Characteristics of DOC concentration with storm density flows in a stratified dam reservoir

ABSTRACT

Among natural organic matter (NOM) defined as the complex matrix of organic materials abundant in natural waters, a gradual accumulation of recalcitrant organic matter (ROM) has been observed in impounded water bodies such as a lake or dam reservoir in spite of extensive efforts made to curtail organic pollutant loadings generated in their catchment areas. This paper aims to identify the effect of diffuse pollution resulting from allochthonous organic matters on the temporal and spatial characteristics of organic matters in a stratified dam reservoir, Daechong Dam, using both intensive observation and CE-QUAL-W2 model simulation. With the limitation of observation data in terms of organic matters of inflow waters from boundary tributaries and impounded water in the reservoir, organic matter was represented by organic carbon including labile particular organic carbon (LPOC), refractory organic carbon (RPOC), labile dissolved organic carbon (LDOC), and refractory organic carbon (RDOC). Both autochthonous and allochthonous origins of organic carbon were considered in the modeling of eutrophication of the reservoir water using CE-QUAL-W2. The result of simulation during the period from 2001 to 2005 was observed to be a gradual accumulation of particular organic carbon (POC). It is clear that the model calculation results enable the explanation of the internal and external movement of constituents in the reservoir. In particular turbidity and NOM were well related in the upper region of the reservoir according to flow distance, gradually changing to dissolved form of organic matter, DOC affected organic matter concentration of reservoir water quality compared to turbidity.

Key words | accumulation, CE-QUAL-W2, organic carbon, reservoir, turbidity

INTRODUCTION

Freshwater dissolved organic matter (DOM) is a dynamic material that can be transported and transformed through natural biogeochemical processes (Opsahl & Benner 1998, Barber et al. 2001; Hertkorn et al. 2002). Most freshwater systems (rivers and lakes) in temperate climates are significantly influenced by terrestrial inputs, and allochthonous organic matter often dominates the organic carbon balance. Allochthonous organic matter enters aquatic systems mainly from the subsequent runoff of overland water flow during rainfall events (McKnight et al. 2001).

The quantity of organic matter that enters a lake ecosystem per unit of time sets an upper limit on the amounts of biomass that can be observed. Organic matter can be estimated by measuring carbon because all organic matter contains reduced carbon atoms. Photosynthetic production of organic matter also is commonly measured in units of carbon. The concentration of organic carbon has been expressed generally as the sum of DOC and POC since Thurman (1985). Strong relationships between DOC concentration and the standing crop and species

doi: 10.2166/wst.2010.537
composition of phytoplankton also have been reported. For example, it has been observed that DOC is highest during the spring and late summer, coincident with blooms of cyanobacteria (Hama & Handa 1983; Fukushima et al. 1996). Wetzel (1972) noted that vertical heterogeneity of DOC concentrations also could occur, with higher levels in the epilimnion than in the hypolimnion, especially during summer stratification. In contrast, Hama & Handa (1983) reported that vertical heterogeneity was not significant in the shallow Lake Suwa, Japan. DOC distribution also can be affected by the mixing of water and various biological processes (Guo et al. 1995). The organic carbon in lake water has two sources: allochthonous and autochthonous. The relative contribution of these sources to the lake carbon budget depends on hydraulic retention time, development of the littoral zone, and the trophic state. With progressing eutrophication autochthonous carbon becomes increasingly important. However, allochthonous carbon from the watershed can substantially impact the lake carbon budget (regardless of trophic state) during periods of intense rainfall when hydraulic residence time is short. During periods of intense rainfall POC loading from a river may be dramatically increased, because the suspended load increases as the flow of the river increases. DOC loading also can increase by 50–100% of the normal conditions (Thurman 1985).

There are many studies of organic carbon cycling in natural lakes and rivers, but few have considered deep reservoirs. In a stratified reservoir, the turbidity flow accompanied with a storm runoff intrudes the water depth of a stratified reservoir water body having the same density with the turbidity flows itself. There have been several reports to point out the seriousness and possibility of secondary water pollution accompanying such a period of strong turbidity while water is detained in the reservoir for a number of weeks (Yu 2005). For instance, eutrophication by very quick intrusions of high loadings of suspended solids (SS) including total phosphorus (TP), contemporary increase of dissolved organic carbon (DOC) concentration in the bulk of reservoir water, dissolved oxygen (DO) depletion in intermediate water layer, sediment deposition on reservoir bathymetry, and reservoir aquatic ecosystem, and water treatment difficulties and so on would be expected to appear during strong storm intrusion in the reservoir stratified. In addition, authors found that allochthonous organic carbon in the Daechong Dam Reservoir is more charged by storm flow compared to carbon load of autochthonous origin (Ha et al. 2004; Yu & Ha 2005).

