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ORIGINAL ARTICLE

Experimental study with hydraulic modeling of a reservoir desilting operation using a sediment bypass tunnel

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Abstract
The storage volume of reservoirs is highly susceptible to the effects of sedimentation. This study investigated the Wushe reservoir in Taiwan, the volume of which dropped to just 31.9% of its original capacity in 2016. Our focus is the improvement of desilting operations via scale model experiments involving a sediment bypass tunnel. The experiment parameters included inflow and outflow boundary conditions, sediment discharge, and the shape of particles used in the scale model (i.e., matching those in the real-world location). This study also performed numerical modeling to select upstream inflow boundary conditions for the experiment. The results revealed that the proposed desilting strategy using a sediment bypass tunnel would not only be more effective than the existing outlet in terms of sediment release, but would also provide economic benefits over dredging. The return on investment should be evident within 8–21 years, depending on the scale of the typhoons that strike. There seems little doubt that a sediment bypass tunnel is the best approach to preserving reservoir storage capacity and relieving concerns of an impending water crisis.

Keywords Reservoir sedimentation · Scale model · Sediment bypass tunnel · Sediment release ability · Economic benefit

Introduction

The global population is expected to reach between 9.6 and 12.3 billion in 2100 (Gerland et al. 2014). To serve increasing population, reservoirs are an effective water-storage solution; however, they are highly susceptible to sedimentation and a corresponding decrease in storage capacity (Asthana and Khare 2022). The most important is that the increasing storage capacity of the new reservoir is considered less than the lost storage capacity due to the continuous inflow of sediment from the upstream watershed (Wisser et al. 2013). It is not only globally but also a highly-mentioned issue in Taiwan, located at a 36,000 km^2 island in East Asia. For instance, the ranked 3rd reservoir, Shimen Reservoir in Taiwan, reduced the total storage by nearly 9%, 24.88 million m^3 due to the dramatic inflow of sediment during Typhoon Aere. (Cheng et al. 2017). Similarly, Typhoon Morakot in 2009 reduced the 600 million m^3 capacity of Zengwen Reservoir, ranked 1st in Taiwan by nearly 90 million m^3 (Wu et al. 2014). More recently, the Wushe Reservoir ranked 5th in Taiwan has experienced a 65% decrease in storage capacity since it was operated. (Huang et al. 2018). Note that, most of the major reservoirs in Taiwan have severe deposition problems and the current storage capacity has decreased to 70% of the total storage. Reservoir deposition has become an inevitable topic, and Taiwan's reservoir is worth investigating to formulate a suitable strategy to solve the water resources problem.

As mentioned above, reservoir sedimentation has been a severe problem threatening reservoir storage capacity and

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lifespan. Numerous methods have been developed to preserve the storage capacity of reservoirs based on the removal and release approach. To increase storage volume, the feasible removal strategies mainly observed are mechanical trucking and hydraulic desiltation. Note that the removal approach is widely employed in most reservoirs; however, sediment inflow during typhoon periods often exceeds this amount, presumably due to the effects of climate change (Annandale et al. 2016). To solve the reservoir sedimentation issue, the release method of turbidity current venting through the bottom sluice gates during the flood season has been shown to enhance sediment release efficiency by up to 60% (Batuca and Jordaan 2000; Chamoun et al. 2016). However, some reservoirs lack enough discharge ability of the bottom outlet to release sufficient sediment to the downstream river. Empty flushing is an effective approach to resolving sedimentation which involves lowering the reservoir water level to the bottom to maximize the release of inflowing material (Chen 2018; Fan and Morris 1998). In many situations, this allows the removal of enough sediment from the bottom of the reservoir to bring the riverbed down to the level of the downstream river, such that flow conditions are similar to those of an open channel. Unfortunately, most of Taiwan reservoirs are ill-suited to empty flushing, due to the country's constant reliance on major reservoirs for water storage. Compared with the methods above, adopting the sediment bypass tunnel to settle sedimentation could be a suitable strategy. Sediment bypass tunnels can be built in the reservoir or upstream. They offer highly-efficient desilting operations because sediments are partially prevented from entering and passing through the reservoir to the downstream river. Sediment bypass tunnels upstream from the reservoir allow the suspended bedload to be flushed downstream without passing through the reservoir (Kondolf et al. 2014; Lee et al. 2022; Sumi et al. 2004). In using this type of tunnel, it is important to balance the inflow and discharge; however, it is feasible in Taiwan because the sediment can be flushed upstream of the reservoir. This avoids hyper-concentrated flow into the reservoir with the corresponding deposition on the floor of the reservoir. In the context of sediment release efficiency and water storage capacity, hydraulic release through sediment bypass tunnels is an effective strategy to preserve the storage capacity of reservoirs during typhoon events.

Using a flume or a hydraulic model to investigate the turbidity current movement is an important and valuable method. Based on a physical model-based can physically realize the deposition pattern and desilting efficiency of a hydraulic desiltation method. Huang et al. (2018) mentioned sedimentation is a severe problem in Taiwan's regional reservoirs, particularly after the Chi–Chi earthquake. A scale physical model of the Wushe Reservoir was built on understanding sediment movement and evaluating sediment trap efficiency. The study proposes modifying Brune's method to predict the reservoir's residual life. Beckers et al. (2018) present an experimental approach to investigate cohesive reservoir sediments, using sediment cores extracted from reservoir beds with a Frahm Sediment Sampler. The sediment properties over depth were analyzed to determine depth-dependent erosion stability in an erosion flume, and the results were combined to investigate correlations. Chamoun et al. (2017) introduce that sedimentation in reservoirs threatens their lifetime and efficiency, but venting of turbidity currents can help manage sediment. It presents venting and evaluates its performance using an experimental model with varying outflow discharges and bed slopes, finding that steeper slopes yield higher venting efficiency. Chamoun et al. (2018) use a flume and investigate the timing and duration of venting, finding that in-time venting is more efficient and should start when the turbidity current is around 300 m upstream of the outlet. Then, the venting should continue for a specific time, depending on the outflow discharge, to evacuate the muddy lake. In addition, an accurate estimation of sediment volume is essential to maintain the proper functioning of reservoirs. While physical models are helpful for this purpose, questions regarding flow and solid discharge in the simulation process remain. Teixeira et al. (2020) propose a methodology for the physical simulation of silting in models, which uses average flows of maximum waves and annual average solid discharges to represent sedimentation in the reduced model accurately. The results suggest that this methodology effectively represents the sedimentation phenomenon in the actual reservoir.

Based on the above literature review, we realize the sedimentation in a reservoir is a crucial issue for the sustainability issue of water resources. The hydraulic experiment of the bypass tunnel was conducted to investigate the benefit of a bypass tunnel for reservoir capacity. The current study created a 1/50 scale model of the first sediment bypass tunnel designed in Taiwan, paying careful attention to the geometry of the design and kinematics of water flow in the creation of hydrographs specific to a variety of events with various return periods. This study also considered the shape of sediment particles by collecting sediment in the field to ensure accuracy in modeling the sediment transport mechanism. We examined variations in bed elevation and sediment trap proportion to assess the stability of the river as a function of flood event severity. Finally, the estimation of the sediment release efficiency was adopted to predict the lifespan of the reservoir with and without the proposed bypass tunnel. The study also provides insight into the operation effect of short-term and long-term periods. The 3-stage research flowchart including prerequisite, and experiment set-up, and result and discussion is shown in Fig. 1.

