Modelling of suspended sediment in a weir reach using EFDC model

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ABSTRACT

Construction of hydraulic structures often leads to alteration of river dynamics and water quality. Suspended solids entering the upstream of the weir cause adverse effects to the hydroecological system and, therefore, it is necessary to build a modelling system to predict the changes in the river characteristics for proper water quality management. In this study, the discharges and total suspended solids upstream and downstream of the Baekje Weir installed in Geum River, Korea, was modelled using the environmental fluid dynamics code (EFDC) model. The resulting trend of four rainfall events shows that as rainfall increases, the total suspended solids (TSS) concentration increases as well. For the two larger events, at the upstream of the weir, TSS was observed to decrease or remain constant after the rainfall event depending on the lowering of the open gate. At the downstream, TSS supply was controlled by the weir during and after the rainfall event resulting in decline in the TSS concentration. The modelling produced good results for discharge based on %Diff. (4.37–6.35), Nash–Sutcliffe efficiency (NSE) (0.94–0.99) and correlation coefficient (r) (0.97–0.99) values as well as for TSS with acceptable values for %Diff. (12.08–14.11), NSE (0.75–0.81) and r (0.88–0.91), suggesting good applicability of the model for the weir reach of the river in the study site.

Key words | EFDC model, Guem River, hydraulics, TSS, weir

INTRODUCTION

In Korea, rainfall occurs mostly during the summer season from June to September. As such, the rainfall concentrated during the summer months is stored using hydraulic structures like dams and weirs to prevent downstream flooding and to secure water stability (MLTM 2009). Starting in 2009, a number of weirs were built in the four major rivers (Han River, Nakdong River, Geum River, and Yeongsan River) of the Korean Peninsula as part of the Four Major Rivers Restoration Project (Ahn et al. 2014).

Weir construction causes change in hydraulic and water quality characteristics such as decrease in velocity and more deposition of sediment than before construction (Vuik 2010). This increase in sediment results in increase in the possibility of water quality degradation in streams. The proportion of suspended sediment is usually more dominant than bed load during flood events, with the latter contributing to approximately only 5–10% of the total sediment load (Alexandrov et al. 2009). The total suspended solids (TSS) is often used as a measure of suspended sediment. Most of the TSS generated during heavy rainfalls move to the downstream, followed by settling at the end of the rainfall. Pollutants in sediment, such as pesticides, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, volatile organic compounds, nutrients, and heavy metals, can have serious effects on the aquatic system (Liu & Huang 2009; Navratil et al. 2012; Rossi et al. 2012). To understand the variety of changes in the river characteristics caused by weirs, it is necessary to monitor sediment transport in the upstream and downstream of the weir depending on rainfall characteristics. In addition to this, it is also useful to build a modelling system for predicting these changes.

Currently, models for prediction of TSS and contaminants, such as Soil and Water Assessment Tool (Wang et al. 2003), environmental fluid dynamics code (EFDC; Zou et al. 2006), Water Quality Analysis Simulation Program
(Rim et al. 2006), and HSPF (Jun et al. 2011), are widely used. However, modelling of hydraulics and TSS during rainfall by EFDC in a weir-installed river reach has not been reported in the literature, although these parameters have an important context regarding human influence on the riverine environment. Moreover, high-resolution data for TSS is limited in availability and can be seldom found in the literature due to the difficulty in measurements.

In this study, the characteristics of the hydraulics and water quality of the Baekje Weir reach of the Geum River were analyzed. The EFDC model was used for simulation of discharge and TSS concentrations in the upstream and downstream of the weir because it can consider the change in hydraulic characteristics as a result of installing hydraulic structures, and also the change in water quality by stream sediment transport. Discharge and TSS data were obtained from gauging stations available in the study site, complemented by actual sampling of stream flow and TSS upstream and downstream of the weir for assessment of the model applicability in this specialized setting.

**MATERIAL AND METHODS**

**Study site – Baekje Weir reach**

The study site is the Baekje Weir reach of the Geum River, which is the one installed at the most downstream location (Figure 1). Baekje Weir’s total length of 311 m consists of a fixed weir (191 × 4.2 m) and movable weir (120 × 4.2 m) designed for a flood discharge of 12,580 m³, maximum water depth of 4.7 m, and minimum water depth of 1.0 m. The movable weir has a rise and fall system of operation, thus called a shell-type roller gate, and may discharge either over or below the weir. The independent operation of the movable and fixed weir has a favourable structure for sediment treatment. Baekje Weir is downstream of Sejong Weir and Kongju Weir; so its hydraulic characteristics (overflow, discharge, etc.) are affected by the two weirs upstream. As shown in Figure 1, observation points are located at Wangjin Bridge, 3.15 km upstream of Baekje Weir, and at Baekmagang Bridge which is 2.40 km downstream of Baekje Weir.