This paper aims to identify the effect of diffusive pollution resulting from allochthonous organic matter on the temporal and spatial characteristics of organic matter in
a stratified dam reservoir. The Daecheong Dam was selected as the subject of this study, and results were obtained from observation and CE-QUAL-W2 modelling. As the observation data was limited in terms of the organic matter content of the boundary tributaries and the impounded water in the reservoir, it was represented by organic carbon including labile particular organic carbon (LPOC), refractory organic carbon (RPOC), labile dissolved organic carbon (LDOC) and refractory organic carbon (RDOC). Both the autochthonous and allochthonous origins of organic carbon were considered in the modeling of the eutrophication of the reservoir water using CE-QUAL-W2.

**STUDIED AREA CHARACTERISTICS AND METHODS**

Figure 1 shows the Daecheong Reservoir in South Korea selected in this study. It is located in the upstream part of the Kum River. The reservoir had been constructed as a multi-purpose high dam reservoir on the Kum River in 1980 and has a total watershed area of 4,166 km² with an effective storage area of 72 km². It is being operated by the Korea Water Resources Corporation for hydro-power generation and water supplying. There are five major tributaries to the river. The reservoir backwater is roughly 86 km long and the water depth at the dam can reach 78 m under normal operating conditions. In addition, the land cover of the reservoir watershed consists of about 70% of mountain forest, about 20% of agricultural cultivation land including rice paddies and upland crops and small towns with urban facilities and rural villages.

We selected three locations as calibration data collection sites: site 1 (upper reach of main reservoir branch), site 2 (confluence with one tributary) and site 3 (dam location with discharge dam gates) as shown in Figure 2. The properties being measured were: dissolved oxygen (DO), biochemical oxygen demand (BOD₅), chemical oxygen demand (CODcr), total suspended solid (TSS), total...
phosphorus (TP), total nitrogen (TN) and pH. Two typical years were selected for this study: 2003, in which heavy precipitation with highly turbid storm inflows were recorded and very sensitive discharge gate operations was conducted and 2005 in which due to comparatively light precipitation, discharge gate operation was moderated. By comparing water quality variations in 2003 and 2005, it was clear that annual DO concentrations in 2003 were higher than that in 2005. It seems that the high concentrations of TSS in 2003 may be attributable to gate operations responding to heavy storm inflow. Storm inflow to the reservoir was much higher in 2003 than in 2005 which is thought to have been the reason for differences in TSS & DO concentration recorded in those years. TSS concentrations lower in 2005 that in 2003. Conversely, in 2005 the concentration of TSS at the site 3 (Dam location) during storm season was very high even though precipitation and storm inflows in the 2005 was not strong. For the purposes of this paper, observed data for these two years, 2003 and 2005 were used to calibrate and verify the CE-QUAL-W2 model parameters.

For each branch as boundary conditions, it was applied trend line of inflow concentrations for observed data. For pretreatment of DOC, water samples were filtered using Whatman GF/F filters with effective pore size 0.7 μm. The filtrates and raw water samples were kept at 4°C in glass bottles until analysis.

DOC of filtrate and TOC were measured by TOC combustion analyzer. Analytical precision was ± 1% based on three or more measurements of each sample. Refractory DOM was regarded as the concentration when DOC was not changed up to incubation of 100 days at 20°C without any inoculate after filtration using Whatman GF/F.

Hydrodynamic modeling

The hydrodynamic model is calibrated with the 2003 data. The comprehensive input data for CE-QUAL-W2 hydrodynamic modeling include reservoir topography, meteorological, inflow and outflow of reservoir, flow and temperature of stream information. The driving force of this model includes: (1) boundary conditions: time-variable main inflows and temperatures at main upstream and one tributary, and (2) meteorological data: air temperature, dew point temperature, wind speed, wind direction, and percent of cloud cover. Stream flows from small tributaries are calculated based on their watershed areas.

The hydrodynamic calculation was performed by solving the two-dimensional momentum equation over discrete space and time domains. Symbols used in the following hydrodynamic calculation, are listed in Table 1. In the model, vertical eddy viscosity varies both in time and space according to mixing energy available from wind shear and shear of water flow, as well as from buoyancy force under vertical density stratification.