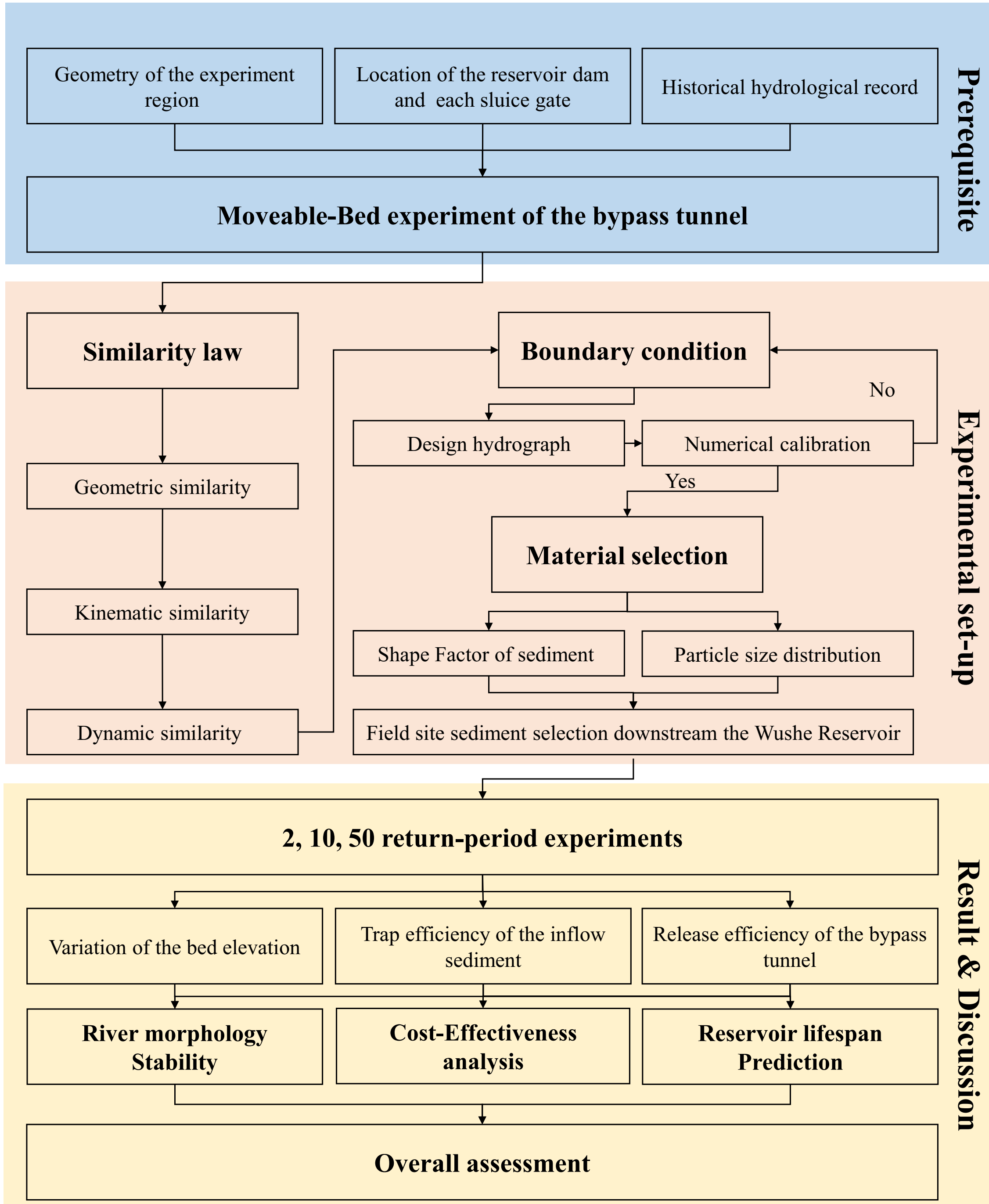


Fig. 1 Flowchart of experiments conducted in this study

Case study site

This study established a hydraulic model based on the area upstream from the Wushe reservoir in central Taiwan (Fig. 2). Completed in 1959, the Wushe Reservoir measures 4750 m in length with a catchment area of 219 km^2 and a designed storage capacity of 150 million m^3. Chou-ishui River is the main stream of the Wushe Reservoir, producing more discharge and sediment than any other rivers in central Taiwan. The Chichi Earthquake in 1999 caused extensive damage to the watershed, which greatly increased the sediment yield. A survey conducted in 2010 indicated a storage capacity loss of 96.21 million m^3, and a follow-up survey in 2016 estimated the loss at 106.34 million m^3. Figure 3 illustrates the trend of deposition in Wushe Reservoir.

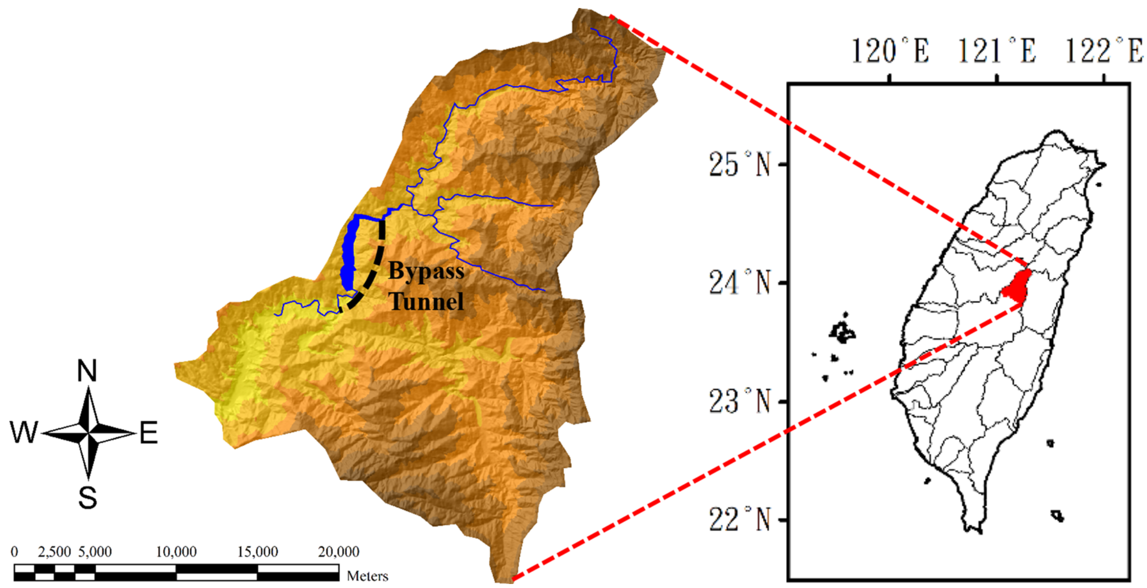
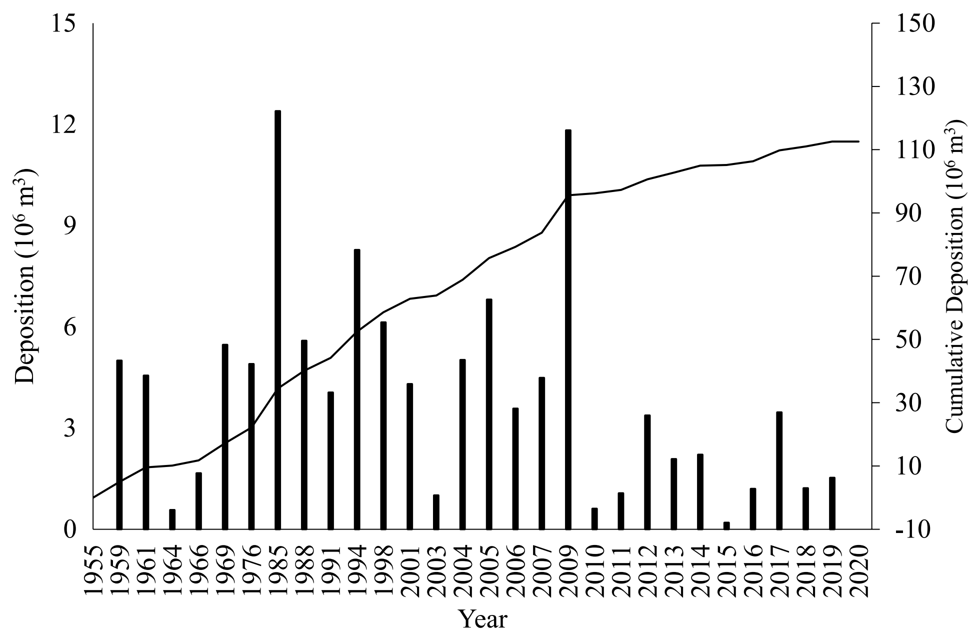


Fig. 2 Location of Wushe Reservoir

Fig. 3 Deposition trend in Wushe Reservoir



The active storage capacity of a reservoir varies as a function of sedimentation rate in the deposition delta and changes in elevation upstream of the dam. Figure 4 presents historical data pertaining to bed elevation and satellite images of the Wushe Reservoir. Based on the bed elevation in 2010 (the initial condition of this hydraulic model), the delta has expanded 2047 m upstream of the dam (located at distance 0 m). Considering that the total length of the reservoir is 4750 m, the delta now encompasses more than half of the reservoir. The 2010 survey also revealed an increase in the upstream elevation from 927 to 952 m a.s.l. since 1959. Note however that the Chichi Earthquake accelerated the rate of deposition from 952 to 969.7 m a.s.l. within one decade. Thus, it appears that in the foreseeable future, the remaining storage capacity will decrease at an alarming rate.

