Modelling a turbidity current in Soyang reservoir (Korea) and its control using a selective withdrawal facility

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ABSTRACT

Persistent turbidity in reservoirs and their downstream after flood events is one of the most important environmental issues in Korea. Recently, modification of withdrawal facility and installation of a new selective withdrawal structure (SWS) have been implemented for the mitigation of downstream impact and sediment loading into water treatment facilities. This study was to explore the characteristics of flood density flow induced into Soyang Reservoir and the transport processes of suspended sediments (SS) through application of coupled two-dimensional hydrodynamic and particle dynamic models (TM-1, TM-2 and TM-3). The TM-3 including a turbidity attenuation rate as a lumped parameter showed best performance in reproducing the magnitude and distribution of SS in the reservoir. The validated model was applied to evaluate the effectiveness of SWS, which was designed for the reservoir, with 6 different historical flood events. The magnitude of vertical mixing of the turbidity plume and its persistence within the reservoir were closely correlated to the ratio of the volume of turbidity flow to the total reservoir storage (the $\theta$ value). The operation of SWS showed a positive effect as long as $\theta$ is between 0.3 and 0.6 but negative when $\theta = 0.83$ for the study reservoir, thus it should be optimized based on the $\theta$ value for a better management of the reservoir.

Key words | density current, sediment transport, selective withdrawal, Soyang reservoir, turbidity modelling

INTRODUCTION

The persistent turbidity, which is attributed to fine suspended sediments (SS) (<10 $\mu$m) induced into a reservoir and associated downstream during flood events, is not only one of the most concerned environmental problems but also obstacle to operate water supply systems in the monsoon-climate region (Chikita & Okumura 1990; Chung 2004; Umeda et al. 2006). A long-term exposure to turbid aquatic environment significantly affects on the populations of aquatic organisms (Henley et al. 2000). It is because turbidity may directly interfere with the ability for higher organisms to graze and reduce primary production due to increased light attenuation limit food available for secondary production. In addition, turbid flood carries large amount of non-point pollutants such as organic chemicals and nutrients to downstream reservoirs.

Management solution for mitigating the negative effects of persistent turbidity has mostly focused on erosion control in the upper catchment. On the other side, operation of selective withdrawal structure (SWS) was chosen to control off-take water quality of the reservoir (Yajima et al. 2006). Selective withdrawal ability often can provide the operational flexibility to respond to water quality demands such as target temperature, dissolved oxygen, and turbidity both in-reservoir and downstream. Recently, either modification of existing withdrawal facility or installation of new SWS has been adopted to mitigate sediment loading into water treatment facilities in many reservoirs of Korea.

The fate and transport of turbidity flows induced into a stratified reservoir are governed by various factors such as thermal structure of the reservoir, the magnitude and location
of withdrawal, physiochemical properties of the suspen-
ded particles, and the density difference between inflow and
ambient water (Fischer et al. 1979; Martin & McCutcheon
1999). Turbid inflows most often propagate as density cur-
rents into a stratified reservoir (Fischer et al. 1979; Imberger
& Patterson 1990), generally forming a plunging underflow
ensued by an interflow if the inflow reaches a level of neutral
buoyancy (Martin & McCutcheon 1999). Despite the progress
of hydrodynamic and water quality models to simulate the
fate and transport of various pollutants in reservoirs, model-
ing turbid density inflows is still a challenge due to the
variability of the inflow characteristics and the spectral set-
tting rates of the particles relative to the fluid (Hürzeler et al.
1995, 1996). Further, the validation of numerical models is
difficult due to the absence of a universal relationship
between turbidity and the concentration and size distribution
of suspended sediment (Davies-Colley & Smith 2001).

The objectives of this study were to explore the hydro-
dynamic characteristics of turbid density inflows induced into
Soyang Reservoir (Korea) and the fate and transport of SS
through application of a coupled two-dimensional (2D)
hydrodynamic and particle dynamic models and extensive
field data, and finally to evaluate the effectiveness of a SWS,
which is newly designed for the reservoir to tackle the
chronic negative impact of turbid flow on downstream river.

SITE DESCRIPTION AND FIELD EXPERIMENTS

The reservoir having total storage of 2,900 × 10^6 m^3 is the
deepest and largest one in Korea, an important source of
drinking water and used for irrigation, hydropower genera-
tion, flood control, and fisheries. The reservoir is relatively
long, narrow and dendritic (Figure 1(a)). The hydraulic
retention time defined as the mean water volume divided by
the mean flow is long (approximately 0.7 yr). Annual pre-
cipitation in the region is 1100 mm/yr. More than 70% of the
precipitation occurs during the flood season from June to
September. Currently, the off-take tower withdrawing water
from EL. 130~150 m is located at right side of the dam
whose elevation is EL. 80~203 m. The off-take facility has no
selective withdrawal function. Meanwhile, the sediment
loaded density inflows normally intrude into the reservoir
by forming interflow regime, which results in long-term
discharge of turbid water to downstream. After a severe
flood event occurred on July of 2006, turbidity flow persisted
within the reservoir and discharged to the downstream of
Han River over the year until May of the following year.