In the model the vertical shear stress is given as follows:

\[
\frac{\tau_{xz}}{\rho} = A_z \frac{\partial U}{\partial z} + \frac{\tau_{wx}}{\rho} \exp(-2kz) + \frac{\tau_b}{\rho}
\]

where \( \tau_{wx} \) is the longitudinal wind shear stress at the surface, and \( k \) stands for wavenumber. The equations for \( k \) and wave period respectively \( T_w \) are given follows:

\[
k = \frac{4\pi^2}{gF_w^2}
\]

\[
T_w = 6.95 \times 10^{-2} p^{0.233} W_{sh} |W_v|^{0.534}
\]

**Table 1 | List of symbols and description for hydrodynamic calculation**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_z )</td>
<td>Vertical eddy viscosity (m² s⁻¹)</td>
</tr>
<tr>
<td>( C )</td>
<td>Constant at 0.15</td>
</tr>
<tr>
<td>( Chz )</td>
<td>Chezy coefficient (m⁻¹/² s⁻¹)</td>
</tr>
<tr>
<td>( F )</td>
<td>Fetch length (m)</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity (m s⁻²)</td>
</tr>
<tr>
<td>( H )</td>
<td>Depth of water (m)</td>
</tr>
<tr>
<td>( k )</td>
<td>Wavenumber</td>
</tr>
<tr>
<td>( \ell_m )</td>
<td>Mixing length (m)</td>
</tr>
<tr>
<td>( Ri )</td>
<td>Richardson number</td>
</tr>
<tr>
<td>( T_w )</td>
<td>Wind wave period</td>
</tr>
<tr>
<td>( U )</td>
<td>Lateral-averaged longitudinal velocity (m s⁻¹)</td>
</tr>
<tr>
<td>( V )</td>
<td>Wind-driven lateral velocity (m s⁻¹)</td>
</tr>
<tr>
<td>( W_{sh} )</td>
<td>Wind sheltering coefficient</td>
</tr>
<tr>
<td>( W_v )</td>
<td>Wind velocity (m s⁻¹)</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Von Karman constant, 0.4</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density (kg m⁻³)</td>
</tr>
<tr>
<td>( \tau_b )</td>
<td>Shear stress at the bottom (N m⁻²)</td>
</tr>
<tr>
<td>( \tau_{wx} )</td>
<td>Longitudinal wind shear stress at the surface (N m⁻²)</td>
</tr>
<tr>
<td>( \tau_{xz} )</td>
<td>Laterally averaged shear stress (N m⁻²)</td>
</tr>
<tr>
<td>( \tau_{yz} )</td>
<td>Wind-driven shear stress (N m⁻²)</td>
</tr>
</tbody>
</table>
Friction stress at the bottom is given as

\[
\tau_b = \frac{\rho_w R}{Chz} U|U|
\]

(4)

where \( Chz \) is the Chezy coefficient. The equation for vertical eddy viscosity \( A_z \) is derived from (Cole & Buchak 1995; Cole & Wells 2000) as

\[
A_z = \frac{k^2}{2} \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right]^{1/2} \exp(-CRi)
\]

(5)

In the longitudinal–vertical model, it is assumed that crosswind shear \( \tau_{wy} \) generates the lateral wave component and decays exponentially with depth \( z \), such that

\[
\tau_{yz} = \tau_{wy} \exp(-2kz)
\]

(6)

Then, using the following model:

\[
\frac{\tau_{yz}}{\rho} = A_z \frac{\partial V}{\partial z}
\]

(7)

the lateral velocity gradient squared becomes

\[
\left( \frac{\partial V}{\partial z} \right)^2 = \left[ \frac{\tau_{wy} \exp(-2kz)}{\rho A_z} \right]
\]

(8)

Thus, the final equation for the vertical eddy viscosity is

\[
A_z = k^2 \frac{2}{2} \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right]^{1/2} \exp(-CRi)
\]

(9)

where the expression for the mixing length \( \ell_m \) (Cole & Wells 2000) is used;

\[
\ell_m = H \left[ 0.14 - 0.08 \left( 1 - \frac{z}{H} \right)^2 - 0.06 \left( 1 - \frac{z}{H} \right)^4 \right]
\]

(10)

where \( H \) is the depth of water. The hydrodynamic calibration was performed by varying the longitudinal eddy viscosity \( A_x \) and Chezy coefficient \( Chz \).

According to hydrodynamic model calibration analysis, the time-variable water surface elevation data are used to estimate the reservoir outflow through a water mass balance.