Given that the amount of inflow sediment has increased significantly after the Chichi earthquake, allowing the inflow sediment to be excluded as much as possible before entering the reservoir is a priority. Determining the optimal location for the bypass tunnel and further studying its sediment release efficiency are the principal aims of this study. The

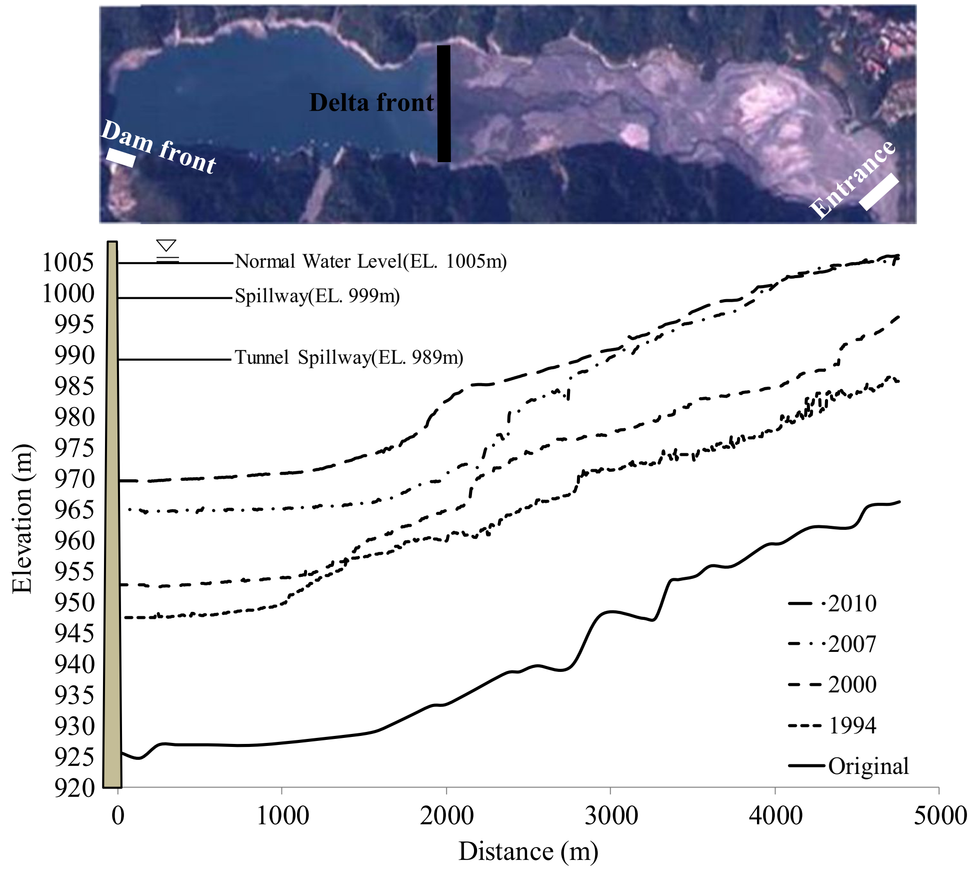


Fig. 4 Longitudinal bed elevation and satellite image of Wushe Reservoir

following introduces the similarity law of this hydraulic model, and the chosen principle of the boundary condition.

Experiment setup

Similarity law

It is crucial that the flow conditions of the hydraulic model and prototype obey the similarity law in terms of geometry, kinematics, and dynamics. The scale of the hydraulic model was 1/50. The ratio of the length, width, and height of the corresponding parts is described as follows:

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

where u, v, and w respectively indicate velocity in the x, y, and z directions and s refers to sediment concentration.

Kinematic similarity relates to time and distance with the velocity ratio matching the direction of movement. It is also important to ensure similarity between the hydraulic model and prototype in terms of transport path and transport duration. Dynamic similarity refers to mass and force. In the current study, gravity is the primary factor controlling all hydraulic phenomena. Here, we use the Froude number to estimate model similarity as follows:

The equation can be written as

$$\frac{\lambda_u \lambda_s}{\lambda_L} = \frac{\lambda_v \lambda_s}{\lambda_W} = \frac{\lambda_w \lambda_s}{\lambda_H}, \quad (2)$$

where λ_u and λ_v indicate the horizontal velocity scale; λ_w is the vertical velocity scale; λ_L and λ_W are the horizontal scales; λ_H is the vertical scale; and λ_s is a concentration scale.

In accordance with the Froude number law of similarity, Eq. (2) can be rewritten as follows:

$$\frac{\lambda_u}{\sqrt{\lambda_g \lambda_H}} = \frac{\lambda_v}{\sqrt{\lambda_g \lambda_H}} = 1, \quad (3)$$

where g is the acceleration of gravity and $\lambda_g = 1$, which can be derived as follows:

$$\lambda_u = \lambda_v = \lambda_H^{1/2}. \quad (4)$$

The time scales $\lambda_t = \frac{\lambda_L}{\lambda_u} = \frac{\lambda_W}{\lambda_v}$, and $\lambda_u = \lambda_v = \lambda_H^{1/2}$, can be derived as follows:

$$\lambda_t = \frac{\lambda_L}{\lambda_H^{1/2}} = 50^{1/2}. \tag{5}$$

The inflow discharge can be written as follows:

$$\lambda_Q = \lambda_L \lambda_H \lambda_u = 50^{5/2}. \tag{6}$$

In the mobile-bed experiment, the sediment particle size can be determined using the following formula:

$$\lambda_{\tau_c^*} = \frac{\lambda_{\tau_c}}{\lambda_g \lambda_{(\rho_s-\rho)} \lambda_d} = 1, \tag{7}$$

where $\tau_c = \rho g R S_f$, and it is the critical shear stress; d is the particle size; ρ and ρ_s respectively indicate the density of water and sediment; R is the hydraulic radius; and S_f is the slope. If $\Delta = \frac{\rho_s-\rho}{\rho}$, Eq. (7) can be rewritten as follows:

$$\lambda_d = \lambda_\rho \lambda_g \lambda_H^2 \lambda_L^{-1} \lambda_{(\rho_s-\rho)}^{-1} = \lambda_H^2 \lambda_L^{-1} \lambda_\Delta^{-1}, \tag{8}$$

where λ_{ρ_s} and λ_ρ are the same as the prototype, and λ_d=λ_H.

Table 1 lists the scale ratios of the hydraulic model and prototype.

Shape of sediment particles

Particle shape can have a profound effect on the accuracy of a hydraulic model and the fidelity of a scale model. Markwick (1937) proposed a system for the classification of particles according to shape, based on the following equation:

$$s_f = \frac{c}{\sqrt{ab}}, \tag{9}$$

where a, b, and c indicate the length, width, and thickness of a particle.

According to Markwick (1937), the sediment particle can be defined as "long" when $a/b > 1.8$. It is defined as "flaky" when $c/b < 0.6$. Note that Eq. (9) can be used to confirm the degree of similarity between particles.

