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Physical Model-Based Investigation of Reservoir Sedimentation Processes

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Abstract: Sedimentation is a serious problem in the operations of reservoirs. In Taiwan, the situation became worse after the Chi-Chi Earthquake recorded on 21 September 1999. The sediment trap efficiency in several regional reservoirs has been sharply increased, adversely affecting the operations on water supplies. According to the field record, the average annual sediment deposition observed in several regional reservoirs in Taiwan has been increased. For instance, the typhoon event recorded in 2008 at the Wushe Reservoir, Taiwan, produced a 3 m sediment deposit upstream of the dam. The remaining storage capacity in the Wushe Reservoir was reduced to 35.9% or a volume of 53.79 million m^3 for flood water detention in 2010. It is urgent that research should be conducted to understand the sediment movement in the Wushe Reservoir. In this study, a scale physical model was built to reproduce the flood flow through the reservoir, investigate the long-term depositional pattern, and evaluate sediment trap efficiency. This allows us to estimate the residual life of the reservoir by proposing a modification of Brune's method. It can be presented to predict the lifespan of Taiwan reservoirs due to higher applicability in both the physical model and the observed data.

Keywords: sedimentation; reservoir; physical model; sediment trap efficiency

1. Introduction

Issues of water resources have been determined as a priority in recent years. Water scarcity is an urgent threat globally. Water scarcity could be solved with the improvement of reservoir operations. Reservoirs are often equipped with multiple functions, including water supply, irrigation, flood control, power generation, recreation, and navigation. Among all of these, water supply is a most important operation and highly depends on the reservoir storage capacity. According to the statistics, the capacity of large reservoirs in the world had decreased 5% from 1901 to 2010 [1]. As the world's population increases, reservoir sedimentation will pose more challenges in the utilization of water resources. In an effort to reduce reservoir sedimentation and the impacts of sediment deficit downstream from dams, various measures have been applied for sediment reduction such as the turbidity current venting technique implemented in Lake Mead, USA [2–4], Guanting Reservoir, China [5,6], or the sediment bypass tunnel built at the Asahi Reservoir, Japan [7]. Recently, the reservoir sedimentation problem is receiving increasing attention worldwide; for example, Taiwan also has serious sedimentation problems in its reservoirs. Yu [8] indicated that the storage capacity of Taiwan reservoirs has declined to 1.9 billion m^3 in 2016, and the lost storage is 0.9 billion m^3, which accounts for 34% of the original design. Thus, the operation of water supply has significantly deviated from the original design. To better understand the problem, the sediment yield from the watershed was adopted for investigation [9]. Also, a sediment release strategy has been applied in a Taiwan reservoir [10]. Even though studies on reservoir sedimentation have sufficed, the issue of long-term reservoir deposition is rarely discussed. If the sediment transportation can be analysed through studying a reservoir, we can better predict the sediment movement during typhoon periods.

In order to investigate the sediment transportation from short-term to long-term deposition in the reservoir, several researchers have proposed different methods. Below, we briefly review relevant studies, including empirical relations, numerical simulations, and physical models. Finally, we propose an improved relationship between capacity inflow ratio (storage capacity/annual inflow) and trap efficiency based on previous empirical research [11].

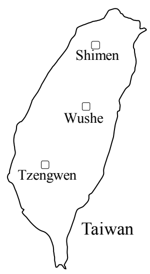
The empirical formula was an early method employed, and the details can be found in the Reservoir Sedimentation handbook [11]. For the long-term reservoir depositional pattern reaching an equilibrium state, the ultimate capacity (remaining storage capacity) of a reservoir can be predicted by parameters including the reservoir water level, cross section, and equilibrium slope. The area-increment method [11] was suitable for reservoirs that had a small meandering in the flow pattern with varied cross sections. It was derived to use the actual flow area at each cross section. However, these methods focus on the ultimate capacity and are unable to calculate the transportation process and reservoir depositional pattern over years. In addition, analyzing the variation of trap efficiency is another approach to understand reservoir storage capacity. Brune [12] and Siyam [13] specifically investigated the relationship of the capacity inflow ratio and sediment trap efficiency. Although these methods cannot describe the sediment flow pattern, they can obtain the amount of sediment deposition by a regression curve.

Numerical models were expected to be viable options to estimate the sediment movement pattern in reservoirs. Therefore, various computer models were adopted. The United States Army Corps of Engineers (USACE) has developed the 1D model, HEC-6, to predict the sediment deposition in a reservoir. Although the simulated erosion pattern was shown to be reasonable with measured data, it barely simulates the meandering patterns through a fluvial reservoir [14]. Nils [15] developed a 2D numerical model to simulate the flushing phenomenon from reservoirs. However, the secondary currents were hard to calculate. The simulated erosion pattern showed the reasonable with measured data. However, 2D models can fairly predict the lateral but hardly predict vertical particle movements in a reservoir due to the fact that the fall velocity term is ignored. In the last decade, 3D models have been adopted to solve sedimentation-related problems. Gessler et al. [16] developed a 3D model to investigate the bed erosion phenomena, further verifying the accessibility of 3D models. Although the 3D numerical model can describe the flow field more specifically and practically, it requires significant computing resources and data mining.