The time series data of one year indicate that the water surface elevation decreases gradually and reaches the lowest in early summer months, then gradually raised and reached a peak in late summer and autumn periods of a typhoon and thunderstorms. In the winter months, the water surface elevation remains relatively constant. Maximum fluctuations in water surface elevations reached about 1 m in the reservoir. Water temperature data are used to evaluate the hydrodynamic results from one-year model runs. Note the model simulation results closely mimic the measured vertical temperature profiles and the seasonal variation of temperature in the water column. Stratification in the reservoir was also reproduced with the correct predictions of the depths in terms of not only the thermocline but also turbidity cline in each year selected.

### Water quality model configuration

The boundary conditions for the water quality model include the dissolved oxygen, chlorophyll \( a \) (Chl.a), nutrient, LDOC and RDOC concentrations at the upstream ends of the main stream of the river. In addition, concentrations of DO, Chlorophyll \( a \), and nutrients in the tributaries are also incorporated. Through numerous model runs, the calibrated kinetic coefficients and constants for the water quality simulation are determined by referencing manual CE-QUAL-W2. In general, they are consistent with literature values.
RESULTS AND DISCUSSIONS

For the model calibration and verification, the elevation of water level and the DOC concentration was observed in Daecheong Dam reservoir. As shown in Figure 3(a) as a result of hydrodynamic model application, relatively good agreement has been achieved between field measurements and model predictions of water surface elevation in 2003. The consistency between the observed data in terms of dissolved organic carbon (DOC) including refractory dissolved organic carbon (RDOC) and labile DOC (LDOC) and the calculated ones was evaluated. As shown as Figure 3(b), the concentration distributions of DOC calculated were, however, were in quite good concordance with the observed results for different water depths during storm season. Figure 4 shows the spatial distributions of TSS and TP concentrations averaged over on seven day period from 11–17th July. In 2003, the discharge gates were opened more frequently than in 2005. It is possible to read the spatial distribution of TSS and TP not only in the longitudinal direction but also in the vertical profile of the reservoir. Storms approach the dam location from upstream of the reservoir.

The dam with controllable discharge gates is located on the far left of the figure whereas the main branch is seen on the right side of Figure. The water course flows from right to left, as seen in Figure 4, so that the storm water containing pollutants is in the vicinity of the dam. As previously mentioned there are two intake towers for drinking water, Munyi for the Cheongju city area and Chudong for the Daejeon metropolitan area in the reservoir; in Figure 4. As shown in Figure 1, two intake towers located near the reservoir and take water from surface layer of the reservoir. Therefore we feel justified in being concerned about water quality changes near these two intake towers. In addition, the water quality of the area in the vicinity of Dam is important because of possible impacts downstream after being discharged from the reservoir. For instance, the concentrations of TSS during gate operations at the dam dramatically increased in the middle layer between 12–24 m below the surface in both 2003 and 2005. This is attributed to the location of the discharge gate for hydro-power generation installed about 20–25 m below the surface of the water.

During stagnation of high turbidity regime in the reservoir, not only TSS but also TP concentrations in the surface layer around the two bays are relatively high as shown in Figure 4. In particular water quality of the surface layer in 2003 was affected by the opening of the spillways during the eight day period as previously mentioned. In the case of nonintervention countermeasure established in 2005, major turbidity was noted in the middle water layer of the Munyi bay area following the hydrodynamic flow of the dam reservoir at that time. On the other hand, concentrations of TP were found to be high in the lower layer in 2005. This is also attributed to the gate control characteristics. In particular, through comparing two
figures, it is also possible to identify the effects of the dam gates’ operations on the water quality distributions within the reservoir from comparing the figures obtained from 2003 and 2005.

On the other hand, Figure 5 represents the spatial distribution of TSS and TP concentrations in the reservoir after seven days after closing the gates on 17th July in 2003. It is clear that the concentrations of TP were high in the middle layer during the storm water intrusion regime on the reservoir. This turbidity, including high concentrations of TP is thought to sink to the lower water layer after the discharge gates have been closed. The nonintervention reaction against the storm regime in 2005 resulted in higher levels of TSS as well as TP in the reservoir after the monsoon period. This may create long lasting problems with regard to the nutrient balance of the storm water intrusion regime on the reservoir. This turbidity, including high concentrations of TP is thought to sink to the lower water layer after the discharge gates have been closed. The nonintervention reaction against the storm regime in 2005 resulted in higher levels of TSS as well as TP in the reservoir after the monsoon period. This may create long lasting problems with regard to the nutrient balance of the reservoir ecosystem.