The current study sought to use in the model particles that matched as closely as possible the shape of models obtained in the field and those used in the hydraulic model. This was achieved by collecting sediment from the banks of the Chou-ishui River at several points upstream from the designed bypass tunnel site. We also collected particles in Mailiao (2000 m upstream of the estuary of the Chouishui River) to compare the diameter distribution with sediment obtained at Wushe. As shown in Fig. 5, the particle size distribution in the Mailiao sample was close to that of the Wushe sample. Based on the definitions proposed by Markwick (1937), particles in both the Mailiao and Wushe samples were identified as “long” and “flaky”. The s_f values were as follows: Mailiao (0.043) and Wushe (0.046). Considering

Table 1 Scale ratios of hydraulic model and prototype

Term	Length (m)	Width (m)	Height (m)	Time (s)	Velocity (m/s)	Discharge (m^3/s)	Particle size (m)
Scale	λ_L	λ_W	λ_H	$\lambda_L \lambda_H^{-1/2}$	$\lambda_H^{1/2}$	$\lambda_L \lambda_H^{3/2}$	λ_H
Proportion	50	50	50	$50^{-1/2}$	$50^{-1/2}$	$50^{5/2}$	50

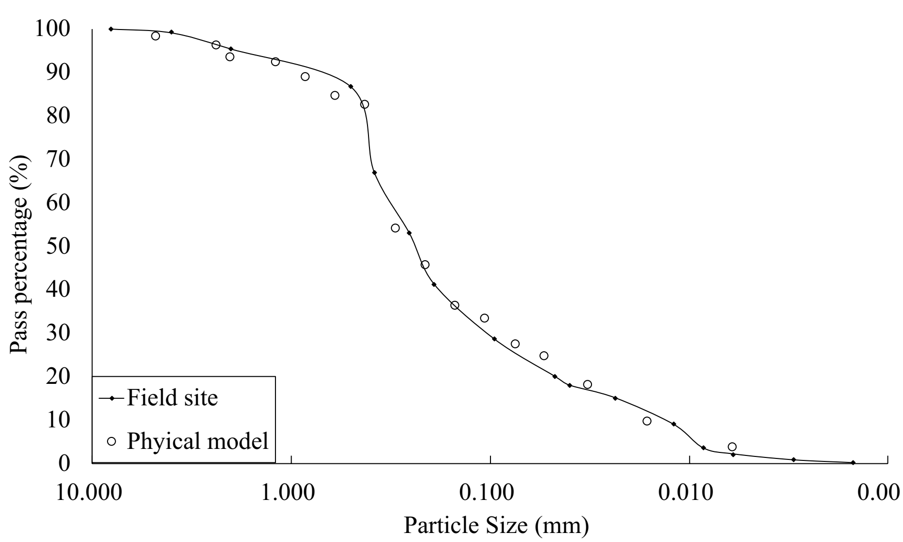


Fig. 5 Distribution of sediment particle sizes

the extremely low error, it appears that sediment from Mailiao could be used for hydraulic modelling. Figure 6 presents high-resolution microscope images of particles collected in Wushe and Mailiao.

Boundary conditions

The historical records of Wushe Reservoir indicate a mean daily discharge of fewer than 9 m^3/s during the dry season when the conditions are insufficient to generate highly-concentrated flow. Note that the hydrographs of typhoon events are too complicated for easy reproduction in hydraulic experiments; therefore, we employed recurrence interval hydrographs in the current research. This involved determining boundary conditions, including inflow discharge and sediment. Three return-period events were used to assess the release efficiency of the bypass tunnel. The 2-year return-period event was indicative of an ordinary case (mild scenario). The 50-year return-period event was indicative of a situation involving probable damage and maximum effectiveness of the bypass tunnel (severe scenario). We also considered a 10-year return-period (moderate scenario). Controlling experiment hydrographs to fit the designed hydrograph can be hindered by the fact that a continuous hydrograph proceeding from the rising limb to the falling limb is a smooth curve. To simplify the operation, the experiment hydrograph was processed via flow classification with the grading of 50 m^3/s, 250 m^3/s, 450 m^3/s, 650 m^3/s, 850 m^3/s, 1050 m^3/s, 1250 m^3/s, and 1450 m^3/s. Note that the amount of inflow material should be consistent with conditions in the field. The sum of the inflow in each stage must correspond to the following calculation:

$$T_i = \frac{\sum Q_t}{Q_n}, \tag{10}$$

where T_i is the duration (hours) of grading discharge in a given stage; i indicates the stage number; Q_n is the discharge adopted for a given stage; and Q_t is the actual discharge during that stage. Table 2 and Fig. 7 present the inflow boundary conditions of the various events. The quantity of inflow sediment in the hydraulic model was as follows: 2-year return period (17.01 tons), 10-year return period (52.79 tons), and 50-year return period (95.53 tons). Besides the relationship between water and sediment discharge shows in following equation.

$$Q_s = 0.203Q_t^{1.628}, \tag{11}$$

where Q_s is the sediment discharge.

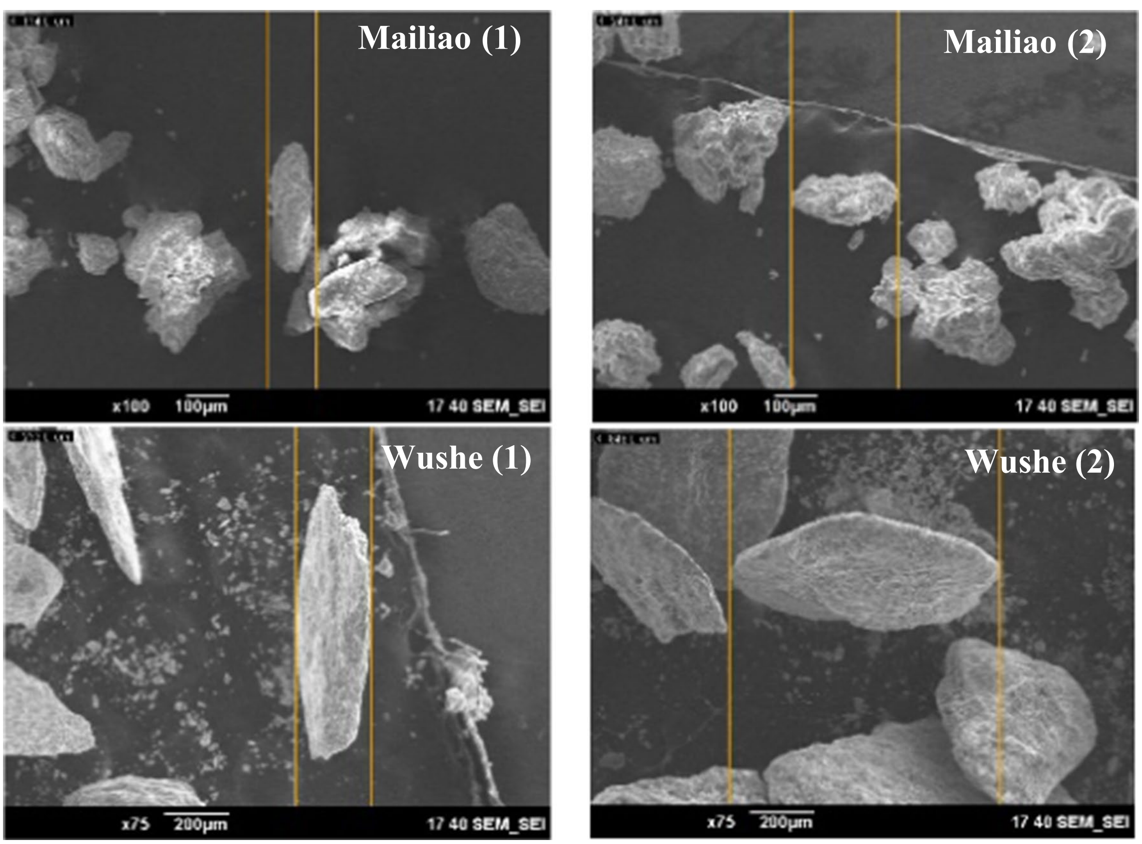


Fig. 6 High-resolution microscope image of particles from Wushe and Mailiao

Table 2 Quantity of inflow material, unit: 10^6 m^3

Term	2-Year	10-Year	50-Year
Water discharge (prototype)	531 (m^3/s)	1063 (m^3/s)	1523 (m^3/s)
Sediment discharge (prototype)	0.72×10^6 (m^3)	2.23×10^6 (m^3)	4.25×10^6 (m^3)
Sediment discharge (physical)	6.12 (m^3)	18.99 (m^3)	34.36 (m^3)

