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SETTLING SIMULATION OF A MUDD   RESERVOIR FOR
IDENTIF   ING PROBLEMATIC TURBIDIT   TO SELECTIVE WITHDRAWAL

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Abstract: The immense sediments left by a flood usually entail the reservoir full of muddy storage composed of fine-sized adherent sediments in Taiwan after a severe earthquake in 1999. The slow clarification of muddy lake usually results in water supply disruption due to the untreatable high turbidities of raw water. In this paper, a unidimensional settling model of cohesive particles based on Kynch's theory of sediment flocculation is presented. This model simulates the settling of sediment flocculation in a reservoir. The parameters of this settling model were calibrated using data from laboratory settling experiments.   The calibrated model was further implemented to simulate the settling process of muddy storage in Shihmen Reservoir following Typhoon Aere in 2004. Simulations were performed using hypothetical operating strategies with an under-construction sluiceway. The result confirmed the effectiveness of sluicing bottom storage through the sluiceway to accelerate settling.

Keywords: Muddy reservoir; Selective withdrawal; Turbidity; Settling simulation

INTRODUCTION

Floodwaters in Taiwan are usually accompanied by enormous amounts of sediment due to frequent earthquakes, steep terrain and dense rainfall. Over the last decade, high turbidity of raw water during typhoons has become one of the major threats for water resources administrators in Taiwan after a severe earthquake in 1999. Turbidity frequently exceeds the treatment limit of treatment plants. Public water demands often suffer serious shortage due to the lack of clean water.

Typhoon Aere of 2004 constitutes a particularly representative case. It brought the heaviest precipitation of the last forty years to the watershed of the Shihmen Reservoir, a major reservoir on the Tahan River of northern Taiwan. The peak reservoir inflow was 8,500 cms, and the total runoff volume approached 700 million m³, which was three times the total capacity of Shihmen Reservoir. Due to the washout by extended torrential rainfall, several hillsides in the watershed of reservoir collapsed, and about 28 million m³ of sediments were

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flushed into the reservoir. The turbidity of streamflow and reservoir storage rose to 100,000 NTU, which significantly exceeds the treatment threshold. The muddy storage of Shihmen Reservoir clarified extremely slowly following Typhoon Aere. All regional treatment plants were unable to process raw water from the Tahan River and the Shihmen Reservoir, causing a 19-day public water supply outage in southern Taoyuan district. Severe economic losses, as well as social and political crises, ensued. Several comprehensive projects were proposed following Typhoon Aere to address the sedimentation and water supply problems. The major objectives were to improve watershed management, reconstruct sluiceway, elevating public water intake and develop backup water supply systems. The proposed backup systems include building backup ponds and expanding trans-district pipes in the public water supply system.

The suspended floc in a muddy lake is comprised primarily of silt- and clay-sized sediments that adhere to each other, while most sand-sized sediments deposit in the backwater zone of the impoundment to form a delta. When the concentration exceeds a specific threshold, the flocs may further link to become a flocculated-framework (Dankers and Winterwerp, 2007), in which particles lose their individual identity and settle en masse (Diplas and Papanicolaou, 1997). Due to the influence of inter-particle forces and the upward flux of displaced water, the flocculated-framework settles much slower than do individual particles, whose motion may be adequately predicted by Stokes law (Toorman and Berlamont, 1991, Shojaeia and Arefinia, 2006). Hsu (2005) also observed this phenomenon of slower settling in experiments using mud of the Shihmen Reservoir.

This study examines how settling of sediment flocs in reservoirs affects post-typhoon public water withdrawal regardless of sedimentation processes near bottom. A one-dimensional phenomenological model was developed based on the theory of Kynch (1952) to simulate the settling of sediment flocs in a muddy lake. The parameters of model were calibrated according to the data from laboratory settling experiments. The calibrated numeral model was further implemented to simulate the settling process of muddy storage in Shihmen Reservoir during Typhoon Aere. The simulation aimed to examine the reason of slow clarification and to inspect the consequences of different reservoir operating strategies after typhoon, in order to provide a reference when designing hydraulic flushing devices and backup water supply systems.

