Modification of SWAT model for simulation of organic matter in Korean watersheds
Jae-Ho Jang, Kwang-Wook Jung and Chun Gyeong Yoon

ABSTRACT
The focus of water quality modeling of Korean streams needs to be shifted from dissolved oxygen to algae or organic matter. In particular, the structure of water quality models should be modified to simulate the biochemical oxygen demand (BOD), which is a key factor in calculating total maximum daily loads (TMDLs) in Korea, using 5-day BOD determined in the laboratory (Bottle BOD5). Considering the limitations in simulating organic matter under domestic conditions, we attempted to model total organic carbon (TOC) as well as BOD by using a watershed model. For this purpose, the Soil and Water Assessment Tool (SWAT) model was modified and extended to achieve better correspondence between the measured and simulated BOD and TOC concentrations. For simulated BOD in the period 2004–2008, the Nash-Sutcliffe model efficiency coefficient increased from a value of –2.54 to 0.61. Another indicator of organic matter, namely, the simulated TOC concentration showed that the modified SWAT adequately reflected the observed values. The improved model can be used to predict organic matter and hence, may be a potential decision-making tool for TMDLs. However, it needs further testing for longer simulation periods and other catchments.

Key words | BOD5, the modified SWAT, TMDLs, TOC, water quality modelling

INTRODUCTION
Physical and chemical monitoring of key streams is the most direct and accurate method of assessing their condition and is also a fundamental tool in the management of water environments (Jang 2010). However, the process of conducting field experiments or collecting long-term data is very expensive and time consuming. There are also uncertainties associated with the measured data and difficulties in repeating the monitoring process without additional resources and time when corrections are warranted (Santhi et al. 2006). In this context, as an alternative, a model calibrated to the desired conditions can be used effectively to predict the hydrology and pollutant transportation within a watershed. Models help us gain insights into the hydrological, environmental, and hydro-geochemical aspects of watersheds (Singh & Woolhiser 2002), which is essential to water pollution management and decision making. In Korea, watershed models have been widely used in watershed environmental management by many environmental institutes, because it is essential to better understand the complicated characteristics of the watershed.

In terms of the Korean water environment, the bed slope is large and the stream runoff rate due to rainfall is high in summer. Moreover, the continuous flow condition of many rivers and streams is interrupted by many weirs, dams, and reservoirs. This causes very active re-aeration of streams and reduces water velocity downstream, and often is characterized by pollutant accumulation. When water pollutants enter rivers and streams, they are mixed and diluted by river water and reduced by degradation and settling while flowing down a river (Kim & Shin 2013; Jang 2010). However, in spite of non-specific pollutant sources, organic matter concentration increases downstream; that is, organic matter increases owing to the internally abundant pollutant sources that satisfy the conditions for algal growth by supplying abundant nutrients, increasing retention time, and providing solar radiation. Overall, biochemical oxygen demand (BOD) and total organic carbon (TOC) concentration are increased by internally abundant organic matter in a water body, especially in the dry season. Therefore, a strong focus must be placed on ensuring

that the watershed model properly reflects both the objective of its application and the characteristics of the watershed environment. Moreover, water quality modeling in Korea needs to shift from dissolved oxygen (DO) to algae or organic matter and, in particular, the structure of water quality models should be modified to enable simulation of BOD (Kim & Shin 2009), which is a key factor in total maximum daily loads (TMDLs) in Korea, using Bottle BOD5.

The SWAT (Arnold et al. 1998), which is widely used in the world, is a well documented model with open source code that can handle hydrology, sediments, nutrients, and pesticides in large complex river basins on a long-term basis. The water quantity processes simulated by SWAT include precipitation, evapotranspiration, surface run-off, lateral subsurface flow, ground water flow and river flow. The channel water quality module uses the main algorithm from the QUAL2E model, which has limitations in simulating algae, organic matter, and Bottle BOD5, etc. QUALKO (NIER 2008) and QUAL-NIER (Park et al. 2008), which were developed based on the QUAL2E model, improved these limitations to allow algae, organic matter, and Bottle BOD5 to be handled appropriately for domestic streams. In this study, the BOD mechanism in the SWAT model is improved by adding water quality algorithms that can estimate the increase of internal organic matter due to the fractionation by algal metabolism and calculate Bottle BOD5 and TOC under domestic conditions. The effects of the improvement are evaluated by comparing BOD and TOC simulations for water quality management of Kyongan Stream watershed (KSW) before and after implementation of the improvement.