Field monitoring has been performed every month from
2005 at 5 reservoir monitoring stations (SY-1 ~ SY-5) and one
upstream station (Sagumi bridge) (Figure 1(a)). Basic para-
meters including temperature, pH, DO, turbidity, and con-
ductivity profiles were measured on site using a continuous
water quality monitoring system (YSI 6000 series), and water
samples were taken and analyzed at laboratory for SS and
other organic and nutrient water quality variables. During the
severe flood event in 2006, more intensive and frequent
monitoring was implemented to capture the flood event.

MODEL DESCRIPTION

Hydrodynamic model

A 2D laterally averaged hydrodynamic and mass transport
model (CE-QUAL-W2), which is appropriate for water
bodies where lateral variations in velocity and temperature
are insignificant, was used. The model solves five governing
equations including momentum equation in horizontal direc-
tion, momentum equation in vertical direction assuming

Figure 1 | Layout of Soyang Reservoir and monitoring locations (a) and grid system based on surveyed bathymetry data (b).
hydrostatic pressure, equation for water surface elevation, continuity equation, and water density state function to get laterally averaged fluid motion and heat transport using finite difference methods (Cole & Wells 2004). The model uses a numerical scheme for a direct coupling between hydrodynamic and water quality simulations. The model can simulate longitudinal-vertical hydrodynamics, temperature, and transport of multiple groups of suspended sediments, and associated effect of various hydraulic structures such as selective withdrawal intake, spillway and weir. Selective withdrawal algorithm of the model calculates the vertical extent of withdrawal zone based on outflow, outlet geometry and upstream density gradients.

A finite difference grid consisting of 1 branch with 138 segments and 134 layers was created based on the surveyed bathymetry data (Figure 1(b)). Daily and hourly (during flood events) inflow and outflow data obtained from a hydrological data base of reservoir management authority (K-Water) were used as upstream and downstream boundary conditions, respectively. Outflow boundary conditions were comprised of the penstock discharge for hydropower generation and spillway discharge for flood control.

**Particle dynamic model**

Three different turbidity models (TMs) were incorporated into the 2D laterally averaged mass transport equation. TM-1 used a single SS for the state variable with a constant settling velocity (0.55 m/d) as the original model assumes. Meanwhile, TM-2 simulated three different SS variables according to their representative particle sizes (1.64, 7.33, 24.05 μm) and dynamically estimates the settling velocity as a function of particle size, density, and water temperature to account for the reservoir stratification using Stokes equation.

TM-3 simulated the same SS particles as used for TM-2 but included a turbidity attenuation rate as lumped parameter (k_s) to consider the effect of organic matter decay and particles aggregation processes that possibly important for long-term turbidity predictions. The effect of aggregation on the attenuation of turbidity was treated as an empirical parameter and determined by calibration using field data. The simulated turbidity profiles with k_s = 0.015/day, approximately 1.5% attenuation of turbidity per day, showed best fit with field data.

In Table 1, B is the reservoir width [m], U, W are the laterally averaged longitudinal and vertical velocities [m/s], Φ is SS concentration [g/m^3], E_x, E_z are the longitudinal and vertical dispersion coefficients [m^2/s], v_s is the settling velocity [m/s], is the dynamic viscosity [kg/m/s], k_s is the first order attenuation coefficient [1/s], g is the gravitational acceleration [m/s^2], d_s is the effective diameter of particles [m], ρ_w and ρ_s are the water and particles densities [kg/m^3]. The model used a constant value (1.2 m^2/s) for E_z, but internally computed E_x based on the eddy diffusivity using the Reynolds analogy and adjusted it according to the stratification strength (Richardson number).

**RESULTS AND DISCUSSION**

**Model calibration and validation**

The performance of hydrodynamic model was validated by model calibration (2005~2006) and verification (2007). The simulated and observed profiles of water temperature at selected times for calibration period (2005~2006) and verification period (2007) are compared in Figures 2 and 3. The AME (absolute mean error) and RMSE (root mean square error)
Figure 2 | Comparison of observed and simulated temperature profiles during calibration period (2005–2006).

Figure 3 | Comparison of observed and simulated temperature profiles during verification period (2007).
error) values were placed within the range of 0.07~1.43C and 0.09~1.99C after parameters calibration and within the range of 0.32~1.40C and 0.49~2.08Cduring the verification period. The model satisfactorily reproduced the seasonal stratification processes and temporal changes of vertical water temperature profiles.