ONE-DIMENSIONAL SETTLING MODEL FOR COHESIVE PARTICLES

Governing E uation and Numerical Scheme
The unidimensional settling model of this study, based on Kynch s theory of flocculent suspension (Kynch, 1952), simulates the settling of sediment flocs in a reservoir. Kynch s settling theory is widely applied to fields such as chemical engineering, mineral processing, food industries and waste water treatment (B rger, et al., 2005). Concha and Bustos (1991), who presented Kynch s theory as a unified kinematic process, developed a rigorous mathematical formulation of batch settling in a cylinder. They presented the following assumptions of Kynch s theory:

1. The solid particles are all small with respect to the container and of the same size, shape and density.
2. Solid particles in suspension and the fluid itself are incompressible.
3. There is no mass transfer between components.
4. The settling velocity, denoted as vs, at any point in the suspension is a function of the local particle concentration only. A mixture obeying such assumptions may be called an ideal suspension.
5. The movement of a suspension is one-dimensional. The field variables are functions of time and only one space variable. Thus, there is no wall effect, and the concentration of particles is constant at any cross-section of the vessel.

On their basis of batch sedimentation in still water, Concha and Bustos (1992) further developed the continuous Kynch settling process to the case of injecting clear water at a specific height and allowing thickened pulp at the bottom of the container. B rger et al. (2004) extended the phenomenological theory of batch and continuous settling to vessels with non-uniform cross-sections.

This study models a typhoon-affected reservoir as a large vessel with varying cross-sections and multiple intakes and outlet works at different elevations. Based on the results of B rger et al. (2004), the analysis of reservoir sedimentation simulation requires the following additional assumptions:

1. Reservoir inflow directly converges into a zone of similar concentration.
2. The inflow and outflow of a reservoir after flood do not cause significant horizontal fluid movement. The flow condition can be regarded as vertically unidimensional. The volume discharge throughout the depth is piecewise uniform. It will vary only at the location of outlets and where the inflow converges.
3. The accumulation of consolidated sediments is negligible.

These assumptions allow the following continuity equations for water and sediment in a reservoir:

$$A(z)\frac{\partial C}{\partial t}+\frac{\partial[A(z)\cdot C\cdot v_s]}{\partial z}=qi\cdot CI-qo\cdot C \tag{1}$$

$$A(z)\frac{\partial[1-C]}{\partial t}+\frac{\partial[A(z)\cdot(1-C)\cdot v_f]}{\partial z}=qi\cdot(1-CI)-qo\cdot(1-C) \tag{2}$$

in which, $A(z)$=the cross-sectional area of the vessel at height z (m^2), C=average volumetric sediment concentration in the vessel, v_f=velocities of the fluid components in the mixture (m/day), v_s=velocities of the solid components in the mixture (m/day), qi=the lateral inflow discharge within unit height (m^2/day), qo=the lateral outflow discharge within unit height (m^2/day), CI=volumetric sediment concentration of the lateral inflow.

Combining (1) and (2) yields:

$$\frac{\partial}{\partial z}\{A(z)\cdot[C\cdot v_s+(1-C)\cdot v_f]\}=\frac{\partial Q(z,t)}{\partial z}=qi-qo \tag{3}$$

where $Q(z,t)$ is the volumetric discharge of the mixture at height z and time t. Substitution of

(3) into (1) yields:

$$A(z)\frac{\partial C}{\partial t} + \frac{\partial[A(z)\cdot C\cdot v_s]}{\partial z}$$

$$= A(z)\frac{\partial C}{\partial t} + \frac{\partial[Q(z,t)\cdot C + A(z)\cdot C\cdot(1-C)\cdot(v_s-v_f)]}{\partial z} = qi\cdot CI - qo\cdot C \qquad (4)$$