METHODS

The watershed area

The KSW is about 589.3 km² in size, 49.5 km in stream length, and populated by 380,000 people. Land uses in the watershed are 64.9% forest, 16.5% agriculture, 11.1% urban or built-up land, 3.1% pasture, and 4.4% others. The KSW has 12 public wastewater treatment plants and a larger residential land-use than other upper watersheds around the Paldang Reservoir. The average annual rainfall is 1,299 mm and follows a typical Asian monsoon climate pattern. The Kyongan Stream flows into the Paldang reservoir, which is an important source of drinking water for several major provinces, including the capital Seoul (Figure 1). The stream has a low flow rate (about 5.4 m³ s⁻¹ mean flow) compared with others, but worse water quality. Water quality in the Kyongan Stream has greatly deteriorated owing to treated wastewater discharge from sewage wastewater treatment plants in the dry-season and nonpoint source pollution in the rainy-season. Recently, along the KSW, three sewage treatment plants have been newly built and five enlarged for water quality protection, maintenance of the water supply, and local community improvement (KMOE 2007).
The soil and water assessment tool (SWAT)

SWAT descriptions

SWAT was developed for assessing the impact of different management scenarios on water, sediment, and agricultural chemical yields in larger ungauged basins. This is a semi-physically based model that has been widely tested in different physiographic regions and in various parts of the world (Santhi et al. 2001; Boorman 2005; Chu et al. 2004; White & Chaubey 2005). The major components of SWAT including the algorithms of in-stream water quality is well explained in the SWAT manual (Neitsch et al. 2002a).

Model parameterization

We used the SWAT 2000 version of the model based on the BASINS tool, where the simulator is integrated into a geographic information system by an ArcView pre-processor. It uses topography, a polygon/grid coverage of soil and land use, and point coverage of climatic and pollutant data as basic input to the model. Hydrologic boundary conditions can be derived from watershed boundaries, stream networks, and digital elevation mapping (DEM). Watershed boundaries and stream networks obtained from the National Geographic Information Institute and detailed soil data (1:25,000 scale) from the National Institute of Agricultural Science and Technology, with soil textures. The sub-basins are in turn divided into 155 hydrologic response units, defined by land use and soil type covering more than 8% area. SWAT required weather data based on daily time-series for precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity, which we obtained from the stations of Suwon, Icheon, and Yangpyeong (Figure 1). Available point source discharges were estimated from the data of wastewater treatment plants on daily values for the period 2004–2008 at each sub-basin. In all cases, the input time series should be available at intervals equal to or less than the simulation time step.

Model application

SWAT results were fitted to the observed daily stream flow and organic matter data from stations Kyongan A and B for a 7-year period (2002–2008), with the first 2 years used to stabilize the model runs. SWAT parameter values were approximated based on a sensitivity analysis and the characteristics of each sub-basin, and calibration guidelines were derived from the report by Neitsch et al. (2002b). The simulated values were evaluated using graphical visualizations and quantitative statistics. Quantitative measures of agreement were based on observed and simulated mean values; percent difference (% diff.) and Nash–Sutcliffe model efficiency (NSE; Nash & Sutcliffe 1970). We used the general guidelines for calibration tolerances or targets from hydrologic simulation program FORTRAN (HSPF) training workshops over the past 10 years (Dongian 2000). Stream flow was calibrated first, until % diff. values were within ±15%, and NSE was more than 0.7. BOD and TOC were calibrated after the flow calibration until % diff. values were within ±35% and more than 0.6 NSE, respectively.

