing is during the typhoon event because the sediment can be packaged by the huge inflow flood and released to the downstream river. The operation of mechanism dredging and truck transportation can be decreased not to generate carbon emissions. In other words, energy-saving and carbon-reduction benefits are the critical points to slow down climate change.

**CONCLUDING REMARK**

A density current model, SRH2D, can assess the sediment release efficiency of the existed sluice gates in the Shimen Reservoir. This study conducted a numerical simulation to evaluate the benefit of a designed bypass tunnel by reproducing the worst scenario, 2004 Typhoon Aere, to calibrate the model ability. Next, this research adopted return-period events (2-
Figure 10 | Release proportion of each sluice gate during different typhoon events.
200-year) and long-term events to estimate the release ability of the ABT and proved it presents the positive effects to prolong the service life of the Shimen Reservoir. Finally, this paper embedded the opportunity cost and reservoir lifespan concept to compare the price-performance ratio by multi-desiltation strategies. This study focuses on the service life, water resources, and economic benefit to completely evaluate the importance of ABT. A robust description can be presented that the current sluice gates and mechanical dredging presented a positive benefit to the reservoir storage capacity. However, these methods are still insufficient to achieve sustainable reservoir development if the ABT is not involved in reservoir operation. The relevant outcome proves that a well-designed bypass tunnel is a better solution to release sediment during flood events. It improves the lifespan of the reservoir, optimizes the water resources, and the future economic benefit potential is higher than current methods. In conclusion, this paper proposes a proper solution to the reservoir sedimentation during extreme flooding event. Besides, the optimization of water resources and economic benefit is also achieved by using the presented desiltation strategy. The most important is that the achievement of the reservoir sustainable development by ABT. The construction of ABT is a practical approach. It can be promoted in worldwide reservoirs through a reliable estimation, especially in the current climate change period.

This paper presents two potential limitations to provide the future study be the improve foundation. Firstly, this study adopted a calibrated down-scale physical model to validate the numerical model due to the insufficient data collection in the field site. However, the down-scale physical model is difficult to consider all sediment sources, such as collapse around the river. Although the deposition measurement could be conducted after the typhoon event to ensure the accuracy of the inflow sediment amount, the observation technique needs to be further improved to obtain the more accurate data during the serious sedimentation process. Secondly, the 2D layer-averaged numerical model shows insufficient simulation

| Year | Construction cost | Discount rate | Hydropower and water sold | Maintenance | Bypass benefit (Slight) | Bypass benefit (Medium) | Total cost (Slight) | Total cost (Medium) |
|------|------------------|---------------|---------------------------|-------------|-----------------------|-----------------------|--------------------|--------------------|
| 2017 | -9.46            | -0.28         | 0.02                      | -           | -                     | -                     | -9.72              | -9.72              |
| 2018 | -29.3            | -0.88         | 0.02                      | -           | -                     | -                     | -39.88             | -39.88             |
| 2019 | -41.59           | -1.25         | 0.02                      | -           | -                     | -                     | -82.70             | -82.70             |
| 2020 | -40.37           | -1.21         | 0.02                      | -           | -                     | -                     | -124.26            | -124.26            |
| 2021 | -26.53           | -0.8          | 0.02                      | -           | -                     | -                     | -151.57            | -151.57            |
| 2022 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -143.06            | -115.16            |
| 2023 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -134.55            | -78.75             |
| 2024 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -126.04            | -42.54             |
| 2025 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -117.53            | -5.93              |
| 2026 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -109.02            | 30.48              |
| 2027 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -100.51            | -                   |
| 2028 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -92.00             | -                   |
| 2029 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -83.49             | -                   |
| 2030 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -74.98             | -                   |
| 2031 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -66.47             | -                   |
| 2032 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -57.96             | -                   |
| 2033 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -49.45             | -                   |
| 2034 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -40.94             | -                   |
| 2035 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -32.43             | -                   |
| 2036 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -23.92             | -                   |
| 2037 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -15.41             | -                   |
| 2038 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | -6.90              | -                   |
| 2039 | -                | -0.2          | 0.02                      | -1.05       | 9.54                  | 37.44                 | 1.61               | -                   |

Unit: million USD.
results to the erosion and deposition trend in the reservoir bed. The proposed limitation is possibly related to its inability to consider the fall velocity term of the sediment material. Although the reservoir bed shows an insignificant variation in normal typhoon events, this study recommends that future investigation pay more attention to sediment fall velocity at the reservoir. An accurate fall velocity term of sediment will help the future model obtain a precise result.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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