The Kynch s kinematical settling theory is based on the assumption that $C\cdot(1-C)\cdot(v_s-v_f)$ in equation (4) can be expressed by an empirical drift flux density function, $f_{bk}(C)$. This governing equation is derived by substituting $f_{bk}(C)$ into (4):

$$A\frac{\partial C}{\partial t} + \frac{\partial[Q\cdot C + A\cdot f_{bk}(C)]}{\partial z} = qi\cdot CI - qo\cdot C \qquad (5)$$

In order to solve (5), the initial concentration of suspension, C_0, is assumed to be constant throughout the volume at t=0:

$$C(z,0) = C_0 \quad for \quad z > 0 \qquad (6)$$

The surface concentration is assumed to clarify immediately as settling begins:

$$C(ZL,t) = 0 \qquad (7)$$

where ZL is the height of storage in the vessel. The bottom of the vessel is assumed to be a closed boundary, which reduces the sediment flux at the bottom to zero:

$$f_{bk}(C)\big|_{z=0} = 0 \quad for \quad t > 0 \qquad (8)$$

In accordance with the aforementioned initial and boundary conditions, (5) can be solved using the explicit upwind difference scheme of B rger et al. (2004):

$$A_j \cdot \frac{C_j^{t+1} - C_j^t}{\Delta t} =$$

$$-\frac{1}{\Delta z}\left\{ Q_{j+1}^t\,C_{j+1}^t - Q_j^t\,C_j^t + [A_{j+\frac{1}{2}}\,f_{bk}^{EO}(C_{j+1}^t,C_j^t) - A_{j-\frac{1}{2}}\,f_{bk}^{EO}(C_j^t,C_{j-1}^t)] \right\} \qquad (9)$$

$$+ qi_j^t\,CI_j^t - qo_j^t\,\frac{C_{j+1}^t + C_j^t}{2}$$

In (9), the outflow concentration term is calculated by averaging the concentrations within the interval where the outlet vents water. The numerical Kynch batch flux density function f_{bk}^{EO} in (9) is given by:

$$f_{bk}^{EO}(C_{j+1}^t, C_j^t) = f^+(C_{j+1}^t) + f^-(C_j^t) \qquad (10.a)$$

$$f^+(C) = f_{bk}(0) + \int_0^C \max[f'_{bk}(x),0]\cdot dx \qquad (10.b)$$

$$f^-(C) = \int_0^C \min[f'_{bk}(x),0]\cdot dx \qquad (10.c)$$

This study assumes that the lateral inflow term of (9), qi_j^t, directly enters the storage zone whose concentration best approximates CI. The convergence zone is formulated as follows:

$$\mathbf{ONE} = \left\{ (jd, jd + n\Delta z) \middle| \; \middle| CI^t - C_j^t \middle| < 10^{-4} \; for \quad \forall j \in (jd, jd + n\Delta z) \right\} \tag{10.d}$$

Then qi_j^t can be calculated by:

$$qi_j^t = \begin{cases} \dfrac{QI^t}{\Delta z \cdot ndz} & if \quad j \in \mathbf{ONE} \\[2mm] 0 & if \quad j \notin \mathbf{ONE} \end{cases} \tag{10.e}$$

where QI^t is the lateral inflow discharge during t to $t + \Delta t$. Thus with the necessary information known beforehand, the field variables can be obtained by solving equations (3), (9) and (10). These necessary information include the initial and boundary conditions, the empirical drift flux function, the discharge and concentration of the lateral inflow, the discharge and range of the lateral outflow, and the geometric characteristics of vessel.

Parameteriation of Empirical Drift Flux Density Function
There exist various forms of the *batch flux density function*, f_{bk}, in the literature (Michaels and Bolger, 1962, Vesilind, 1968, Brger and Tory, 2000, Garrido, et al., 2000, Garrido, et al., 2003). The value of function f_{bk} is 0 for $C \leq 0$ or $C \geq C_{\max}$ and less than 0 for $0 < C < C_{\max}$, where $C_{\max}$ is the maximum solids concentration. It is usually assumed to be piecewise differentiable, $f_{bk}'(0) < 0$ and $f_{bk}'(C_{\max}) > 0$.