Model improvements for organic matter

Concept of improvement

For reliable water quality simulation by a semi-distributed model, accurate daily runoff simulation is needed first. Therefore, to improve the limitation of abnormal computation of water depth in channel flow routing, we used the code that was modified to consider average flow rate in a day, expressed as water volume per second, by Kim et al. (2007). The algorithm of in-stream water quality is the same as the QUAL2E model, which has limitations in simulating algae, organic matter, and Bottle BOD5. In particular, the BOD parameter is simulated by SWAT as ultimate carbonaceous BOD (CBODu), in contrast with domestic practice. To overcome this problem, NIER (2008) developed QUALKO ver.2 to improve algorithms for modeling the increase of internal organic matter due to the fractionation process of algal metabolism and computing Bottle BOD5 in line with domestic practice. However, the QUAL-model series can only be used to simulate a single rainfall event and is not valid for continuous and long-term runoff. Therefore, we propose an improved channel water quality module for the SWAT model that can simulate hydraulic, hydrologic, and water quality on a long-term basis, by linking the algorithms of...
QUALKO ver.2 to SWAT. In general, it is hard to explain how organic pollution increases in natural rivers and reservoirs using the observed BOD$_5$ or COD data. In Korea, external sources have more effect than internal sources in rivers and reservoirs during the wet-season (summer), while internal sources are more significant during the dry-season (spring, autumn, and winter). Internal sources range from 51 to 68% in large reservoirs such as Soyang, Chungju, Daecheong, and Andong in Korea. Thus, as well as reducing external sources, a method for reducing internal sources should be established for effective management of organic matter; the assessment criterion should be changed from COD and BOD to TOC in the near future. Table 1 compares the simulation algorithms of QUAL2E, QUALKO ver.2, and QUAL-NIER, respectively, with this study. Figure 2 shows the schematics of water quality module change in the SWAT model.

**Original source code and modifications**

QUAL2E uses a dimensional advection–dispersion equation including: (1) advection, which transports pollutants with a moving fluid in a reach, (2) dispersion, which transports pollutants through turbulent flow and a difference of pollutant concentration, (3) internal loading variation by biological and chemical reaction and interaction, and (4) external loading variation by inflow and outflow. In particular, QUAL2E simulates BOD by the following equation (Thomas 1948):

\[
\frac{dL}{dt} = - (K_1 L + K_2 L)
\]

Table 1 | Comparison of simulation characteristics of QUAL2E and developed models

<table>
<thead>
<tr>
<th>Consideration</th>
<th>QUAL2E</th>
<th>QUALKO ver.2</th>
<th>QUAL-NIER</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBOD: Increasing organic matter by algal death</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>BOD$_5$: Deoxidation by algal death/respiration, CBOD$_5$, NOD$_5$, AOD$_5$</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>DO: Division of algae respiration (death/respiration)</td>
<td>X</td>
<td>Respiration</td>
<td>Respiration</td>
<td>O</td>
</tr>
<tr>
<td>Algae: Division of decreasing algae biomass (death/respiration)</td>
<td>X</td>
<td>Death/respiration</td>
<td>Death/respiration</td>
<td>O</td>
</tr>
<tr>
<td>N, P: Include labile organic nitrogen, phosphorus</td>
<td>X</td>
<td>Death/respiration</td>
<td>Death/respiration</td>
<td>–</td>
</tr>
<tr>
<td>TOC: Organic carbon</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Figure 2 | Schematics of water quality module change.
where \( L \) is the carbonaceous biological oxygen demand (CBOD) concentration (mg/L); \( K_r \), the CBOD deoxygenation rate coefficient; \( K_s \), the rate of loss of CBOD due to settling (/day); and \( t \), the flow duration time.

The BOD simulation used in SWAT, based on the above equation from QUAL2E, uses the following equation:

\[
bod = \text{cobodcon} - (rK_1 + rK_3) \cdot \text{cobodcon} \cdot \text{tday} \quad (2)
\]

where \( \text{cobod} \) is the carbonaceous biological oxygen demand concentration in a reach (mg/L); \( \text{cobodcon} \), the initial CBOD concentration in a reach (mg/L); \( rK_1 \), the CBOD deoxygenation rate coefficient in a reach at 20°C; \( rK_3 \), the rate of loss of CBOD due to settling in a reach at 20°C (/day); \( \text{tday} \), the flow duration (fraction of 24 h).