The three turbidity models were evaluated by comparisons of simulated profiles with observed ones of total SS concentration near dam site (Figure 4). For the conversion of observed turbidity data (NTU) to model state variable TSS (mg/L), a linear regression equation (SS = 0.8×Turbidity, correlation coefficient r = 0.97) was used based on experiment data. TM-2 and TM-3 reasonably captured the density flow regimes and the magnitude of peak turbidity at the early stage of the flood events. Although the TM-2 model that include dynamic settling velocity for the three different Elevation(m)

Figure 4 | Comparison of observed and simulated 2007 TSS profiles at (a) SY-1 and (b) SY-2.
particles better described the physical settling processes of SS below the thermocline than the single SS model (TM-1), it could not improve the errors for long-term simulation. The TM-2 showed less error values during the short period from Julian day 229 to 240, but it started to overestimate the magnitude of peak concentrations of the turbidity plume. The magnitude of error of TM-2 model was propagating as time went on. Meanwhile, the TM-3 model substantially reduced the errors and showed best performance in replicating the observed temporal variations of turbidity profiles. The average values of AME and RMSE of TM-2 over the comparison period were 7.47 mg/L and 9.59 mg/L, while those of TM-3 were 4.46 mg/L and 6.45 mg/L. Both the field data and simulation results justify that addition of the lumped turbidity attenuation rate that implicitly accounts for the effect of organic matter decay and particles aggregation processes is reasonable assumption in the reservoir. However, further intensive experimental and modelling studies are needed.

**Effect of selective withdrawal**

**Simulation scenarios**

The effectiveness of SWS installation in the reservoir was assessed by applying the TM-3 model for 6 different flood events that occurred historically in the reservoir. The date of event, duration of flood, daily averaged peak flow rate, total amount of turbidity inflow, reservoir elevation and storage before the flood event for the simulation scenarios, and θ values are presented in Table 2. The θ value is the ratio between the volume of turbidity flow that exceed SS > 25 mg/L (approximately 30 NTU) to the total reservoir storage, which is a useful indicator to measure the strength and significance of turbidity flow for a flood event.

**Simulation results**

The simulated temporal and spatial profiles of turbidity flow without and with SWS operation near the dam for 1999 flood event are compared in Figure 5(a) and (b). The withdrawal depth fixed was varied to surface layer during Julian days of 216 ~ 280 with the SWS operation to supply cleaner water to the downstream (see the lines for withdrawal depth). The simulated profiles show that the modification of withdrawal depth to surface layer may slightly affect on the vertical mixing of the turbidity plume, but the most of the turbid water was settled and discharged before the turnover period.

The results presented in Figure 5(a) and (b) are a specific condition for θ value of 0.53. The simulation results (not shown all in here) showed that the magnitude of vertical mixing of the turbidity plume and its persistence within the reservoir is highly correlated with the θ value. During the significant flood event (θ = 0.83) that occurred in 2006, selective withdrawal of clean water from upper zone caused a longer persistence of the turbidity flow within the reservoir, and consequently resulted in increase of turbidity in epilimnion layer during the turnover period (see Figure 5(c) and (d)).

**Effect on downstream turbidity control**

The dam release SS concentrations without and with the SWS operation during the 1999 flood events are compared in Figure 6. The time series of inflow SS concentrations can be assumed as a natural condition of the turbidity environment of the river system during the flood events before the dam construction. The SWS was operated to maintain the dam release SS concentration less than 25 mg/L determined as the operational criteria. The optimal start time and duration of the surface water withdrawal for clean water supply were

<table>
<thead>
<tr>
<th>Run</th>
<th>Dates of Event</th>
<th>Duration (day)</th>
<th>Peak Flow (m³/s)</th>
<th>Total inflow (10⁶ m³)</th>
<th>Initial EL. (EL. m)</th>
<th>Initial storage (10⁶ m³)</th>
<th>θ*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1</td>
<td>1981-06-22</td>
<td>2</td>
<td>1.378</td>
<td>183</td>
<td>179</td>
<td>1.720</td>
<td>0.10</td>
</tr>
<tr>
<td>Run2</td>
<td>2006-07-15</td>
<td>8</td>
<td>4.212</td>
<td>1.396</td>
<td>166</td>
<td>1.189</td>
<td>0.83</td>
</tr>
<tr>
<td>Run3</td>
<td>2004-07-13</td>
<td>7</td>
<td>2.810</td>
<td>745</td>
<td>174</td>
<td>1.511</td>
<td>0.39</td>
</tr>
<tr>
<td>Run4</td>
<td>1999-08-02</td>
<td>5</td>
<td>4.665</td>
<td>1.110</td>
<td>174</td>
<td>1.504</td>
<td>0.53</td>
</tr>
<tr>
<td>Run5</td>
<td>1990-09-11</td>
<td>4</td>
<td>7.063</td>
<td>934</td>
<td>192</td>
<td>2.470</td>
<td>0.59</td>
</tr>
<tr>
<td>Run6</td>
<td>2002-09-01</td>
<td>3</td>
<td>2.872</td>
<td>345</td>
<td>181</td>
<td>1.809</td>
<td>0.40</td>
</tr>
</tbody>
</table>

θ*: the ratio of the volume of turbidity flow (SS > 25 mg/L) to the total reservoir storage.
selected by a number of feedback simulation processes considering the vertical mixing during turnover period. As shown in Figure 6, the SWS operation controlled the downstream turbidity reasonably well.