For f_{bk} functions with no more than two inflection points, Concha and Bustos (1991) used the method of characteristics to present five modes of sedimentation. These five modes indicate that the zones of uniform initial concentration lie above concentration gradients; in between shocks, or sharp discontinuities in the concentration profile; or in combination. Brger and Tory (Brger and Tory, 2000) proposed two additional sedimentation modes indicating that the bulk suspension could be separated from the supernatant by a rarefaction wave.

The settling experiments of Hsu (2005) using Shihmen Reservoir mud revealed that both upper and lower concentration gradients existed during settling. Due to the lack of a generalized f_{bk} form to accommodate this phenomenon, this study parameterizes the f_{bk} function by dividing the feasible concentration range between 0 and $C_{\max}$ into 10 intervals. Each interval is represented by $[C_{i-1}, C_i]$, where $i = 1$ 10, $C_0 = 0$ and $C_{10} = C_{\max}$. A corresponding value, denoted as b_i to represent $f_{bk}(C_i)$, is assigned to the concentration C_i. The b_i is set to obey the following sequence:

$$b_5 < b_4 < b_3 < b_2 < b_1 < b_0 = 0 \quad \text{and} \quad b_5 < b_6 < b_7 < b_8 < b_9 < b_{10} = 0 \tag{11}$$

After defining the (C_0, b_0), (C_1, b_1), ... , (C_{10}, b_{10}) points, the other possible f_{bk} values within these intervals are interpolated by the cubic spline approach during the numerical simulation. The coordinates of these pre-defined points are regarded as parameters that must be calibrated.

Calibration Algorithm
Calibration analysis was conducted based on the settling experiments by Hsu (2005) using field slurry sampled from the detention pond downstream from the Shihmen Reservoir. The experiments were performed in a cylindrical settling tube of uniform cross section with height 200 cm and diameter 23.8 cm at initial concentrations of 20,000 ppm and 70,000 ppm

respectively. There is not any lateral inflow to or outflow from the tube. Applying the experimental data, the parameters of the f_{bk} function are calibrated by the Gauss-Newton least-square method. The objective function minimizes the deviation of simulated concentrations from the corresponding experimental value. Beginning with assumed initial parameter values, the Gauss-Newton algorithm iteratively modifies these parameters toward local minima. Nevertheless, the ordinary Gauss-Newton least square algorithm is an unconstrained nonlinear optimization approach. It cannot directly accommodate the upper and lower limit constraints of the parameters of this study as expressed below:

$$C_{l-1} \leq C_l \leq 1.0, \text{ for } l = 1 \ 10 \tag{12.a}$$

$$b_{min} \leq b_l \leq b_{l-1}, \text{ for } l = 1 \ 5 \tag{12.b}$$

$$b_{l+4} \leq b_{l+5} \leq 0.0, \text{ for } l = 1 \ 4 \tag{12.c}$$

where C_l s and b_l s are parameters, and b_{min} is a predefined lower limit of the f_{bk} function. In order to incorporate the parameters of (12.a) through (12.c) into calibration process, this study applies a transformation procedure to convert the original parameters into unconstrained surrogate parameters to apply Gauss-Newton algorithm. The relationship between the original and surrogate parameters can be expressed as below:

$$C_l = \frac{1 - C_{l-1}}{1 + e^{-P_l}} + C_{l-1}, \quad \text{for } l = 1 \ 10 \tag{13.a}$$

$$b_l = \frac{b_{l-1} - b_{min}}{1 + e^{-P_{l+10}}} + b_{min}, \quad \text{for } l = 1 \ 5 \tag{13.b}$$

$$b_{l+5} = \frac{-b_{l+4}}{1 + e^{-P_{l+15}}} + b_{l+4}, \quad \text{for } l = 1 \ 4 \tag{13.c}$$

where P_l is the l-th transformed surrogate parameter. The initial original parameters are first transformed into an initial surrogate parameter set. The Gauss-Newton algorithm is then utilized to calibrate these surrogate parameters. While the numerical settling model is invoked during calibration to evaluate the objective function or the element of Jacobian matrix, back transformation of the unconstrained surrogate parameters through (13.a) to (13.c) determines the constrained original parameter values.