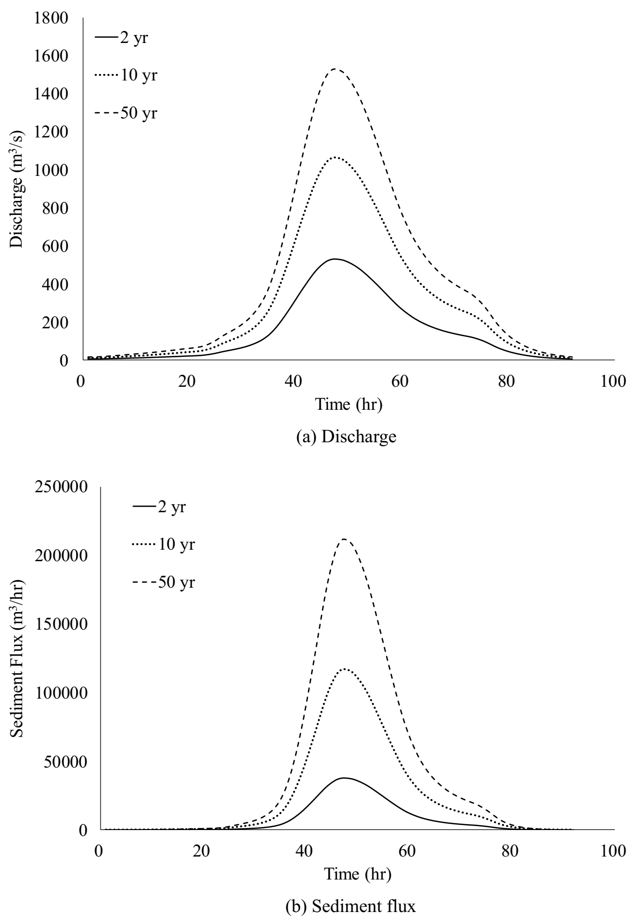


Fig. 7 Inflow boundary conditions

The dominating role of the outflow boundary was another major factor in the hydraulic experiment. In the region of interest, the slope grade of the bypass tunnel would be 1.6%, with the inflow 1800 m upstream of the reservoir entrance (1009.5 m a.s.l.) and the outflow 3100 m downstream of the Wushe dam (909.0 m a.s.l.). Under these conditions, the inner diameter of a bypass tunnel providing discharge of 450 m^3/s would measure 6.6 m. This route should make it possible to release incoming sediment via the bypass tunnel rather than having it flow into the reservoir. In addition, it would also be advisable to install a check dam downstream of the bypass tunnel to trap the remaining sediment. The outflow boundary of this hydraulic model is presented in Fig. 8 and the geographic region is indicated in Fig. 9. At a scale of 1:50, the length of the scale model was 10 m and the width was 8 m.

The location of the inflow is crucial to the stability and reliability of the hydraulic experiment. We selected three candidate upstream locations, and a 2-D shallow water model (SRH2D; Lai 2009; Lai et al. 2006) was used to derive the velocity distribution of each cross-section (see Fig. 10). Sec. 57 presented the velocity distribution with the highest uniformity.

Results

Sediment release efficiency can be used as a standard indicating the effectiveness of a bypass tunnel design. Figure 11 presents the sediment release efficiency of the bypass tunnel under three return-period events (mild, moderate, and severe). Figure 11a indicates the amount of sediment released under the three scenarios and the remaining sediment (as a percentage of the total) in the bypass tunnel and reservoir. In the first 95 min, all of the inflow sediment was carried through the bypass tunnel due to the fact that the discharge exceeded the inflow (450 m^3/s). The check dam trapped a portion of the sediment; however, it was unable to prevent the flow of all sediment into the reservoir for 96–129 min. At 130 min, the actual discharge did not meet the designed discharge. Therefore, the sediment could be released depending on the bypass tunnel, and no more flowed into the reservoir. The cumulative release efficiency was 95.8%, with only 1.4% making it all the way from upstream into the reservoir.

The overall results were similar under moderate and severe rainfall conditions. As in the mild case, discharge of up to 450 m^3/s enabled the transport of inflow sediment via the bypass tunnel; however, the peak discharge under moderate and severe conditions was 2–3 times that of the 2-year return period, which undermined the effectiveness of the tunnel. As shown in Fig. 11a–c, the total release efficiency of the bypass tunnel decreased from 95.8 to 77.5 to 61.9%. Figure 12. shows the percentage of incoming sediment passed downstream, captured by the check dam, or deposited in the reservoir. The value of sediment trapped by the check dam was as follows: mild (2.8%), moderate (6.7%), and severe (15.2%). The percentage of sediment transported to the reservoir was as follows: mild (1.4%), moderate (15.8%), and severe (22.9%). Note that

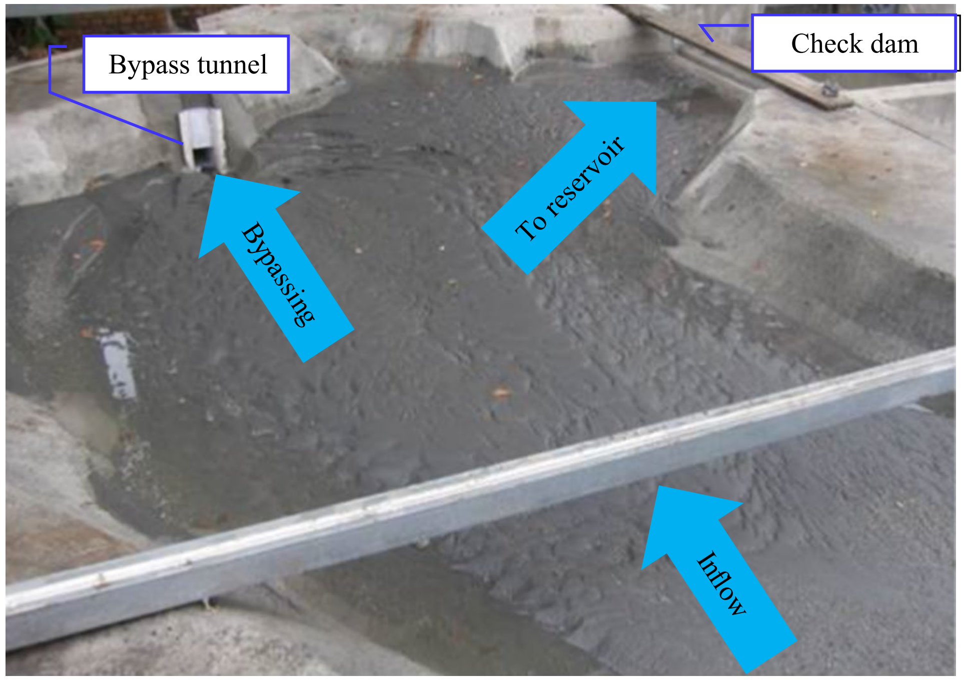


Fig. 8 Physical model of bypass tunnel experiment

most of the inflow sediment would be released from the bypass tunnel and trapped by the check dam even in a severe scenario. In other words, the inflow sediment could be released again by operating the sluice gate to slow down the deposition trend.

Figure 13 presents the morphology of the river under mild rainfall conditions at the end of the experiment. The inflow boundary was nearly vertical to the bypass tunnel. It influenced the flow direction to face the tunnel due to the curved channel. Therefore, the initial inflowing material could be fully-released from the bypass tunnel, although the discharge increased to 531 m^3/s. The flow direction is still kept without significant change. Note that peak discharge during the moderate event was double that of the mild event; however, the scour holes did not vary significantly. Slight deposition was observed in the main channel and on the left side of the riverbank. The bed morphology shown in Fig. 14a had a similar variate trend with the slight event. Next, the extreme event, the severe event shows in Fig. 14b presented a significant difference between the first two events. Firstly, the vast flood affected the main channel to transform from the right to the center. The main channel also expanded to the left riverbank. The tremendous amount of sediment generated under severe flood conditions increased the depth of the deposits along the left riverbank upstream, while the downstream riverbed rose by 1–5 m. In all three experiments, the front of the bypass tunnel presented a clear scour hole roughly horizontal to the bottom of the gate. Taken together, these results indicate that even under extreme typhoon conditions, the bypass tunnel would be highly effective in the removal of sediment.

Discussion

The storage capacity of the Wushe Reservoir is constantly decreasing under the effects of sedimentation. The total quantity of sediment that was missed by the bypass tunnel and check dam can be estimated by measuring sedimentation in the reservoir. The cumulative release of sediment was as follows: mild conditions (0.84 million m^3), moderate conditions (1.73 million m^3), and severe conditions (2.63 million m^3). The capture of sediment by the check dam was as follows: mild conditions (0.02 million m^3), moderate conditions (0.15 million m^3), and severe conditions (0.65 million m^3). The increase in sediment release appears due to reduced bypass efficiency under the effects of increased inflow. The cutoff was inflow of 450 m^3/s, below which the sediment was easily extracted by the bypass tunnel and above which sediment was carried toward the reservoir. The sediment trapping capacity of the check dam is another important issue in protecting the reservoir from storage degradation. Under mild conditions, sediment capture was below 3%, due to high bypass efficiency. Under severe conditions, the check dam was overwhelmed. Thus, it appears that the check dam should be carefully constructed to facilitate on-going dredging. The quantity of sediment that passed the check dam is listed in Table 3 as a function of flood conditions.

