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Multiple segmented reaches per subwatershed modeling approach for improving HSPF-Paddy water quality simulation

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Abstract Reach segmentation influences predicted water quality concentrations in water quality modeling. Many lumped or semi-distributed watershed models, including Soil and Water Assessment Tool (SWAT) and Hydrologic Simulation Program-Fortran (HSPF), simulate stream/river water quality with a single segmented reach per subwatershed (SSRS) modeling approach. A multiple-segmented reaches per subwatershed (MSRS) modeling approach was developed, and simulated BOD_5 concentrations for this approach were compared with results from the SSRS modeling approach using the HSPF-Paddy model. The SSRS modeling approach has potential systemic errors for predicting BOD_5 concentration even when the model is well calibrated. When the point source was loaded at the most upstream location with the same decay rate, the predicted BOD_5 concentration using the SSRS modeling approach was higher compared with results for the MSRS modeling approach, and the difference between two methods increases with increasing load and decay rate. When BOD_5 was loaded more downstream, BOD_5 concentration using the SSRS modeling approach was lower compared with results for MSRS modeling. For a case study, simulated streamflow and BOD_5 concentration for the SSRS and MSRS modeling approaches demonstrated good agreement with observed data. However, the estimated decay rate for the SSRS modeling approach was smaller than that for the MSRS modeling approach because BOD decays through total volume in the SSRS modeling approach, although BOD may be loaded anywhere in the reach. The MSRS modeling approach can minimize systematic errors and provide more detailed variation of water quality concentrations along a river length. The MSRS modeling approach does not always need to be applied to all subwatersheds but is recommended for reaches significantly polluted by point source pollution.

Keywords HSPF-Paddy · Watershed modeling · BOD_5 · Reach segmentation · Water quality modeling

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Introduction

Models simulate environmental phenomena. Models can be expressed by mathematical formulations to describe natural processes. Although most model studies focus on model development and application, much of the recent research in modeling techniques is centered on the effect of input data accuracy on the simulation results of models. An important issue for modelers is how well input information or designation of model application describes the relevant characteristics of the watershed or waterbody.

For lumped or semi-distributed watershed modeling, a watershed is divided into subwatersheds to avoid scaling impact based on the differences in climate, topography, soil, and geology which govern the hydrologic response (Arnold et al. 1998). A watershed model linked with a receiving water quality model typically adopts a single segmented reach per subwatershed modeling approach (Neitsch et al. 2002; Duda et al. 2001). This approach assumes that one segmented reach receives loading from land and point source pollution, and these pollution sources are well mixed and then reacted. A TMDL (Total Maximum Daily Load) establishes the maximum amount of a pollutant allowed to enter a waterbody, also known as a loading capacity, so that the waterbody will meet or continue to meet water quality standards for a particular pollutant even after a technology-based permit is in place (http://www.epa.gov/owow/tmdl/intro.html, accessed June 2010). The effluent from waste water treatment plants (WWTPs) can have a large impact on stream water quality considering the capacity of WWTPs. In addition, considering the importance of the spatial distribution of planned WWTPs for TMDLs and water quality control strategies, there are limitations of the one reach per one subwatershed approach to evaluate the effect of WWTPs.

Robinson et al. (1995) reviewed the roles of hillslope processes, channel routing, and stream network geomorphology in the hydrologic response of natural catchments, and they concluded that the hydrologic response for large catchments is governed primarily by stream network geomorphology. Many researchers have tried to determine the effect of land segmentation on simulation results for lumped watershed models. Bingner et al. (1997) studied the effect of land segmentation on simulation runoff and fine sediment and reported that runoff volume is unaffected, but fine sediment yield simulation is significantly affected by the number and size of subwatersheds. They concluded these size effects of land segmentation come from physical topographic characteristics such as subwatershed's slope length and slope. FitzHugh and Mackay (2000) found that land segmentation does not significantly influence the streamflow and outlet sediment network because channel parameters are more important in determining the behavior on SWAT's outlet sediment predictions. In their other study (FitzHugh and Mackay 2001), land segmentation affected SWAT model behavior differently depending on whether the watershed was sediment source-limited or transport-limited. Jha et al. (2004) found sediment load from one of four study areas increased in response to increasing number of subwatersheds with small variations of slope and slope length. Nitrate concentration of all study areas was significantly increased with increasing number of subwatersheds. They concluded that the deposition, degradation, and transformation in stream routing were sensitive factors that can strongly influence simulation results. Arabi et al. (2006) identified land segmentation influences on the performance of best management practices (BMPs) for sediment and nutrient removal. They found that as the number of segments is increased, channel degradation is dominant in simulation without BMPs but deposition in channels is dominant in simulation with BMPs because some of the structural BMPs used were related to channels. Chapra (1997) explained the effect of water body segmentation on water quality simulation. Son et al. (2008) analyzed the effect of subwatershed size on the water flow and BOD loading using HSPF model and concluded water flow estimates did not make a significant difference for the change in subwatershed size, while a smaller number of subwatersheds results in lower BOD loading. Most researchers focused on topographical differences of watersheds or channels for explaining the effect of land segmentation on sediment or nutrient simulation results. They overlooked the effect of reach segmentation in watershed partitioning.