Calibration Results

Experimental values yielded by both initial concentrations --70,000 ppm and 20,000 ppm-- were used as the observed data for calibration. The discrete temporal and depth intervals for simulation were set as 5 minutes and 0.01 m. Figure 1 depicts the calibrated f_{bk} function and associated parameters.

CASE STUD

Shihmen Reservoir

The Shihmen Reservoir, constructed in 1964 of northern Taiwan was chosen as a case study. Shihmen Reservoir was designed as a multi-purpose reservoir for irrigation, hydrogeneration, public water supply, flood control, and recreation. Public water supply, however, has gradually become its primary function.
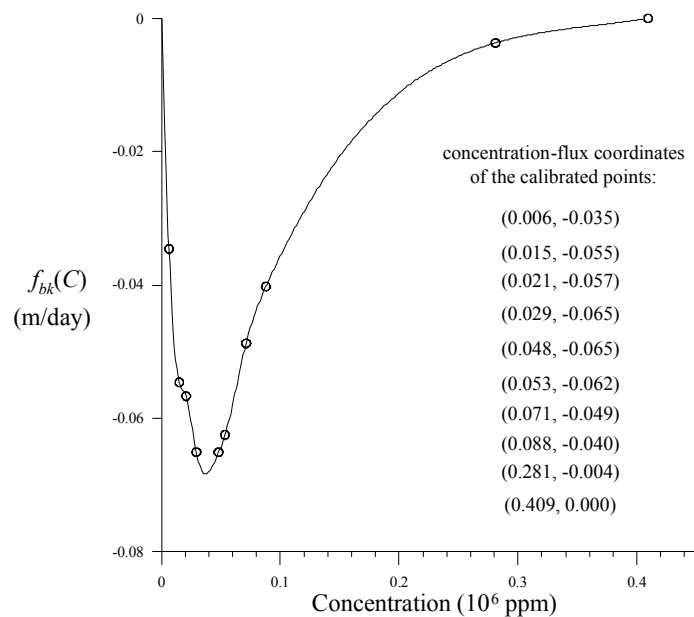
Fig. 1. Calibrated fbk function and associated parameters.

Typhoon Aere and Backup Water Supply Projects

Typhoon Aere provoked severe water supply shortage as it invaded Taiwan between August 23 and 26 of 2004. The inflow of Shihmen Reservoir peaked at 8,500 cms on August 25. During Typhoon Aere, the Shihmen Reservoir operator released water primarily through the tunnel spillway, whose crest elevation is 220 m. Hydropower gates and permanent river outlet were closed from August 29 through September 6. The turbid reservoir clarified extraordinarily slowly after Typhoon Aere. Three treatment plants in the southern Taoyuan sub-district failed to process the mud flow pumped from the Shihmen Irrigation Canal which withdraws water near the bottom of the reservoir. The southern Taoyuan sub-district suffered overwhelming water supply disruption between August 25 and September 5.

Following Typhoon Aere, the Northern Water Resources Office (NWRO) of the Water Resources Agency, Taiwan, decided to reconstruct the desiltation infrastructure for the Shihmen Reservoir (G.T. International, 2006). The first proposal calls for the construction of a sluiceway with a maximum discharge of 300 cms originated from the hydropower penstock of Shihmen Power Plant.

Another proposal entails building a multi-level outlet work (G.T. International, 2005) to withdraw the less turbid, higher storage of the Shihmen Reservoir for public demand during typhoons. This work consists of a diversion shaft from the reservoir. The shaft will be divided into three levels, with diversion tunnels to convey water from the Reservoir. The operating elevations of these tunnels will be 236 m, 228 m and 220 m respectively.