The continuous simulation of BOD considering the increase of internal organic matter due to the fractionation process of algal metabolism based on QUALKO (NIER 2008) could be modified as follows:

\[
bod = \text{cobodcon} + [(ai_7 \cdot \text{excr} \cdot \text{gra} \cdot \text{algcon}) + (ai_7 \cdot \text{dear} \cdot \text{algcon}) - (rK_1 + rK_3) \cdot \text{cobodcon}] \cdot \text{tday} \quad (3)
\]

where \( ai_7 \) is the rate of CBOD production per unit of algal oxidation (mg CBOD/mg algal); \( \text{excr} \), the algal excretion rate at 20°C; \( \text{gra} \), the local algal growth rate at 20°C; \( \text{dear} \), the total algal death rate at 20°C; \( \text{algcon} \), the initial algal biomass concentration in a reach (mg/L). The other variables are as defined above.

By adding the above-calculated CBOD, deoxidation by nitrification, and deoxidation by algal respiration, which were developed and improved by NIER (2008), Bottle BOD5 could be calculated as follows:

\[
\text{bottle BOD}_5 = \text{cbodu} \cdot \left(1 - e^{-5 \cdot \text{kdb}}\right) + 4.57 \cdot (\text{NH}_3) \\
\quad \times \left(1 - e^{-5 \cdot \text{knb}}\right) + ai_4 \cdot \text{algcon} \cdot (1 - e^{-5 \cdot \rhoq}) \quad (4)
\]

where Bottle BOD5 is the Bottle BOD5 concentration in the laboratory (mg/L); \( \text{kdb} \), the deoxidation rate coefficient in Bottle CBOD5 at 20°C (/day); \( \text{NH}_3 \), the ammonia concentration in a reach (mg/L); \( \text{knb} \), the nitrification rate coefficient in Bottle CBOD5 at 20°C (/day); \( ai_4 \), the rate of oxygen uptake per unit of algae respiration (/day); and \( \rhoq \), the algae respiration rate at 20°C (/day). The other variables are as defined above.

In addition, TOC can be used as an important index for evaluating the organic matter in bodies of water in the future. The organic matter in water is composed of refractory and labile forms, classified as POC (particulate organic carbon) and DOC (dissolved organic carbon). POC and DOC can also be divided into labile POC, refractory POC, labile DOC, and refractory DOC. On the other hand, TOC can be classified as non-living organic carbon and assimilable organic carbon. The amount of organic matter was calculated based on the amount of organic carbon, as organic matter in water consists primarily of carbon (Riemann & Sondergaard 1986). CBODu was expressed in terms of Bottle BOD5 for calculating TOC in this study:

\[
\text{cbodu} = [\text{bottle BOD}_5 - 4.57 \cdot (\text{NH}_3) \cdot (1 - e^{-5 \cdot \text{knb}}) - ai_4 \cdot \text{algcon} \cdot (1 - e^{-5 \cdot \rhoq})]/(1 - e^{-5 \cdot \text{kdb}}) \quad (5)
\]

where all terms are as defined previously. The TOC concentration in a reach is calculated in this study using the following series of equations:

\[
\text{toc} = \text{ntoc} + \text{aoc} = \text{cbodu} + \text{aoc} \quad (6)
\]

\[
\text{aoc} = \text{chlcon} \cdot (\text{D.W}/\text{chlcon}) \cdot (\text{O}_2/\text{D.W}) \cdot (1 - e^{-5 \cdot \rhoq}) \quad (7)
\]

\[
\text{cbodu} = 2.67 \cdot \text{toc} \quad (8)
\]

\[
\text{toc} = (\text{cbodu} + \text{aoc})/2.67 \quad (9)
\]

\[
\text{toc} = [\text{cbodu} + ai_0 \cdot ai_8 \cdot \text{algae} \cdot ai_4 \cdot (1 - e^{-5 \cdot \rhoq})]/2.67 \quad (10)
\]

where \( \text{toc} \) is the total organic carbon concentration in a reach (mg/L); \( \text{ntoc} \), the non-living organic carbon concentration in a reach (mg/L); \( \text{aoc} \), the assimilable organic carbon concentration in a reach (mg/L); \( \text{chlcon} \), the chlorophyll \( a \) concentration in a reach (mg/L); \( \text{D.W}/\text{chlcon} \), the dry weight of chlorophyll \( a \); \( \text{O}_2/\text{D.W} \), the oxygen demand per dry weight of chlorophyll \( a \); \( ai_0 \), the ratio of chlorophyll \( a \) to algal biomass; \( ai_8 \), the ratio of carbon to algal biomass; and \( \text{algae} \), the algae concentration in a reach (mg/L). The others terms are as defined above.
RESULTS AND DISCUSSION