Due to the limitations in numerical models, physical models can better estimate the reservoir sedimentation. Furthermore, to predict the elevation variation along a reservoir, Lai and Capart [17] reported on different laboratory experiments constructed to reproduce reservoir delta movements. Their research figured out the variation of reservoir delta movement. Lai and Chang [18] built a physical model of the Ta-Pu Reservoir in Taiwan using a 1:100 length scale equivalent model to explore the variation of the overall storage capacity. In addition, the timing of empty flushing operation and sediment release efficiency can be used as the reference for reservoir operation. Another 1:50 equivalent model of the Sun Moon Lake Reservoir operated sediment flushing during typhoon periods to lead the reservoir sediment to return downstream. Different boundary conditions were used for verification, and the sedimentation problem can be effectively alleviated [19]. Wu [20] investigated the deposition of the Shimen Reservoir using a scale model. The variation of bed elevation and release efficiency of the sluice outlets were observed specifically. The findings brought more information on the sedimentation of Shimen Reservoir. The scale model was also adopted in the experiment of the Agongdian Reservoir [21] to investigate flushing efficiency during typhoon events. The horizontal and the vertical ratios of the model were 1:60, and 1:15, respectively. Insights from this study provided suggestions for future operations. Furthermore, the study demonstrated the effectiveness of the distorted scale model. Huang et al. [22] also used a distorted physical model to investigate the long-term evolution of deposition due to reservoir sedimentation. The above studies show that physical models can effectively evaluate the effect of short-term deposition in reservoirs. Next, the long-term sedimentation problem will be further discussed in this study.

Above all, the empirical formula can estimate the ultimate capacity or trap efficiency of the reservoir. However, different reservoirs have various characteristics, so the input parameters need to be calibrated. Besides, although the numerical models could calculate the sediment transport mechanism, limitations were noticed. Reservoir sedimentation is a 3D physical phenomenon. Lateral and vertical transport mechanisms are ignored in 1D models; the vertical transport mechanism is ignored in 2D models. Moreover, the sediment grain size in front of the Wushe Dam is less than # 200, and the sediment is classified as the clay or silt property. The kinematic behavior of non-Newtonian fluid is influenced by the concentration of sediment. Existing 3D numerical models have difficulty in computational efficiency to simulate such phenomena, especially for long-term sedimentation processes. In order to select an applicable approach, a physical model is adopted to investigate the short-term reservoir bed evolution and long-term storage process. First of all, field data will be collected to verify the physical model. Second, a repeated experiment is conducted to estimate the long-term reservoir deposition. Finally, the research proposes the relationship between the reservoir storage capacity and the proportion of sediment release efficiency. This study is expected to attest to the applicability of Brune's [12] and Siyam's [13] method. Furthermore, the results from the physical model of the Wushe Reservoir in central Taiwan and the field data obtained from the Shimen Reservoir in the north of Taiwan and the Tzengwen Reservoir in the south of Taiwan are shown in Table 1 and selected for comparison. Next, the results show that sedimentation in these reservoirs, which rank among the five largest in Taiwan, can reasonably be approximated by Brune's method [12]. Finally, the distinctive sediment trap characteristics in Taiwan reservoirs can be presented by the modification of Brune's [12] in the research.

Table 1. Characteristics of three main reservoirs in Taiwan.

Reservoir	Original Capacity, Completion Year (10^6 m^3)	Current Capacity (10^6 m^3)	Deposition Rate (%)	Location
Wushe	148.60 (ranking the 5th), 1957	53.79 (2010)	63.4	
Shimen	309.12 (ranking the 3rd), 1964	208.26 (2015)	32.6	
Tzengwen	748.40 (ranking the 1st), 1973	468.01 (2015)	37.4	

2. Methodology

2.1. Description of Research Site

Reservoir sedimentation has recently gained much attention all over the world. However, the issue of reservoir sedimentation caused by natural disasters is highlighted in Taiwan. Among all the reservoirs in Taiwan, the Wushe Reservoir, observed to have very serious deposition problems, was selected to be our research site. The Wushe Reservoir is located in the Wushe Mountains, upstream of the Chouishui River, where the first storage of reservoir water occurred in April 1957. The Wushe Reservoir is a curved concrete gravity dam type with a height of 114 m and a total capacity of 150 million m^3. After five decades of operation, only 53.79 million m^3 currently remain [23]. Propagation of sediment deposits filling more than half of the Wushe Reservoir can be clearly seen in Figure 1.

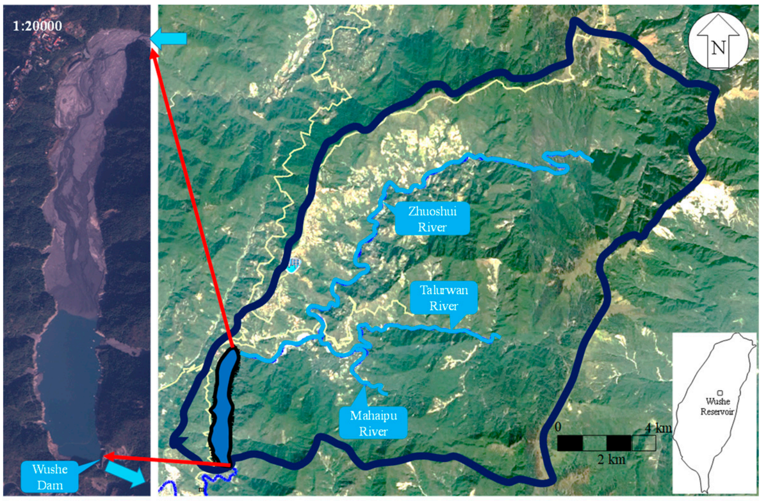


Figure 1. Relative position of Wushe Reservoir.