Simulating the Turbidity Profile of Shihmen Reservoir during Typhoon Aere

The linear relationship between concentration and turbidity calibrated by Hsu (2005) was employed to transform sediment concentrations into turbidity units. This highly correlated relationship equates 1 ppm concentration with approximately 1.28 NTU. The simulation

period was set from August 26 to September 11 in 2004. The initial storage concentration was assumed as 25,000 ppm, which was converted from the turbidity data observed by the Pingcheng treatment plant on August 26 in 2004. The concentration of reservoir s recession inflow was assumed to be 0. The simulation also retained the historical releasing record of each outlet. In addition to the historical release case, an alternative releasing policy was synthesized as below to probe the possible consequence of a different reservoir operating strategy:

1. The sluiceway sluices the bottom mud for the first 3 days following the flood peak.
2. The hydropower plant also releases turbid water since the storage is greater than the upper limit of the operating rule curves of Shihmen Reservoir.
3. The tunnel spillway vents excess inflow to assist desiltation.

The clear and muddy interfaces using the discrimination standard as 3,000 NTU of both strategies were shown in Fig. 2. The interface of historical case was above the elevation of Shihmen Canal intake during simulation period, yet again confirming the reason for water shortage in southern Toayuan County Fig. 2 also revealed that venting muddy storage by the lower outlets effectively accelerate the settling process. The result also showed that it might take 1-2 days for the interface to descend from the storage surface to below the operating level of multi-elevation withdraw device set up after the critical Aere event. This indicates that in the future, before typhoon arrives, the treatment plants should backup sufficient clear water amount for at least two days operation.
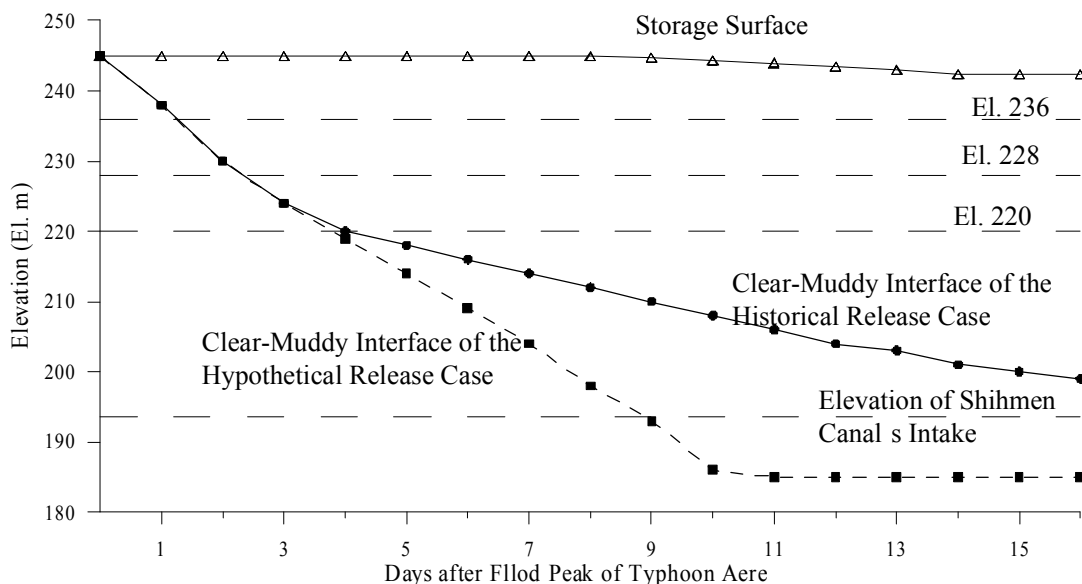

Fig. 2. Simulated clear-muddy interfaces using historical and synthesi ed sluicing strategies.