![Figure 1](https://iwaponline.com/wst/article-pdf/73/7/1583/183368/wst073071583.pdf)
Model description

The EFDC model, a three dimensional hydraulic dynamic model, was developed by the Virginia Institute of Marine Science (Hamrick 1992) initially for estuary and coastal as well as reservoir, lake, and river applications. It can simulate the water level and velocity, salinity, and temperature in addition to movement of cohesive and non-cohesive sediments, eutrophication mechanisms, and the movement and reactions of toxic pollutants (Tetra Tech, Inc. 2007). A number of alternatives are in place in the model to simulate general discharge control structures such as weirs, spillways, and culverts (Zhou & Endreny 2013).

The model requires definition of the domain of the region being modelled, through manual grid generation methods. The model interface simplifies the setup and application of EFDC through a shape file format-based graphical interface and associated windows. It supports input of EFDC model run control and model parameter designation, and it links directly to boundary condition/source data, e.g. watershed model output and point source contributions.

The EFDC sediment transport model, which was the major focus of calibration in this study, is capable of simulating the transport and fate of multiple size classes of cohesive and non-cohesive suspended sediment, including bed deposition and resuspension. Water column transport is based on dynamically coupled transport equations for turbulent kinetic energy and turbulent length scale which implement the Mellor-Yamada level 2.5 turbulence closure scheme (Mellor & Yamada 1982). Sediment mass conservative deposited bed formulations are included for both cohesive and noncohesive sediment. Water column/sediment bed interface elevation changes can be optionally incorporated into the hydrodynamic continuity equation.

Sampling and analytical method

To determine the change in the characteristics of discharge as an effect of weir installation, data collection was done at the study reach. In the upstream, the monitoring events consisted of two dry season sampling and four rainfall events at Wangjin Bridge, upstream of Baekje Weir, resulting in two and 52 samples, respectively. The discharge data were obtained with the use of USGS Type AA Current Meter model 6200. The frequency of the measurement was every 2, 3, 6 or 12 hours depending on the stream depth variation and was performed before and during the rainfall event. At the downstream, daily data from the Gyuam observatory station were used.

In setting up the model domain of EFDC, Jindu gauging station was set up at the upstream and Banjoweon gauging station at the downstream end, while Guem and Ji streams were set up as tributary inflows (Figure 1). Due to the shallow depth of the stream (1–6 m), it was thought that 2-D modelling is sufficient for this study. For building the stream network in a 2-D model, a 1,25,000 digital elevation model was used and the mesh for the numerical analysis was constructed by using ArcGIS. The developed mesh, which consisted of curvilinear, boundary-fitted, structured grids with cell length sizes ranging from 50 to 200 m, was imported into EFDC through the surface water modelling system tool. To determine if the model results are sensitive to grid size, grid dependency tests were performed by comparing the variation in maximum values of discharge and TSS concentration as shown in Table 1. Considering the cost of time and precision of prediction, 2,024 grid cells were adopted in this study.

The meteorological data required for the simulation of EFDC (pressure, temperature, relative humidity, precipitation, etc.) were obtained from the Daejeon Meteorological Observatory of the Korea Meteorological Administration, while the hydraulic data (condition of discharge and water level in the upstream, downstream and tributary) and water temperature data were obtained from...
the observatories within the study reach. Input data for TSS concentration modelling in the upstream, Ji stream, and Geum stream within the study area were derived from the constructed flow-sediment curve obtained from the Ministry of Construction & Transportation (2006).

In the model, using the ‘Hydraulic Structure’ option, the weir was set up in the cell according to the actual location of the installed weir in the study area for which the boundary conditions were set up. Using the HEC-RAS software (US Army Corps of Engineers 2010), the upstream boundary conditions and weir geometry were set up and run for a range of flowrates to produce elevation–discharge (Elev. vs Q) curves to be supplied to the EFDC model. For each cell where the weir is located, the bottom elevation was set at 4.25 m, which is the height of weir; Elev. vs. Q table was provided; and upstream and downstream cells were connected to calculate the overflow discharge.