The sedimentation problems in Taiwan are primarily due to extraordinary earthquake disasters [24] and some of the most extreme precipitation events in the world [25]. Among them, the 1999 Chi-Chi Earthquake has been ranked the worst damage disaster in the last two decades, especially in Central Taiwan [26]. Therefore, the serious sedimentation problems in Taiwan reservoirs can be attributed to two factors. First, before the reservoir was constructed, the upstream sediment from the watershed could be transported to the downstream river with heavy floods. However, upon the completion of the reservoir construction, the inflow sediment could be trapped by the dam. Second, the original design of the Wushe Reservoir had two major outlet works: a spillway (999 m a.s.l. (meters above sea level)) and a tunnel spillway (983 m a.s.l.). However, it does not have any bottom outlet to release sediment during flood events. Hence, the sedimentation worsened after several years of operation. Furthermore, the sedimentation became more threatening after the 1999 Chi-Chi Earthquake. The sedimentation yield per year in reservoirs has increased, adversely affecting the functions of water supplies. Due to an excessive number of landslides and debris flows caused by the earthquake, extreme hydrological events brought greater amounts of sediment into the reservoir. According to field-measured data, the average annual sedimentation rate had increased from 1.78 million m^3 (1959–2010) to 4.25 million m^3 (1999–2010). Based on field measurement in December 2010, the deposition elevation had reached 969.7 m on the upstream side of the dam. The remaining capacity of the reservoir accounts for 35.9% of the original design. As a consequence, the lifespan of Wushe Reservoir is worthy of investigation.

In order to investigate the long-term depositional pattern and the storage capacity variation of Wushe Reservoir, a scale physical model was adopted to simulate possible events. The proportions of the reservoir length, width, and maximum water depth were evaluated. The length and the width of Wushe Reservoir are about 4750 and 600 m, respectively; however, the maximum water depth is only 35.3 m (normal water level = 1005 m a.s.l.). Consequently, a huge disparity exists between the proportions of the length and width of the reservoir, and the maximized water depth. In addition, if a scale model were to be adopted, the flow pattern of this scale model might not reflect the real field due to a shallow water level. Therefore, a distorted physical model was considered. To validate the effectiveness of this distorted model, the design of a physical model was based on the Buckingham π theorem. Next, the distorted physical model should be compared with the field-measured data to prove that deposition of this distorted model would reflect that of the reservoir after typhoon events. After the verification of the distorted model, the long-term pattern of the Wushe Reservoir was investigated.

2.2. Scale and Similarity of Physical Model

In the Buckingham π theorem, hydrodynamic similarity and sediments similarity should satisfy the similarity theory. The Froude number should be matched with the similarity method between the prototype and this model. Froude number dynamic similarity and sediment fall velocity are important factosr. Therefore, the horizontal and the vertical scale should be confirmed, and then the sediment flow pattern can be described well.

A simplified sediment transport equation was applied to define model-prototype similarity. The equation can be written as

$$\frac{\partial s}{\partial t} = \frac{\partial}{\partial x}(us) + \frac{\partial}{\partial y}(vs) + \frac{\partial}{\partial z}(ws) \tag{1}$$

where u, v, w are velocity of x, y, z direction; s is sediment concentration. In addition, u and v are horizontal terms, which could be combined, and present to U.

According to Buckingham π theorem, $\frac{\partial}{\partial x}(Us) = \frac{\partial}{\partial z}(ws)$. Moreover, the prototype and this model must have the same shape, and the scale ratio could be derived as follows:

$$\frac{\lambda_U \lambda_s}{\lambda_L} = \frac{\lambda_w \lambda_s}{\lambda_h} \tag{2}$$

where λ_U is the horizontal velocity scale; λ_w is the vertical scale. In this case, λ_L is the horizontal scale, λ_h is the vertical scale, and λ_s is a concentration scale. (2) can be rewritten as (3)

$$\frac{\lambda_U}{\lambda_L} = \frac{\lambda_w}{\lambda_h} \tag{3}$$

Furthermore, according to Froude number law of similarity, $\frac{\lambda_U}{\sqrt{\lambda_g \lambda_h}} = 1$. g is the acceleration of gravity and $\lambda_g = 1$. (4) can be derived as follows:

$$\lambda_U = \lambda_h^{1/2} \tag{4}$$

(3) and (4) can be combined as (5)

$$\lambda_h = (\lambda_L \lambda_w)^{2/3} \tag{5}$$

The purpose of this research is reservoir deposition type. The prototype and this model must have the same vertical velocity ($\lambda_w = 1$). Therefore, this study can use field sediment to do the experiment. Due to model site constraints, this physical model sets $\lambda_L = 1000$. Hence, (5) can be used to obtain the vertical depth ratio as (6)

$$\lambda_z = \lambda_h = 100 \tag{6}$$

The time scale $\lambda_t = \frac{\lambda_L}{\lambda_U}$, and $\lambda_U = \lambda_h^{1/2}$, which can be derived as (7)

$$\lambda_t = \frac{\lambda_L}{\lambda_h^{1/2}} = 100 \tag{7}$$

The inflow discharge can be written as follows:

$$\lambda_Q = \lambda_L \lambda_h \lambda_U \tag{8}$$

(4) is substituted into (8), and available as follows:

$$\lambda_Q = \lambda_L \lambda_h^{3/2} = 1000000 \tag{9}$$

In summary, the scale ratio of the prototype and the model are shown in Table 2.

Table 2. Scale ratio of the prototype and the model.

Term	Length (m)	Width (m)	Height (m)	Time (s)	Velocity (m/s)	Discharge (m^3/s)
Scale	λ_L	λ_L	λ_h	$\lambda_L {\lambda_h}^{-1/2}$	${\lambda_h}^{1/2}$	$\lambda_L {\lambda_h}^{3/2}$
Proportion	1000	1000	100	100	10	1,000,000

2.3. Initial and Boundary Condition of the Physical Model

The initial and boundary conditions for the physical model need to be confirmed as a prerequisite. The following are described separately: the inflow boundary condition, the initial bed morphology, the sediment particle distribution, and the outflow operation strategy.