The CE-QUAL-W2 Model simulation results showed that concentrations of SS change when inflow is strong. Figure 6 shows the spatial distribution of SS concentrations when inflow is low. This displays the spatial distribution of SS concentrations before 8th July. The increase in rainfall

---

**Figure 6** | Distribution of SS Concentration during opening spillway gate.
and the subsequent increase of inflow seemed to change SS concentrations in 2003. Although, the SS concentrations in the middle of the reservoir were found to be higher than those upstream and in the vicinity of the dam, when the reservoir is regarded as a whole, the SS concentrations are not considered significantly high. Figure 6 shows the spatial distribution of the SS concentrations in the reservoir for the 8th July, four days prior to the opening of the spillway gates. It is clear that the high concentrations of SS move to the middle layer from the upper layer and gradually move on towards the dam. When the spillway gates are opened, the water within all levels becomes greatly disturbed leading to a mixing effect which causes the SS concentrations to become uniform at all depths within the reservoir. It is thought that although it is common practice to open the spillway gates during periods of heavy rainfall, the disturbance to the reservoir waters this causes may have a negative effect on the ecosystem within the reservoir due to the mixing of lower level sediments into higher levels.

The effect of turbidity storm intrusion on the SS concentration in the reservoir is depicted in Figure 7.

Figure 8 shows the relation between SS, TP and Chl-a. Sta.1 analyzes a point upstream of the other stations. It analyzes at a depth of 7–8 m. Sta.2 analyzes at three separate depths, 0–5 m, 5–13 m and over 14 m in depth. Sta.3 analyzes at three separate depths, 0–15 m, 15–25 m and over 25 m in depth.

This shows a high correlation between SS and TP for all stations. When rainfall flows into the reservoir, the flow contains SS and TP from upstream regions. The concentration of Chl-a was found to increase after an increase in the concentrations of TP in the upper layer in Sta.2 and Sta.3. Therefore, it is thought that levels of TP strongly influence levels of Chl-a in the reservoir. Figure 6 shows the allochthonous and autochthonous mechanisms in the reservoir. A clear relationship is noted between TP and Chl-a.
Figure 9 shows the relationship between TP and Chl-\(a\) concentrations. At Sta.2 and Sta.3 the concentrations of TP and Chl-\(a\) were found to vary over time according to the relationship previously mentioned. This figure shows relative concentrations of TP and Chl-\(a\). The concentrations of Chl-\(a\) in upper layer was shown to be much higher than that found in the middle and bottom layers.

Figure 10 demonstrates the changes to Chl-\(a\) that result in the formation of other organic matter such as Labile DOM, Refractory DOM, Labile POM and Refractory POM. This is important internal mechanism is shown in Figure 7.

This shows the production of Labile DOM and Refractory DOM due to the mortality and excretion of
algae. And it is shows the production of Labile POM and Refractory POM due to the mortality of algae.

Figure 10 shows the relation between the organic matter and Chl-a. Together with the highly significant relationships between DOC and Chl-a, the results support the interpretation that most of the DOC originates from the algae. The figure shows greater correlation between levels of Chl-a and Labile DOC and with Refractory DOC. Sta.2 and Sta.3 demonstrate greater correspondence in the levels of Labile DOC and Chl-a in the middle layer that in other stations. This confirms the relationship between Chl-a and Labile DOC by means of excretion and mortality. It is clear that the increased concentrations of DOC after strong rainfall are due to the rainfall inflow with high levels of nutrient pollution.

CONCLUSIONS

Summer monsoon rains play an important role in changing the spatial and temporal distribution of organic carbon in Daechong reservoir, Korea. Turbid storm runoff supplied allochthonous organic carbon to the middle layer of the reservoir very quickly during its density intrusion. In the upper layer, there was a high rate of autochthonous carbon production by phytoplankton after the monsoon ended. Most of the allochthonous carbon loading was concentrated after heavy rainfall events in the summer, and total allochthonous loading was as large as autochthonous generation. However, autochthonous organic matter appears to be a more important energy source for secondary producers because most of the allochthonous organic carbon is discharged by the dam water withdrawal without affecting the upper water layer. There was a significant relationship between DOC concentration and chlorophyll a. Further research is needed to quantify the role of DOC excretion from living algae cells and loss from dead cells in this and other deep reservoir.

ACKNOWLEDGEMENTS

This research was supported by the Chungbuk National National University Research and Education Grant Program.

REFERENCES