Although sluicing the bottom storage into downstream Tahan River might solve the shortage problem of southern Taoyuan, it will inevitably break down northern Taoyuan s water supply system. Fig. 3 illustrated the modeled outflow turbidity of Shihmen Reservoir in two releasing strategies as well as the measured turbidity data in Yuanshan Weir. Since there was

lateral flow from the sub-watershed between Shihmen Reservoir and Yuanshan Weir, the outflow of reservoir might be diluted thus lead to lower turbidity measurements in Yuanshan Weir. Nevertheless the simulation result by historical operating strategy still possesses a similar trend with the downstream observation data, in which Danan treatment plant was unable to withdraw water from Tahan River until four days after the typhoon had left. As for the outflow concentration of the synthesized sluicing strategy, the malfunction of Danan plant would extend to 12 days. Because Shihmen Reservoir will have to enhance its desilting operation during typhoon, backup facilities or water reallocation strategies will be urgently necessary for alleviating the impact of reservoir desilting on public water supply of northern Toayuan district.
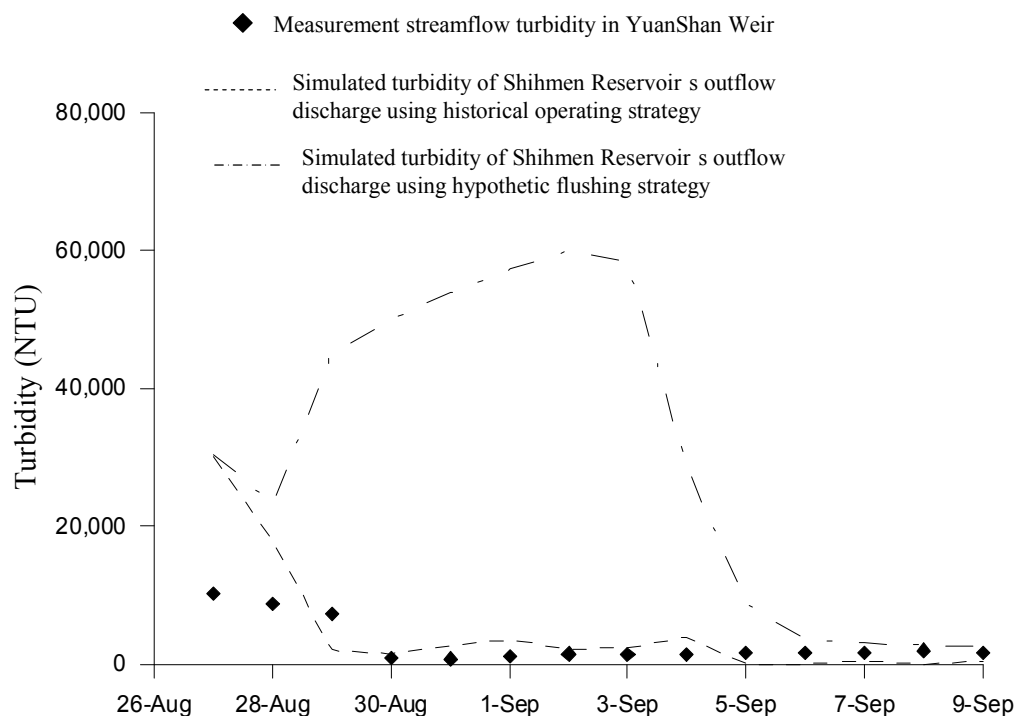

Fig. 3. The simulated outflow turbidity of Shihmen Reservoir.

CONCLUSIONS AND SUGGESTIONS

This paper presented a unidimensional settling mode to quantify the level and impacts of high turbidity in reservoir. It is based on Kynch s theory of sediment flocculation (Kynch, 1952) and calibrated with laboratory experiment data via Gauss-Newton algorithm.

A historical water shortage event due to slow settling of muddy lake in Shihmen Reservoir was investigated using the proposed approach. A hypothetic simulation was carried out using a synthesized operating strategy and an under-construction sluiceway. The result of case study confirmed the effectiveness of accelerating settling by sluicing bottom storage through the sluiceway. Nevertheless there will be critical shortage potential for the public demands withdraw water downstream from the reservoir due to the turbid bottom release. A backup storage tank or trans-basin clear water transfer plan will be urgently necessary for maintaining

stable public water supply in this area.

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