First, the upstream boundary conditions of inflow water and sediment discharges should be determined. The current research includes two events: a replication of historic typhoon events and a pattern prediction of long-term reservoir deposition. In order to validate the effectiveness of this model, the selection principle was that the field measured data should be able to reflect the severity of deposition in the particular year. The typhoon events in the year 2008 were used as the verification case. According to the field-measured data, the deposition of the Wushe Reservoir reached 3 million m^3 after Typhoon Sinlaku in 2008. However, besides Typhoon Sinlaku, the other two events—Typhoon Fongwong and Typhoon Jungmi—occurred in the same year, which caused the reservoir bed elevation to increase from 965 to 968 m. The huge amount of deposition during these typhoon events led to a certain level of difficulty in the physical model estimation. If the physical model can be proved effective, it can be further applied to future sedimentation prediction.

The inflow boundary conditions of the second event is shown in Figure 2. With careful consideration of inflow sediment affecting the long-term deposition case, the total sediment yield amount of 4.25 million m^3 was used. The peak flow discharge of design hydrograph is 1523 m^3/s [23]. In the physical model, the design hydrographs of inflow water and sediment were imposed with an unsteady flow state. The boundary conditions of different events are listed in Table 3.

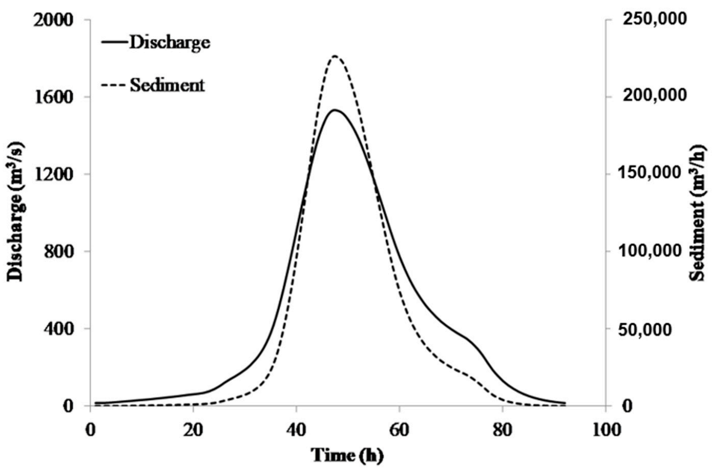
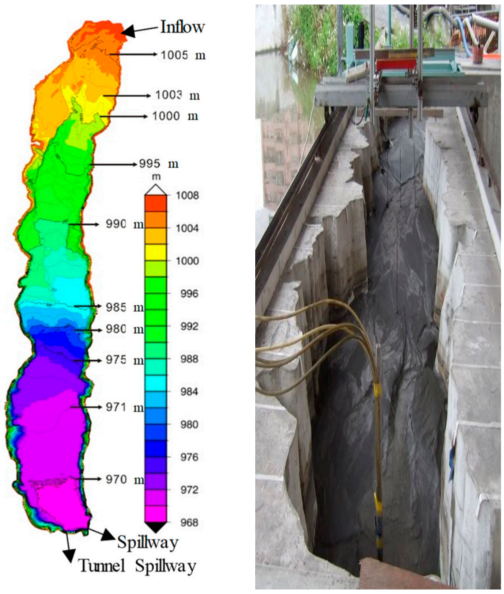


Figure 2. Inflow boundary conditions of the long-term case.

Table 3. Boundary conditions of different events.

Item	Event	Duration (h)	Peak Discharge (m^3/s)	Sediment Yield (m^3)	Flow Condition
1	Fongwong	92	513	690,160	Unsteady
	Sinlaku	160	1493	4,101,562	Unsteady
	Jangmi	152	612	1,739,730	Unsteady
2	Long-term case	92	1523	4250,000	Unsteady

In order to investigate the long-term depositional pattern of the Wushe Reservoir, a mobile-bed physical model was adopted. After the verification case of 2008 was completed, the pattern prediction of long-term reservoir deposition based on the bed elevation of 2010 was applied. The bed elevation and physical model of the Wushe Reservoir are shown in Figure 3.



(**a**) (**b**)

Figure 3. (**a**) Bed elevation of the Wushe Reservoir; (**b**) physical model.

In the mobile-bed experiment, the sediment particle size should be carefully considered. Samples were collected after the flood season during October 2010 and January 2011. Figure 4 shows the grain size distributions measured within 1m-deep bed surface for each sampling location are indicated in the Wushe Reservoir. The D_{50} is about 0.015 mm.

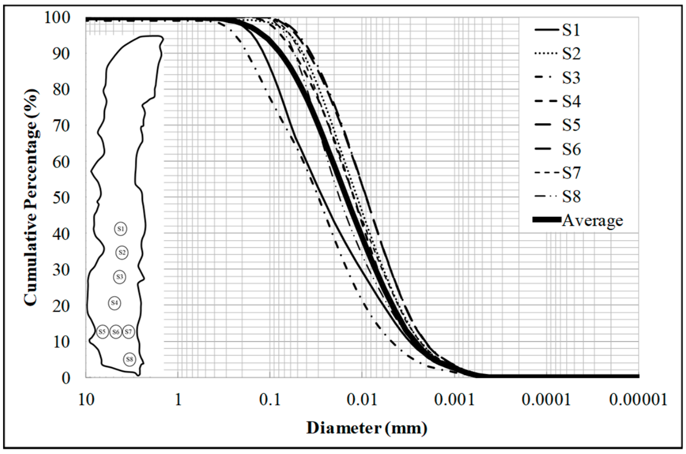


Figure 4. Grain size distribution from samples collected in the lower Wushe Reservoir.