Calibration results

For KSW, the hydrologic and water quality parameters are calibrated based on the 8-day outflow and water quality data observed at Kyongan A and B. The results of simulation for daily stream flow are shown in Table 2. The simulated stream flow matched very well with the observations. Both % diff. and NSE are within 15% and more than 0.7, respectively, for the simulation periods. Overall, the model simulated stream flow satisfactorily within the target range but the simulated BOD before the proposed improvement showed quite poor fits with the observed values (Table 2 and Figure 3). Therefore we tried to improve the module of organic matter in the SWAT model to simulate well within the simulation target.

Improvement results for organic matter

The results of the proposed model were compared with values observed at the stations of Kyongan A and B

Table 2 | Stream flow, BOD$_5$ and TOC statistical results both before and after improvement

<table>
<thead>
<tr>
<th></th>
<th>Kyongan A</th>
<th></th>
<th>Kyongan B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 years (2004–2008)</td>
<td>Q($\text{m}^3/\text{s}$)</td>
<td>BOD$_5$ (mg/L)</td>
</tr>
<tr>
<td>Obs.(mean)</td>
<td></td>
<td>6.02</td>
<td>6.80</td>
</tr>
<tr>
<td>Sim.(mean)</td>
<td></td>
<td>6.70</td>
<td>6.72 (0.93)</td>
</tr>
<tr>
<td>% diff.</td>
<td></td>
<td>–11.39</td>
<td>1.12 (80.20)</td>
</tr>
<tr>
<td>NSE</td>
<td></td>
<td>0.85</td>
<td>0.58 (–2.19)</td>
</tr>
</tbody>
</table>

(): Simulation performance before improvement.

Figure 3 | BOD$_5$ and TOC simulation results after improvement at Kyongan A and B.
Although SWAT were generally closed to the simulation targets. the watershed and pollutant sources. were within expectations, considering the complexity of stations the reliability and performance of the simulations improvement. The KSW before and after implementation of comparing simulation results for water quality manage-
ment of the SWAT model. In future, we can also expect that this will of organic matter in rivers and streams using the improved NIER, which attempted to improve the limitation of production of algae, referring to the QUALKO and QUAL-
NIER, which attempted to improve the limitation of BOD5. The effects of the improvement were evaluated by calculating Bottle increase of internal organic matter due to the fractionation adding water quality algorithms that can estimate the reasonable predictions can be made. Therefore, the BOD mechanism in the SWAT model can be improved by channel water quality module in SWAT. Journal of Korean Society on Water Quality 25 (6), 902–909. (In Korean)
Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R. & Williams, J. R. 2002b Soil and water assessment tool user’s result in increased reliability of water quality simulations, as there has been an increasing demand for the development of TMDLs as a decision making tool to manage water quality in watersheds. However, the proposed model needs further testing for longer simulation periods and other catchments to improve the codes and enhance simulation reliability.

CONCLUSIONS

In this study, an attempt was made to modify the modeling of organic matter in the source code of the SWAT model to improve the limitations of domestic practice. If experimental data for organic matter are available and reliable, reasonable predictions can be made. Therefore, the BOD mechanism in the SWAT model can be improved by adding water quality algorithms that can estimate the increase of internal organic matter due to the fractionation process of algal metabolism and by calculating Bottle BOD5. The effects of the improvement were evaluated by comparing simulation results for water quality management of the KSW before and after implementation of improvement.

We confirmed that BOD simulation was improved by adding the Bottle BOD5 simulation and internal production of algae, referring to the QUALKO and QUAL-NIER, which attempted to improve the limitation of BOD simulation. Furthermore, by adding TOC, we can expect to simulate in detail the generation and reduction of organic matter in rivers and streams using the improved SWAT model. In future, we can also expect that this will

REFERENCES

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R. & Williams, J. R. 2002b Soil and water assessment tool user’s

NIER 2008 Development of a stream water quality model for the management of total maximum daily loads (III). (In Korean)


Thomas Jr., H. A. 1948 Pollution load capacity of streams. *Water and Sewage Works* 95 (11), 409–413.


First received 26 March 2012; accepted in revised form 26 June 2012