The most critical issue is the amount of sediment that flows into the reservoir. Huang et al. (2018) linked sediment-trapped efficiency to reservoir capacity and inflow discharge, thereby making it possible to estimate the lifespan of the Wushe Reservoir. The analysis of this study was based on the assumption that the upstream sediment in the

Fig. 9 Geographic region depicted in hydraulic model

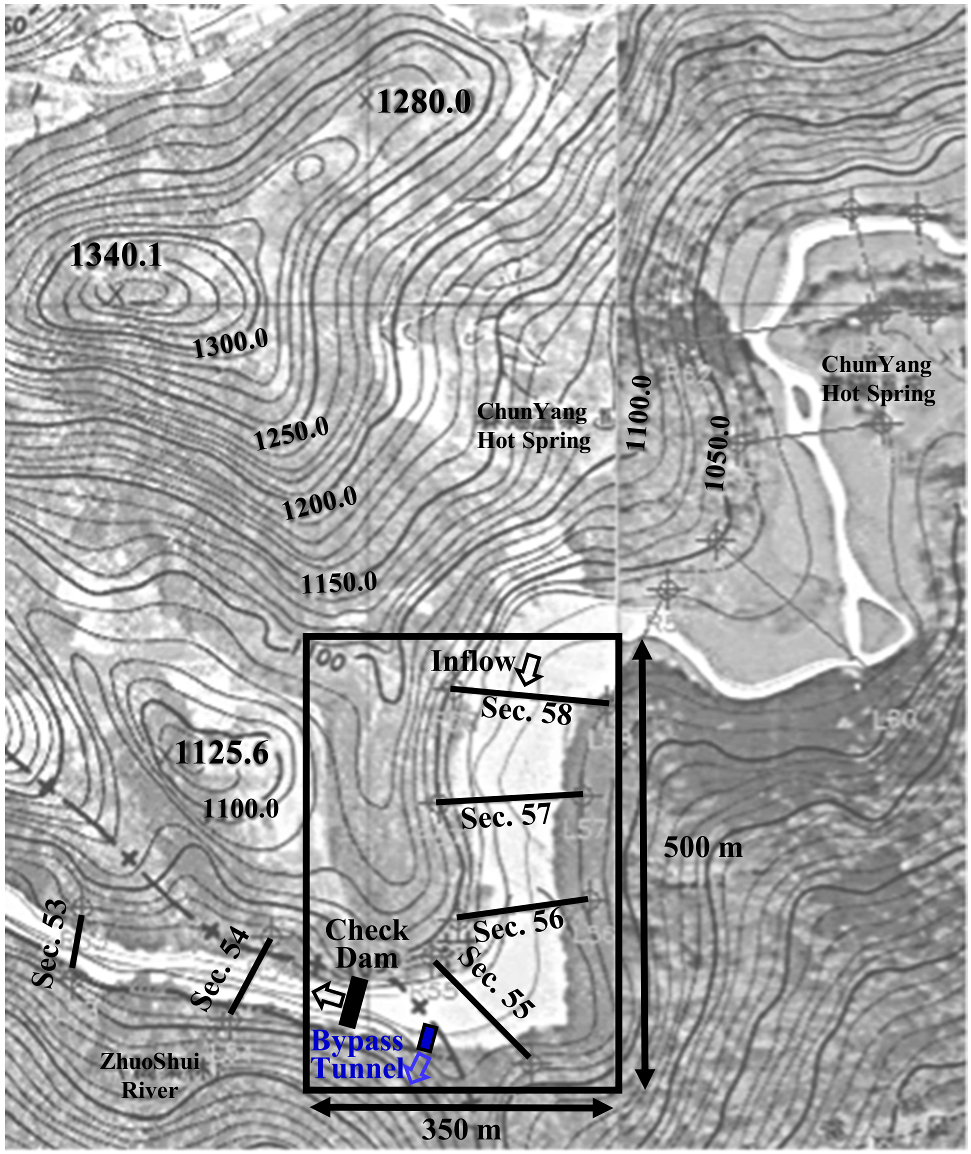
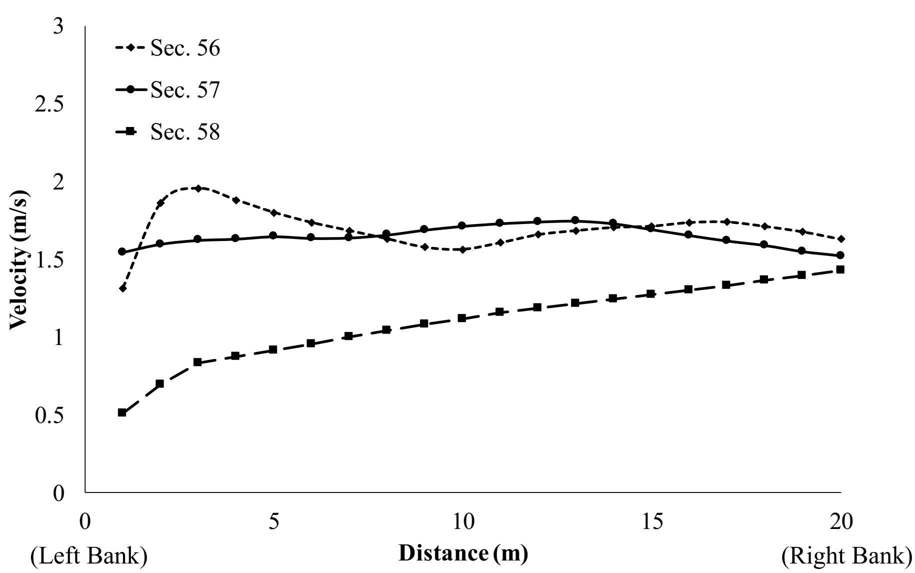


Fig. 10 Horizontal velocity distribution in cross-section upstream of the reservoir