Reservoir operation was the other important factor that affected the depositional pattern of the reservoir. The operation strategy and water level of this model need to be determined. First, the spillway and the tunnel spillway were two major outflow boundaries. The model spillway was prioritized to release flood until the inflow discharge reached 850 m^3/s. Since the maximum design outflow discharge of the spillway was 850 m^3/s, when the inflow discharge amount was greater than 850 m^3/s, the tunnel spillway, of which maximum discharge was 1200 m^3/s, was operated to release the flood. Next, the tunnel spillway was closed when the discharge became less than 850 m^3/s. The spillway was then closed until the end of the flood event. After the operation strategy was confirmed, the water level of this model was considered to match the field record. The water level measured at the Wushe Dam was between 1002 and 1004 m. Therefore, the designed water level was set at 1003 m in this experiment. At the end of the experiment, the water level was reduced to 980 m to simulate the field scenario at a low water level.

The same procedure was repeated until the reservoir was filled up with sediment. That is, the sediment release efficiency reached 100% (trap efficiency = 0%). Sampling locations were chosen to calculate the sediment release efficiency. The locations included one inflow boundary, the reservoir entrance and two outflow boundaries, the spillway, and the tunnel spillway. Therefore, the cumulative sediment release efficiency of the experiment was obtained. The equation can be written as (10)

$$\text{Sediment Release Efficiency}(\%) = 1 - \text{Trap Efficiency} = \frac{\sum \text{Outflow Sediment}}{\sum \text{Inflow Sediment}} \tag{10}$$

3. Physical Model Results

In the first place, the physical model should be verified with the field measured data. The repeated experiment were conducted since the verification was proved applicable. In the following description, the comparison of similarity in the depositional pattern between the physical model and field data and the variation of sediment release efficiency are discussed.

The experiment results and the measured data of longitudinal bed elevation along the thalweg are compared in Figure 5. The longitudinal bed elevations in November 2007 and March 2009 are demonstrated with the solid line and the dashed line, respectively. Also, the dashed line can be seen as the base and was compared with the result obtained from the physical model (dotted line). It can be observed that the inflow sediment led the reservoir delta to move forward after the typhoon events of 2008. In this case, much sediment flowed into the reservoir and caused serious deposition. The physical model reflects this movement pattern. First, the physical and the measured delta front had a similar movement trend. Next, the elevation of deposition was approximately matched by 968.2 m in the physical model and 968.6 m in the measured data.

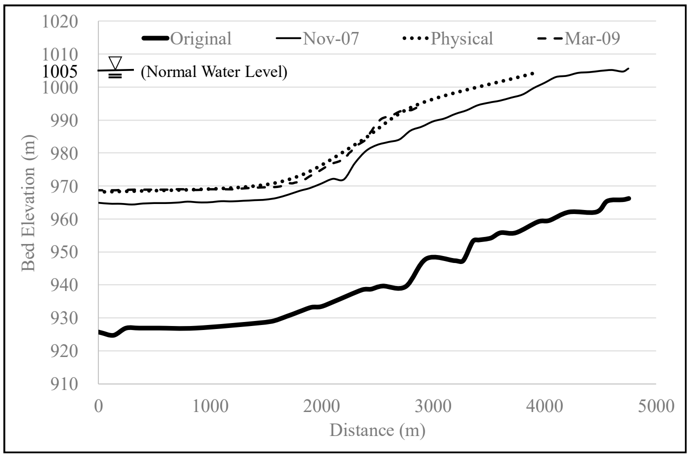


Figure 5. Longitudinal bed elevation of the physical model and field-measured data.

In the above study, the depositional pattern of typhoon events was verified by using the same grain size distribution in the field. Model results closely matched the patterns of deposition measured in the field. Therefore, using the same sediments as a prototype in the specified scale model can properly simulate the sedimentation pattern in the Wushe Reservoir. That is, the sedimentation pattern of the physical model was consistent with that of the measured data, leading to the possibility of predicting the long-term deposition of the Wushe Reservoir.

The verification case has proved the reliability of the physical model. Hence, the long-term depositional pattern can be discussed. In order to analyze the propagation pattern of the delta front, we measured the reservoir bed topography after every three consecutive experiments (i.e., three events in three consecutive years in the field). The experiments were conducted repeatedly until the physical model was filled up with sediment to understand its lifespan in the future (2013 to 2037).

The depositional patterns of the delta from 2013 to 2037 are shown in Figure 6a–h. The black dotted line represents the delta front, with the sub-aerial portion of the delta to the top of the dotted line. In the year 2013 (Figure 6a), the delta front is about 3000 m away from the dam. Movement of the delta front from 2013 to 2019 is shown in Figure 6b,c. The delta front moves 750 m, which is about 2250 m upstream from the dam. During this period, the slope of the delta front extending to the dam front (the transition zone of blue and green) shows a steep trend. In 2022 and 2025 (Figure 6d,e), the delta has been moved to a distance of 1800 and 1700 m from the dam. Moreover, the delta of the right bank moved faster. Figure 6f–h shows that in 2028, 2031, and 2034, the delta front shifts from the left to the right-hand side due to the operation of the spillway tunnel (the height of the spillway tunnel is lower than that of the spillway). Thus, we predict that the Wushe Reservoir will fill up with sediment within three years in 2037. The delta moves to the dam site, and the water storage extent is only about 250 m left before the dam. As a consequence, the delta front migrates with a significant speed to almost fill up the reservoir within 24 years.