Model evaluation

To evaluate the simulation statistics, the %Diff.; correlation coefficient, \( r \); and Nash–Sutcliffe model efficiency (NSE; Nash & Sutcliffe 1970) were used. These are defined by Equations (1), (2), and (3) given as

\[
\text{\%Diff.} = \left| \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} O_i} \right| \times 100
\]

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\left( \sum_{i=1}^{n} (O_i - \bar{O})^2 \right)}
\]

\[
r = \left( \frac{n \sum_{i=1}^{n} (O_i - \bar{O})(S_i - \bar{S})}{\left( \sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sum_{i=1}^{n} (S_i - \bar{S})^2} \right)} \right)
\]

where \( O_i \) is the observed daily flow, \( \bar{O} \) is the average observed daily flow, \( S_i \) is the simulated daily flow, and \( \bar{S} \) is the averaged simulated daily flow. These statistical criteria were selected because they are the most commonly used for the evaluation of hydrologic and water quality models (Moriasi et al. 2007). The percent mean errors or differences (% Diff.) between simulated and observed values attempt to provide some general guidance on what level of agreement or accuracy may be expected from the model application. The correlation coefficient, which ranges from −1 to 1, is an index of the degree of linear relationship between observed and simulated data. The NSE coefficient is also very commonly used and ranges between \(-\infty \) and 1.0, with NSE = 1 being the optimal value.

RESULTS AND DISCUSSION

Figure 2 shows TSS concentration and water level upstream of the weir at the Wangjin and downstream of the weir at the Baekmagang Bridge. In the upstream, during the early rainy season (Events 1 and 2), the concentration range was 20–40 mg/L on average, which was increased 3–5 times during the early season of heavy rain (Event 3). Especially for Event 4, the TSS concentration was increased to about 10–15 times the concentration during Events 1 and 2 on average, and was observed to remain constant after the rainfall within the observation period with the lowering of the open gate. Rapid increase of TSS concentration was observed particularly for Event 4. This rapid increase in concentration may be attributed to the sudden increase in rainfall. The same trend where sediment concentration increases during high intensity events has also been reported in several studies (Mishra et al. 2007; Jones & Schilling 2011). Similar to the observations at the upstream, the TSS concentration in the downstream during the early rainy season (Events 1 and 2) ranged from 20 to 25 mg/L on average and was increased 3–4 times during the early season of heavy rain (Event 3). Especially for Event 4, the TSS concentration increased to 14–16 times the concentration during Events 1 and 2 on average, and was observed to decrease rapidly with the lowering of the open gate. It can also be observed from Figure 2 that the TSS concentrations increased during the times when the gates were open thereby confirming that the TSS concentration is affected by the opening and closing of the weir gates.

For evaluation of model applicability in determining the impacts of weir installation on the changes in stream

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Grid dependency test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grid</td>
<td>( O_{\text{max}} ) (m³/s)</td>
</tr>
<tr>
<td>520</td>
<td>2.094</td>
</tr>
<tr>
<td>1,048</td>
<td>2.080</td>
</tr>
<tr>
<td>2,024</td>
<td>1.998</td>
</tr>
<tr>
<td>4,873</td>
<td>1.980</td>
</tr>
<tr>
<td>6,884</td>
<td>1.924</td>
</tr>
</tbody>
</table>
discharge and sediment characteristics, calibration of model was performed using the observed data. Upstream discharge and TSS concentration were measured at the Wangjin Bridge during two dry season samplings and four rainfall events. Downstream discharge was obtained from the Gyuam gauging station while TSS was measured at the Baekmagang Bridge during the same duration. It should be noted that the actual monitoring data for TSS were transformed to daily averages in order to be consistent with the daily time step used in the EFDC model calibration. The results of the model simulation were compared with the observed data to test the applicability of EFDC model based on the performance statistics including %Diff., correlation coefficient, and NSE coefficient. The samples have not been split and only calibration has been performed in this study due to limited availability of TSS data as a result of the challenging nature of obtaining high-resolution TSS data, especially during rainfall events.
According to Donigian (2002), %Diff. between simulated discharge and recorded values of less than 10 is considered ‘very good’. As for water quality, %Diff. under 15 is considered ‘very good’. Edgar et al. (2012) gave a ‘very good’ performance rating for NSE values between 0.75 and 1.0 and ‘good’ for values between 0.65 and 0.75. In addition, EPA (1998) considers \( r \) values over 0.85 for discharge and 0.6 for water quality as acceptable results.

The seven calibration parameters listed in Table 2 were found to be those which influenced the model results significantly. By trial-and-error method, calibration was performed to match the data obtained from gauging stations and separate monitoring efforts. The reference values of three parameters for cohesive sediment were obtained from the work by Lee (2011).