Meanwhile, the SWS operation caused an extended residual of turbidity flow within the reservoir. This means that the control of turbidity flow is a sort of trade-off problem between reservoir and downstream water quality management. It was found that the magnitude and length of the residual of turbidity flow in the reservoir are highly dependent on the $\theta$ value. Normally, the SWS can be effectively used to intake clean water from upper zone to reduce the length of turbid water discharge to downstream without negative impact on the reservoir’s water quality when $\theta$ value is less than 0.7.

![Figure 6](https://iwaponline.com/wst/article-pdf/63/9/1864/444974/1864.pdf)
However, the SWS ought to be used for a quick discharge of turbid water from middle layer when the $\theta$ value is greater than 0.7, otherwise the turbidity plume may persist in the reservoir until the turnover period and result in discharge of turbid water to the downstream even during the following drought season.

The main objective of SWS installation in the reservoir is to mitigate the duration of turbid water discharge to the downstream. Thus it is important to assess the effect of SWS operation on the reduction of the number of days that exceed the designated turbidity criteria. The results show that the effect of SWS installation on the downstream turbidity control varies dependent on the $\theta$ value (Table 3). There was no violation of downstream turbidity criteria with the flood event of $\theta$ of 0.11 (Run1). The results indicate that the turbidity plume that exceed 30 NTU not arrived at dam, thus the SWS operation is not required under the condition. The SWS showed best performance and substantially reduced the duration of turbid water discharge to the downstream for flood events having $\theta$ values between 0.3 and 0.6. But the operation of SWS even increased the number of days that exceed the designated turbidity criteria when the $\theta$ value is 0.85 (Run2). Therefore, the SWS operation needs to be optimized based on the $\theta$ value that can be obtained from a real-time monitoring and modelling of the turbidity flow for a better management of the reservoir.

**CONCLUSIONS**

This study explored the hydrodynamic characteristics of the stream density flows and the fate and transport of suspended sediments, and evaluated the effectiveness of SWS that is newly designed to tackle the chronic negative impact of turbid flow on downstream river. The performance of the model was validated for data collected during the flood season of 2005 and 2007 in the reservoir. TM-3 among three different particle dynamic models (TMs), which includes a lumped turbidity attenuation rate, showed best performance in replicating the observed variations of in-reservoir turbidity profiles as well as in reproducing the reservoir thermal structure, flood propagation dynamics and the magnitude and distribution of SS in the reservoir. The effectiveness of SWS operation was assessed using the TM-3 model for different historical flood events.

The magnitude of vertical mixing of the turbidity plume and its persistence within the reservoir were closely correlated to the ratio of the volume of turbidity flow to the total reservoir storage ($\theta$ value). The operation of SWS showed a positive effect for mitigating the length of turbid water discharge to downstream as long as $\theta$ is between 0.3 and 0.6, but negative when $\theta = 0.83$ for the study reservoir. This implies that the SWS operation needs to be optimized based on the $\theta$ value that can be obtained from a real-time monitoring and modelling of the turbidity flow for a better management of the reservoir. However, the conclusions withdrawn in this study should be interpreted carefully because the effectiveness of the SWS in a reservoir is not only dependent on the $\theta$ value, but is also dependent on the depth of the reservoir.

**ACKNOWLEDGEMENTS**

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<table>
<thead>
<tr>
<th>RUN</th>
<th>$\theta$</th>
<th>Without SWS operation</th>
<th>With SWS operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30 NTU</td>
<td>40 NTU</td>
</tr>
<tr>
<td>Run1</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Run2</td>
<td>0.83</td>
<td>227</td>
<td>156</td>
</tr>
<tr>
<td>Run3</td>
<td>0.39</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Run4</td>
<td>0.53</td>
<td>61</td>
<td>35</td>
</tr>
<tr>
<td>Run5</td>
<td>0.59</td>
<td>69</td>
<td>59</td>
</tr>
<tr>
<td>Run6</td>
<td>0.40</td>
<td>61</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 3 | The number of days that exceed the designated turbidity criteria without and with the SWS operation
REFERENCES