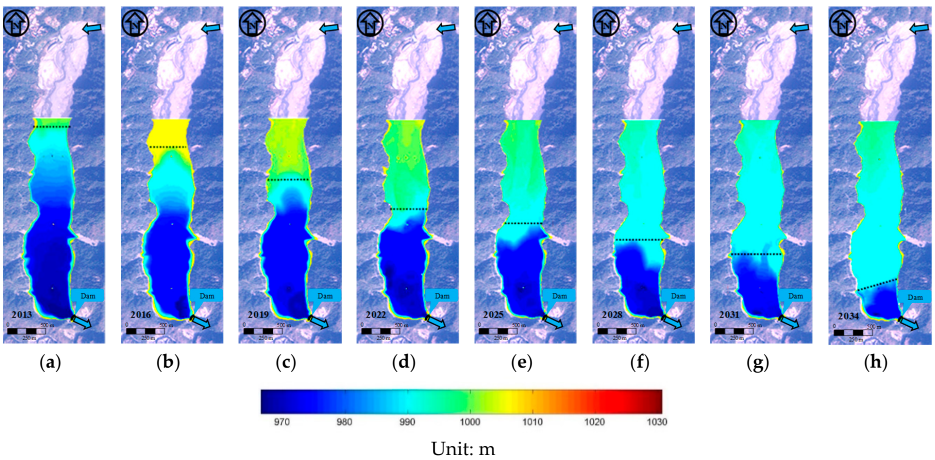


Figure 6. Deposition delta movement patterns from 2013 to 2034. (**a**) 2013; (**b**) 2016; (**c**) 2019; (**d**) 2022; (**e**) 2025; (**f**) 2028; (**g**) 2031; (**h**) 2034.

The release efficiency is a method to judge the remaining lifespan of the Wushe Reservoir. In order to monitor the sediment release efficiency of different years, we collected released water samples from the spillway and the spillway tunnel and then calculated the sediment concentration of water samples to estimate the cumulative release sediment volume of different outlets.

The variation of sediment release efficiency from 2013 to 2037 is shown in Figure 7. The cumulative release efficiency of each experiment increased with the time series. The rate of increase gradually diminished over each experiment, especially after peak discharge (33rd minute). Overall, the cumulative release efficiency increased significantly over the first 25 min of each experiment. This phenomenon showed that the reservoir would not flush sediment before its transport to the dam front. Also, the cumulative release efficiency increased at a much slower degree after the first experiment was conducted for 41 min. In this case, the cumulative sediment efficiency increased due to the fact that the delta gradually moved to the dam front. Otherwise, the slope of the cumulative sediment efficiency also increased year by year. This phenomenon showed that the inflow sediment had insufficient space to deposit. In other words, the reservoir trap ability is reduced due to the declining storage capacity caused by sediment accumulation. Finally, when the release efficiency reaches 100% in 2037, the reservoir storage capacity will no longer change.

Based on the results, the active storage, the ultimate capacity, and sediment release efficiency can be determined after experimental tests. The relationship of the capacity inflow ratio and the trap efficiency will also be developed by scale model tests of the Wushe Reservoir.

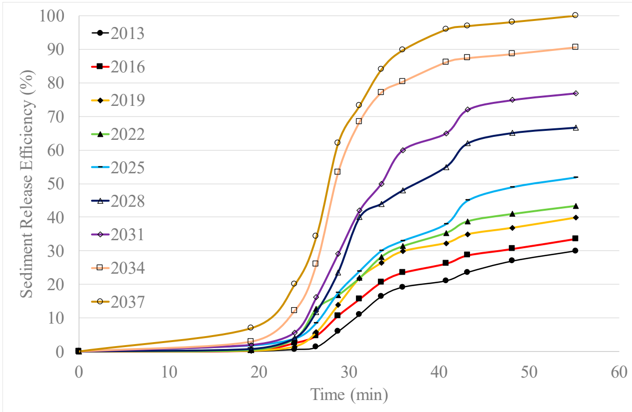


Figure 7. Sediment release efficiency from 2013 to 2037 as computed from measurements in the physical model.

4. Discussion

First, the ultimate depositional pattern and reservoir capacity will be discussed. Next, the annual sediment release efficiency and remaining storage are presented in relation to the trap efficiency. Finally, most important is the comparison of Brune's [12] and Siyam's [13] method and the physical model result.

Figure 8 shows the ultimate depositional pattern of the Wushe Reservoir. In the year 2037, the bed elevation reaches close to 999 m, which equals that of the threshold of the spillway. Although outlet works can be operated, the development of deposition of the Wushe Reservoir has reached a balance. In other words, the amount of inflow sediment will equal that of the outflow sediment, and the flow pattern will be similar to the shallow water flow. When the capacity reduces year by year, the ultimate storage capacity will decrease to 3.96 million m^3. Compared with the original design, the remaining storage is only 2.66% and will be located just above the tunnel spillway.

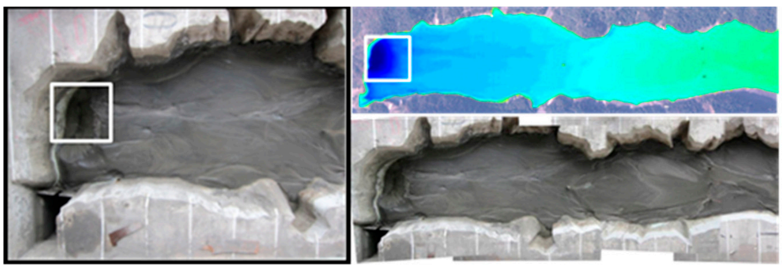


Figure 8. Ultimate depositional pattern of the Wushe Reservoir.

Figure 9 shows the remaining storage of the Wushe Reservoir. The x-axis represents the time in years. The y-axis on the left represents the sediment release efficiency, and the y-axis on the right represents the remaining storage. This research compares the relationship between release efficiency and remaining storage and finds that the critical point is the year 2025. In the Wushe Reservoir, the high sedimentation rate period will be from 2010 to 2024. The efficiency increases from 26.5% to 48.4% to have the increment of 21.9%. The annual amount of deposition reaches 2.68 million m^3. By contrast, the time series from 2025 to 2037 can be called the high sediment release period. During this period, the release efficiency will increase significantly from 51.9% to 100.0%. In addition, the demarcation point can be determined at year 2025, and the disparity rate between the release efficiency of 2010 to 2024 and that of 2025 to 2037 is nearly 2.2 times. Further, the investigation of the trap characteristics in Taiwan reservoirs is presented below.