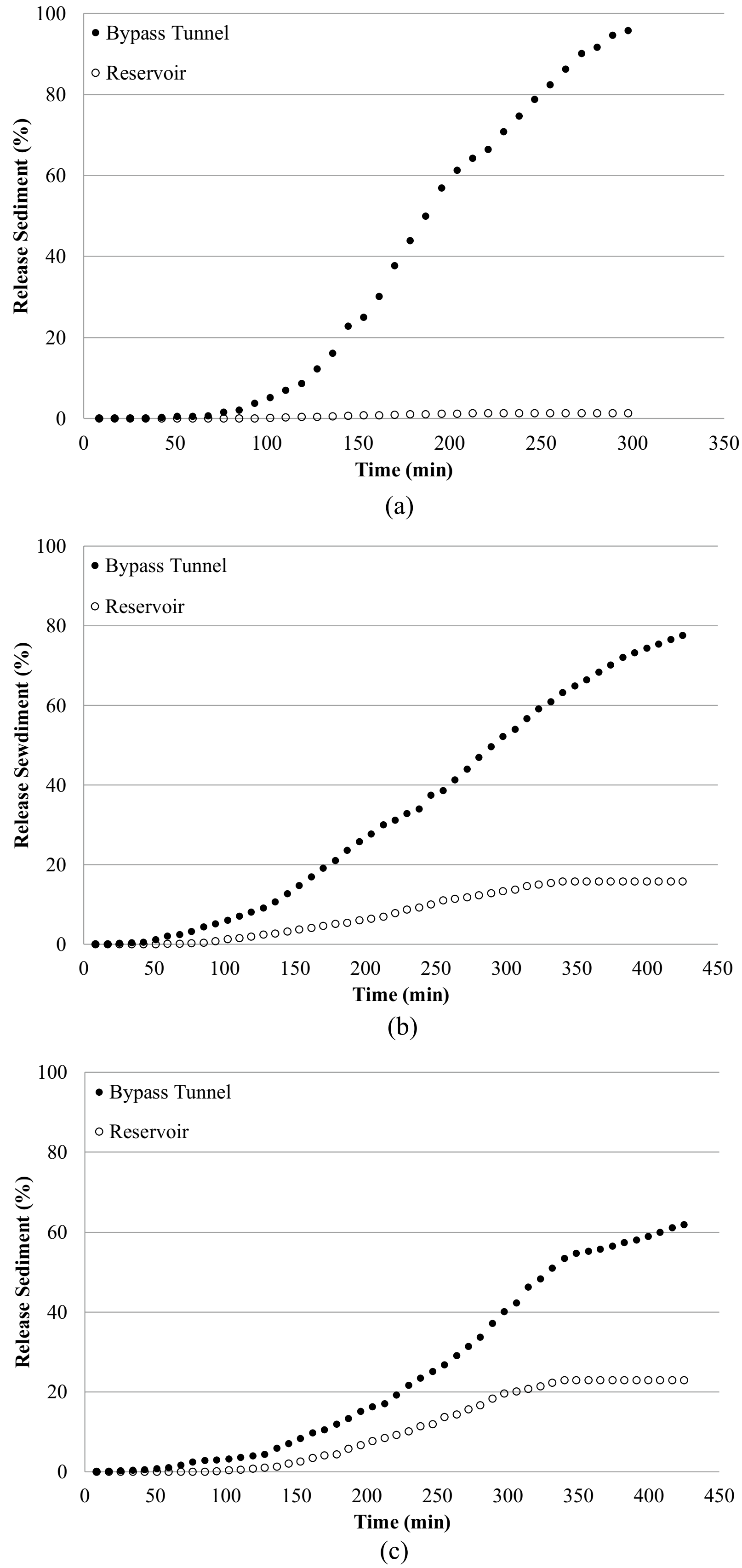


Fig. 11 Sediment release efficiency under three scenarios: **a** 2-year return period; **b** 10-year return period; **c** 50-year return period

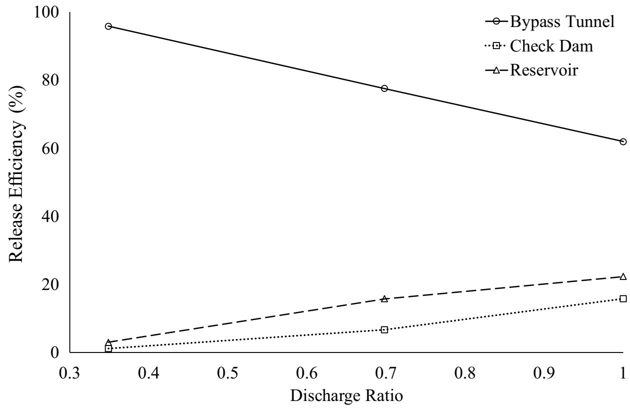


Fig. 12 Percentage of incoming sediment passed downstream, captured by the check dam, or deposited in the reservoir

check dam would be dredged every year. Thus, sediment flows into the reservoir should be calculated by subtracting the total sediment funnelled off by the tunnel as well as that captured by the check dam. Figure 15 shows the lifespan of Wushe Reservoir under the three scenarios addressed in this study, based on the research of Huang et al. (2018). The only difference between the findings reported by Huang et al. (2018) and our findings is the existence of a bypass tunnel. Note that in Fig. 15, we omitted the results obtained under mild conditions, because mild events would have little or no effect on sedimentation (i.e., a dynamic equilibrium in which inflow sediment equals outflow sediment). A comparison of the black dotted line (with the bypass tunnel) versus the black line (without the bypass tunnel) shows that without a bypass tunnel, storage capacity will disappear by 2037, while construction of a bypass tunnel would prolong the life of the reservoir to 2117 (by 80 years), even under extreme rainfall events. Under moderate conditions, the construction of a bypass tunnel would decrease annual inflow sediment to 419,000 m3, extending the reservoir's life to 2260.

It is also important to consider the cost-benefits of bypass tunnel construction and dredging. Based on current market prices for moving sediment (17 USD per m^3), the cost of dredging would be as follows: mild conditions (0.42 million dollars), moderate conditions (2.54 million dollars), and severe conditions (10.98 million dollars). Considering a cost of 295 million dollars for the bypass tunnel, the corresponding cost-recovery period would be as follows: mild conditions (21 years), moderate conditions (10 years), and severe conditions (8 years). If the bypass tunnel had been completed by 2010, then break-even would have been achieved in 2031, 2020, and 2018, respectively. At present, excavation is the primary method used to reduce sediment volumes. A bypass tunnel would also overcome the air and noise pollution associated with excavation equipment.

Note that further work is required to elucidate the effects of bypass tunnel construction on the morphology of the riverbed as a function of storm severity. In experiments, we demonstrated that only 2.99 to 22.30% of inflow sediment ended up in the reservoir. Nonetheless, this still involves non-negligible channel erosion and sediment deposition in highland regions. Under mild and moderate conditions, the riverbed morphology should remain relatively stable, considering that the contribution of new sediment would account for only 1.20 or 6.70% of the total. Under severe conditions, the fact that 15.8% of the sediment would eventually be trapped along the riverbed could profoundly influence riverbed morphology. Much of the remaining sediment would be deposited along the left riverbank, which would increase the highland elevation by 1–5 m. The accumulation of sediment along the right riverbank would require mechanical dredging to ensure the smooth operation of the bypass tunnel.

Conclusions

This article investigates a bypass tunnel from the reservoir upstream to the downstream based on three hydrological conditions. First, we focus on its bypass efficiency of total load sediment yield with suitable grain size and discuss its long-term effect on reservoir storage. Based on the literature review, this sediment bypass condition is limited. Therefore, under a scientific law of similarity and shape effect consideration, we conducted a physical model to study the benefit of a bypass tunnel for reservoir capacity. It is valuable for experimental studies on the bypass issues and the applicability of particle shape for hydraulic modeling. It is also helpful to further understand the operation effects of short-term (single event) and long-term periods in reduction of reservoir sedimentation. In reservoirs used for water storage, bypass methods are the preferred strategy to relieve sediment deposition. This study investigated sediment movement using a 1/50 hydraulic model of a bypass tunnel proposed for an existing reservoir. Experiment parameters included the shape of sediment particles, the movement of which should match that of sediment at the actual dam site. We also examined the effectiveness of the bypass tunnel under extreme weather events with a range of return periods (2 years, 10 years, and 50 years) with a focus on the estimated reservoir lifespan. Finally, we analyzed the cost effectiveness of constructing a bypass tunnel.

Under mild rain events, the proposed bypass tunnel should be able to preserve storage capacity for decades. The benefits gradually decrease with an increase in event severity; however, even under a 50-year return period, the lifespan of the facility could be prolonged by more than 50%.