Table 2 | EFDC sediment transport model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>–</td>
<td>2.65 (calibrated)</td>
</tr>
<tr>
<td>Settling velocity</td>
<td>m/s</td>
<td>0.00003 (calibrated)</td>
</tr>
<tr>
<td>Tau critical-deposition</td>
<td>m²/s²</td>
<td>0.0002 (reference)</td>
</tr>
<tr>
<td>Tau critical-erosion</td>
<td>m²/s²</td>
<td>0.0002 (reference)</td>
</tr>
<tr>
<td>Reference of surf erosion</td>
<td>g/m²/s</td>
<td>0.005 (reference)</td>
</tr>
<tr>
<td>Non-cohesive sediment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settling velocity</td>
<td>m/s</td>
<td>0.00001 (calibrated)</td>
</tr>
<tr>
<td>Critical shear stress</td>
<td>m²/s²</td>
<td>0.0004732 (calibrated)</td>
</tr>
<tr>
<td>Critical shields stress</td>
<td>m²/s²</td>
<td>0.0325 (calibrated)</td>
</tr>
<tr>
<td>Bed and deposition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum layer thickness</td>
<td>m</td>
<td>0.1 (measured)</td>
</tr>
<tr>
<td>Deposition/constant porosity</td>
<td>–</td>
<td>0.8 (calibrated)</td>
</tr>
<tr>
<td>Minimum void ratio</td>
<td>–</td>
<td>0.5 (calibrated)</td>
</tr>
</tbody>
</table>

Table 3 | Statistical performance of EFDC model

<table>
<thead>
<tr>
<th>Location</th>
<th>%Diff</th>
<th>NSE</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge ( m³/s )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wangjin Bridge (upstream)</td>
<td>6.35</td>
<td>0.99</td>
<td>0.97</td>
</tr>
<tr>
<td>Gyuam Station (downstream)</td>
<td>4.37</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>TSS ( mg/L )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wangjin Bridge (upstream)</td>
<td>14.11</td>
<td>0.75</td>
<td>0.88</td>
</tr>
<tr>
<td>Baekmagang Bridge (downstream)</td>
<td>12.08</td>
<td>0.81</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 3 and Figure 3 show the calibration results in the upstream and downstream of the weir. It can be seen that the %Diff. and NSE values for all durations of discharge simulation are considered ‘very good’ both at the upstream and downstream, and \( r \) values are over 0.85, which satisfy the EPA criterion. In the case of TSS, the %Diff., NSE and \( r \) values are ‘very good’ at both the upstream and downstream. The high correlation of simulated and actual values suggests that the EFDC model is highly applicable for the weir reach of the river in the study site.

Results of simulating the characteristics of discharge and TSS during the four rainfall events show good applicability of the model. However, to improve the model performance, long-term simulation using more detailed data including the dry season should be considered. In addition to this, the study results show that the characteristics of sediment transport are affected by the weir discharge and opening and closing of weir gates. Therefore, more study regarding the real operation of the weir can also improve the performance of the model. Currently, the weir has been in operation for only a year; so long-term data are not yet available, which is a limitation to testing the model’s applicability for long-term period application.

CONCLUSIONS

In this study, the characteristics of changes in sediment transport as a result of weir installation are considered and evaluation of the EFDC model for this application has been done. The TSS concentrations were estimated by sampling and analysis at the upstream and downstream of the weir during four rainfall events. As a result, average TSS concentration in the upstream for larger events (Events 3 and 4) increased to 3–15 times the concentration for smaller events (Events 1 and 2), following the increase in amount of precipitation. Events 1 and 3 have almost the same amount of precipitation but the average TSS concentration in the downstream for Event 3 was about 3–5 times higher than for Event 1, as a result of opening the weir gates during Event 3, which allowed the sediments to be transported further downstream. For the heaviest rainfall event (Event 4), the average TSS concentration increased 14–16 times the concentration of the smaller events (Events 1 and 2), again because of the opening of the weir gate.

Based on the calibration results, performance statistics of the EFDC model applied on the weir-installed reach of the stream show that the model did very well in predicting the discharge and TSS concentration.
9.76), NSE (0.99; 0.77), and \( r \) (0.97; 0.90) values at both the upstream and downstream sections of the weir were in agreement with recommendations from the literature, suggesting the high applicability of the EFDC model for the weir-installed reach of a river.

The result of this research is thought to be useful for the evaluation of water quality and sediment in a weir reach of a river and can help operation of the weirs to minimize environmental damage. Suggestions for future study include testing model applicability for long-term simulation once the long-term data become available.

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