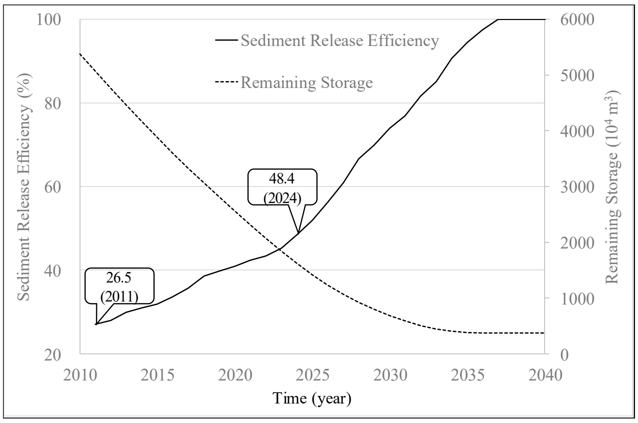


Figure 9. Annual sediment release efficiency and remaining storage of the Wushe Reservoir.

Reduced deposition after 2025 appears to be due to increased water velocities and transformation from 3D to 2D flow within the diminishing open water portion of the reservoir. Sediment is more efficiently transported through the reservoir due to both of these factors.

Next, to extend the applicability of this study, the Shimen Reservoir and the Tzengwen Reservoir have also been adopted for comparison. The relationship of the capacity inflow ratio and the trap efficiency is shown in Figure 10. The results show that Siyam's [13] does not match the trap efficiency obtained from the physical model and the observed data, thus being less applicable here. However, the three reservoirs present an approximate similarity with Brune's [12], while the capacity inflow ratio was between 0.12 and 0.5. The last and most important result was that the Shimen Reservoir represented the same trapping characteristics as those of the Wushe Reservoir, while the capacity inflow ratio was smaller than 0.12. The findings prove that this study validates Brune's [12] and further discovers the sediment trap characteristics of the Wushe Reservoir and the Shimen Reservoir. When the trap efficiency of the Wushe Reservoir reaches 48.1%, the modification is proposed starting with the demarcation point in 2025. It can be more appropriately applied to the other reservoirs, especially for the range of capacity inflow ratio between 0.01 and 0.1.

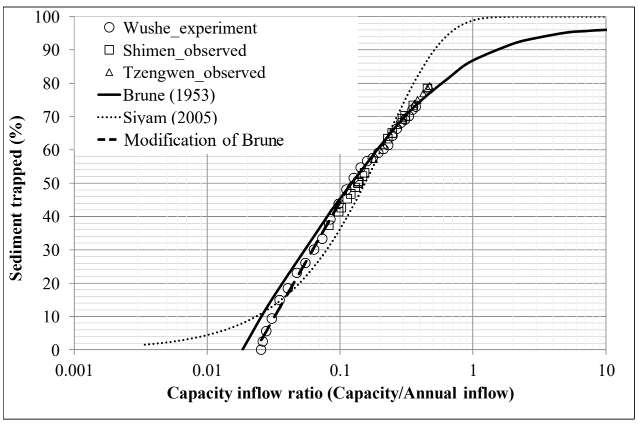


Figure 10. Relationship of the capacity inflow ratio and the trap efficiency.

5. Conclusions

Reservoir sedimentation has been a highly discussed issue globally. To investigate the movement pattern of reservoir sediment, we developed a physical model to investigate the sedimentation pattern and implications for sediment trapping and release for the Wushe Reservoir. Typhoon events of a single year were applied to verify the short-term depositional pattern. Furthermore, the recurring hydrological events were used to predict longer-term, future sedimentation and trapping efficiency. Additionally, the sediment release efficiency was measured to investigate the relationship of the release efficiency and the reservoir storage capacity. A research study of high credibility (Brune [12] and Siyam [13]) was selected to validate the effectiveness of the current research. These results are concluded below.

The movement of the reservoir delta and the elevation of deposition were used to verify the physical model in the specified scale. Model results closely matched the patterns of deposition measured in the field. Hence, the model can properly simulate the sedimentation pattern in the Wushe Reservoir, leading to the possibility of predicting its long-term depositional processes.

The reservoir delta moved toward the dam site every year. In other words, the reservoir capacity reduced as a result. In the model simulations, by year 2037, the sedimentation reached the threshold of the spillway of the dam. At this time, the model predicts that the difference between the bed elevation and crest of the dam (1005 m) would be only 6 m. With such little storage capacity and increased water velocities, in this condition, the sediment trapping efficiency is negligible, and nearly all sediment entering the reservoir is transported downstream. In conclusion, the flow pattern of the Wushe Reservoir will be transformed into a shallow water flow.

The cumulative sediment release efficiency increases gradually and slowly within the first 14 years but significantly in the 15th year. Therefore, the demarcation point of the sediment release efficiency is in 2025. As a result, the sediment release efficiency will increase nearly 2.2 times by comparing the two time periods before and after that demarcation point.

Based on the physical model tests, we modified the conventional regression line of Brune for use when the trapping efficiency falls within the range 48.1% to 0%. The modification of Brune's method is also found to be feasible for the range of capacity inflow ratio between 0.01 and 0.1, which should be more suitable for estimating the long-term storage capacity of the Wushe Reservoir. This approach also allows us to predict changes in trapping efficiency in other reservoirs throughout Taiwan. The Shimen Reservoir and the Tzengwen Reservoir, the important reservoirs in the north and south of Taiwan, show good agreement with predictions using this formula. In other words, this method can be used to predict their reservoir sedimentation processes, followed by an investigation into the release strategy to approach the goal of sustainable reservoir development.