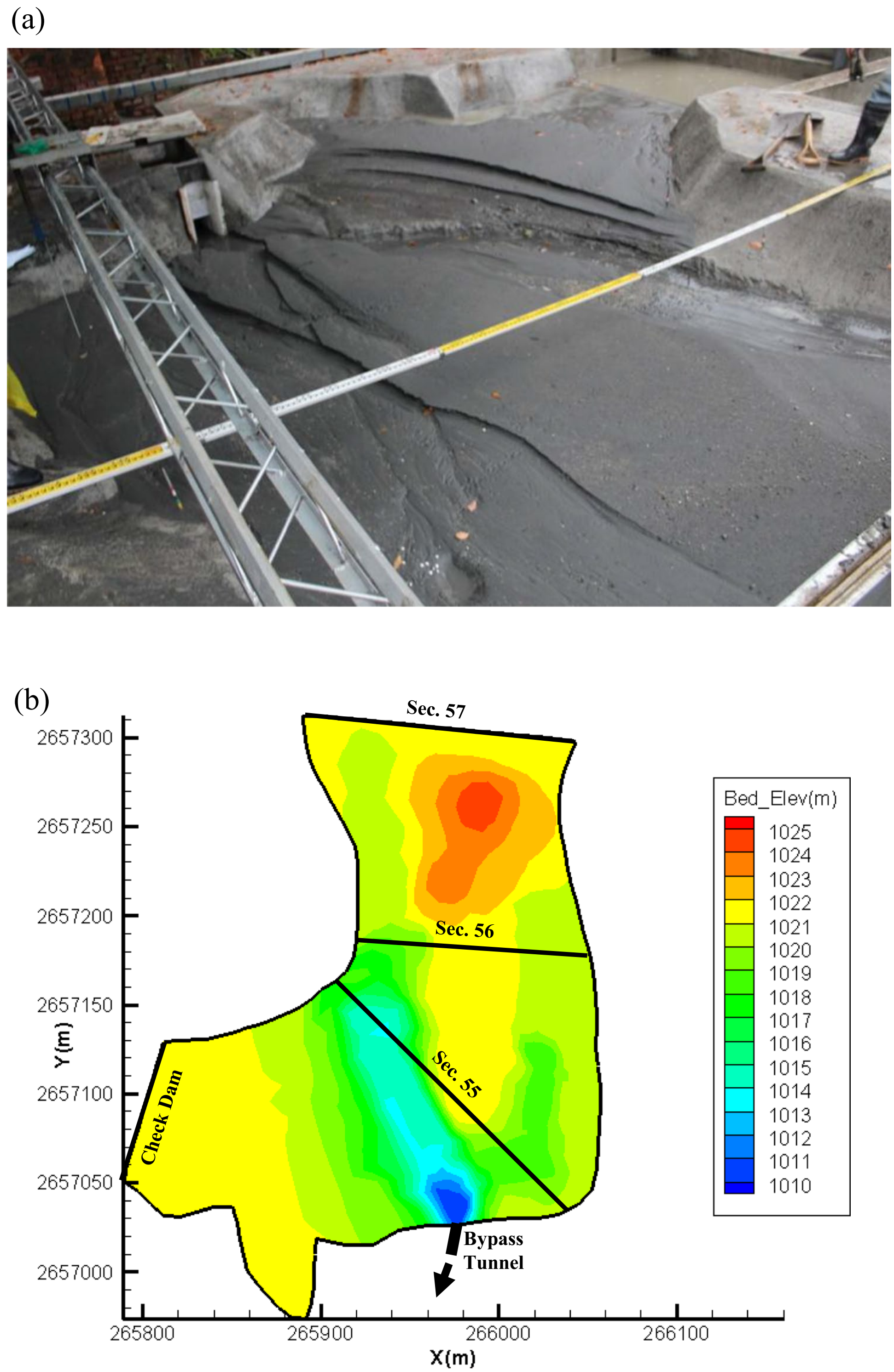
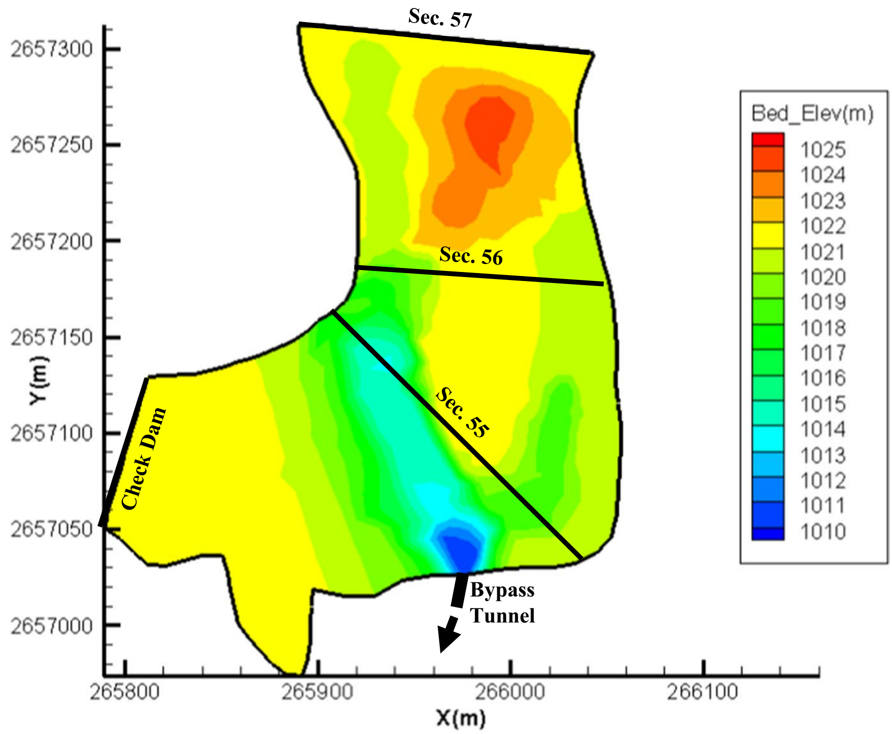


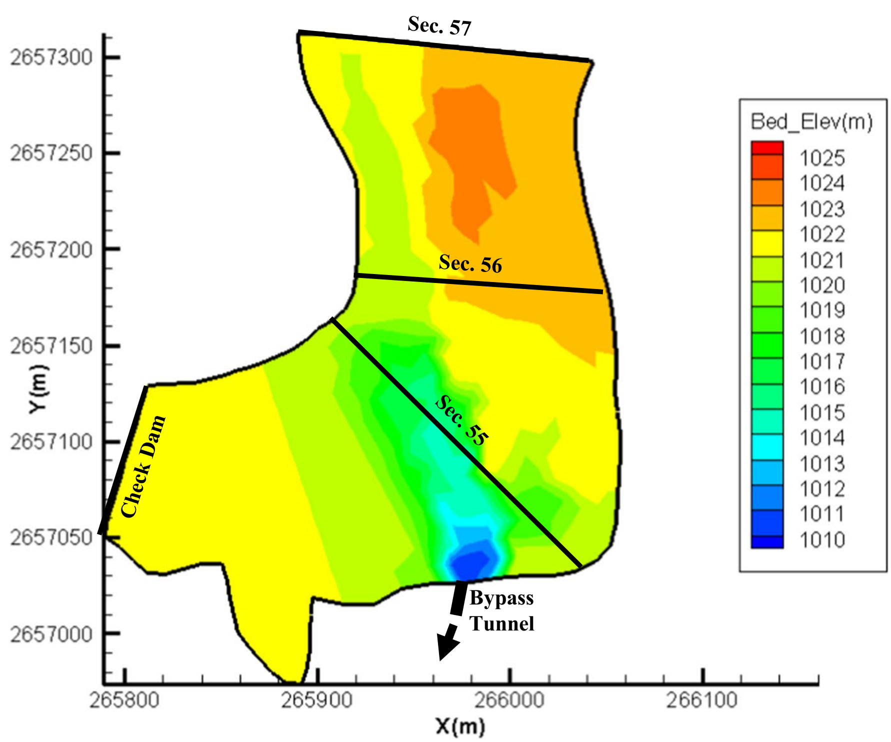
Fig. 13 River morphology following mild typhoon: **a** hydraulic model; **b** contours

In the analysis of river morphology, this study determined that the front of the bypass inlet would create a scour hole, which means that any accumulated sediment could be transported away without too much difficulty. Nonetheless, mechanical dredging would be required to remove sediment deposits from the right highland area to prevent collapses, which might otherwise affect the effectiveness of the bypass tunnel.

Implementing a bypass tunnel would prolong the lifespan of the reservoir far beyond the current desilting methods. The bypass tunnel also offers significant economic benefits, compared with dredging.



(a)



(b)

Fig. 14 River morphology following typhoons: **a** moderate; **b** severe

Table 3. Amount of sediment passing the check dam as a function of flood conditions, unit: 10^6 m^3

Term	2-Year return	10-Year return	50-Year return
Bypass	0.84	1.73	2.63
Dam	0.02	0.15	0.65
Reservoir	0.01	0.35	0.97

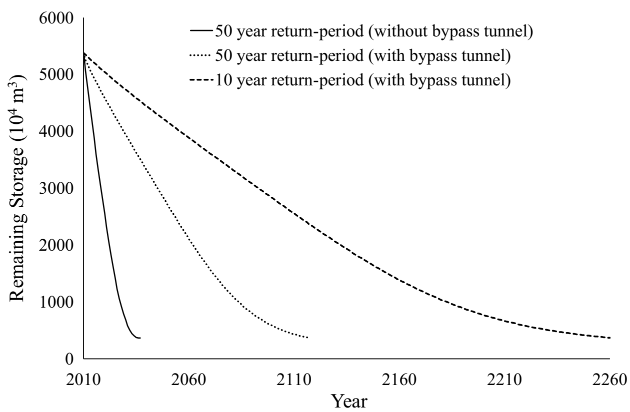


Fig. 15 Lifespan of Wushe Reservoir under three scenarios

Taken together, these results indicate that a sediment bypass tunnel is an optimal strategy for releasing inflow sediment and preserving reservoir storage capacity.

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Author contributions C-CH and H-CH wrote the main manuscript text. H-CH and C-CH come up with the concept for the experiment. C-CH, J-SL and F-ZL did the physical model experiments. H-CH worked on the numerical simulation. All authors reviewed the manuscript.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declarations

Conflict of interest The authors declare no competing interests.

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