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References

1. Wisser, D.; Frolking, S.; Hagen, S.; Bierkens, F.P.M. Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs. *Water Resour. Res.* **2013**, *49*, 5732–5739. [CrossRef]
2. Smith, W.O.; Vetter, C.P.; Cummings, G.B. *Comprehensive Survey of Sedimentation in Lake Mead, 1948–1949*; United States Government Printing Office: Washington, DC, USA, 1960.
3. Ren, Z.; Ning, Q. *Lecture Notes of the Training Course on Reservoir Sedimentation*; IRTCES: Beijing, China, 1985.

4. Schmidt, J.C.; Wilcock, P.R. Metrics for assessing the downstream effects of dams. *Water Resour. Res.* **2008**, *44*. [CrossRef]
5. Batuca, D.G.; Jordaan, J.M. *Silting and Desilting of Reservoirs*; A.A. Balkema: Rotterdam, The Netherlands, 2000.
6. Kondolf, G.M.; Rubin, Z.K.; Minear, J.T. Dams on the Mekong: Cumulative sediment starvation. *Water Resour. Res.* **2014**, *50*, 5158–5169. [CrossRef]
7. Sumi, T.; Okano, M.; Takata, Y. Reservoir sedimentation management with bypass tunnel in Japan. In Proceedings of the Ninth International Symposium on River Sedimentation, Yichang, China, 18–21 October 2004.
8. Yu, G.-H. The essentiality of water resource development in Taiwan. *J. Taiwan Water Conserv.* **2016**, *64*, 1–8.
9. Chen, C.-N.; Tsai, C.-H.; Tsai, C.-T. Simulation of sediment yield from watershed by physiographic soil erosion-deposition model. *J. Hydrol.* **2006**, *327*, 293–303. [CrossRef]
10. Chen, C.-N.; Tsai, C.-H. Estimating sediment flushing efficiency of a shaft spillway pipe and bed evolution in a reservoir. *Water* **2017**, *9*, 924. [CrossRef]
11. Morris, G.L.; Fan, J. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use*; McGraw-Hill: New York, NY, USA, 2010.
12. Brune, G.M. Trap efficiency of reservoirs. *Trans. Am. Geophys. Union* **1953**, *34*, 407–418. [CrossRef]
13. Siyam, A.M. Assessment of the current state of the Nile Basin reservoir sedimentation problems. In *Nail Basin Capacity Building Network (NBCBN)*; River Morphology Research Cluster: Khartoum, Sudan, 2005.
14. US Army Corps of Engineers Hydrologic Engineering Center. Scour and deposition in rivers and reservoirs. In *Scour and Deposition in Rivers and Reservoirs, User's Manual*; US Army Corps of Engineers Hydrologic Engineering Center: Davis, CA, USA, 1993.
15. Nils, R.B.O. Two-dimensional numerical modelling of flushing processes in water reservoirs. *J. Hydraul. Res.* **1999**, *37*, 3–16.
16. Gessler, D.; Hall, B.; Spasojevic, M.; Holly, F.; Pourtaheri, H.; Raphelt, N. Application of 3D mobile bed, hydrodynamic model. *J. Hydraul. Eng.* **1999**, *125*, 737–749. [CrossRef]
17. Lai, S.Y.-J.; Capart, H. Reservoir infill by hyperpycnal deltas over bedrock. *Geophys. Res. Lett.* **2009**, *36*. [CrossRef]
18. Lai, J.-S.; Chang, F.-J. Physical modeling of hydraulic desiltation in Tapu Reservoir. *Int. J. Sediment Res.* **2001**, *16*, 363–379.
19. Sinotech Engineering Consultants. *Applicability Research of Numerical and Physical Model-Based Sedimentation Improvement in Sun-Moon Lake*; Taiwan Power Company: Taipei, Taiwan, 2013.
20. Wu, C.-H. A Study on Flood-Induced Sediment Transport and Its Sluicing Methods in a Reservoir. Ph.D. Thesis, National Cheng Kung University, Tainan City, Taiwan, 2015.
21. Water Resources Planning Institute. *Hydraulic Model Studies on the Functions and Operations of Silting Prevention in A-Kung-Tien Reservoir*; Water Resources Agency, Ministry of Economic Affairs: Taichung, Taiwan, 2003.
22. Huang, C.-C.; Lee, F.-Z.; Khadeeda, S.H.; Liao, Y.-J.; Lai, J.-S.; Tsung, S.-C.; Tan, Y.-C. Long-term evolution of sedimentation in a reservoir. *J. Taiwan Water Conserv.* **2015**, *63*, 24–32.
23. Sinotech Engineering Consultants. *Applicability Research of Sedimentation Improvement of Wushe Reservoir*; Taiwan Power Company: Taipei, Taiwan, 2010.
24. Shyu, J.B.H.; Chuang, Y.-R.; Chen, Y.-L.; Lee, Y.-R.; Cheng, C.-T. A new on-land seismogenic structure source database from the Taiwan Earthquake Model (TEM) project for seismic hazard analysis of Taiwan. *Terr. Atmos. Ocean. Sci.* **2016**, *27*, 311–323. [CrossRef]
25. Water Resources Agency. *Analysis of Storm Rainfall and Flood Discharge of Typhoon Morakot*; Terrestrial, Ministry of Economic Affairs: Taichung, Taiwan, 2009.
26. Yanties, B.J.; Tucker, G.E.; Hsu, H.-L.; Chen, C.-C.; Chen, Y.-G.; Mueller, K.J. The influence of sediment cover variability on long-term river incision rates: An example from the Peikang River, central Taiwan. *J. Geophys. Res.* **2011**, *116*. [CrossRef]