In this study, we hypothesize that reach segmentation can influence water quality simulation for a watershed model linked with a water quality simulation. A multi-segmented reaches per subwatershed modeling approach is introduced and the BOD simulation results for this new approach were compared with those for the traditional single segmented reach per subwatershed modeling approach under various identical loading conditions and actual watershed conditions using the HSPF-Paddy model.

Backgrounds

Basic concept of single and multiple segmented reaches per subwatershed

The schematics of the single and multiple segmented reach concept per subwatershed are illustrated in Fig. 1. In this study the single and multiple segmented reach modeling approaches are referred to as "SSRS" and "MSRS" modeling approaches, respectively. For the SSRS modeling approach, pollution is completely mixed and decayed through total volume, although sources are input anywhere. For multiple segments, pollution is completely mixed in the reach which is directly connected with the pollution outlet, and the pollution decays from this point to the final reach. This is sometimes referred to as a cascade of continuously stirred tank reactors (CSTRs) (Chapra 1997).

In HSPF including HSPF-Paddy, the BOD decay process is assumed to follow first-order kinetics and is represented by (Bicknell et al. 2001):

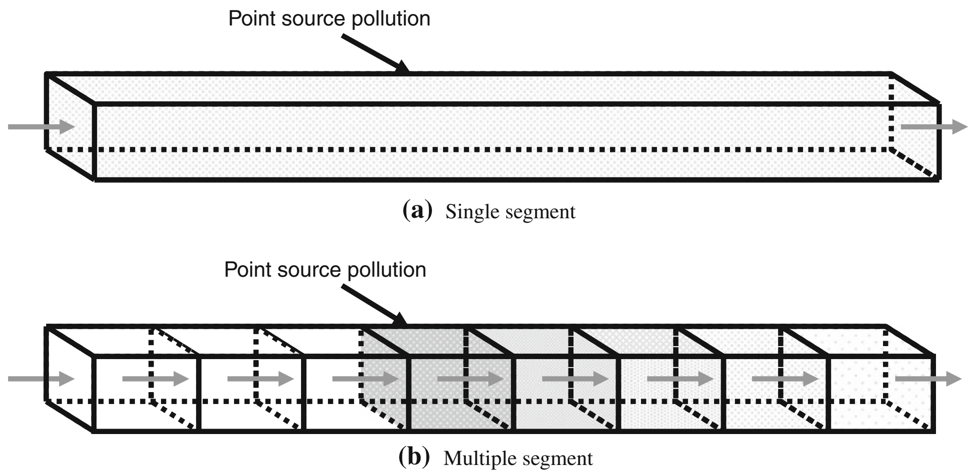

Fig. 1 Schematic of single- and multiple-segmentation representation

$$\mathrm{BODOX} = \mathrm{BOD_{init}} \times k_{20}\theta^{T-20} \quad (1)$$

where BODOX is the quantity of oxygen required to satisfy BOD decay, mg/l per interval; $\mathrm{BOD_{init}}$ the BOD concentration at model simulation time step, mg/l; k_{20} the BOD decay rate at 20°C,/interval; θ the temperature correction coefficient, and T is the water temperature, °C.

If we set $k_{20}\theta^{T-20}$as k_T, BOD concentration after a model simulation time step can be expressed by:

$$\mathrm{BOD_{final}} = \mathrm{BOD_{init}} \times (1 - k_T) \quad (2)$$

where $\mathrm{BOD_{final}}$ is the BOD concentration after model simulation time step, mg/l.

If all the conditions (e.g., water temperature) are the same and pollutants enter the nth segment, the final concentrations of single and multiple segments after a model simulation time step follow:

- Single segment

$$\mathrm{BOD_{final}} = \mathrm{BOD_{init}}(1 - k'_T) \quad (3)$$

- Multiple segments

$$\begin{aligned}
&\mathrm{BOD}_1 = 0\\
&\mathrm{BOD}_2 = 0\\
&\vdots\\
&\mathrm{BOD}_n = \mathrm{BOD_{init}}(1 - k_T)\\
&\mathrm{BOD}_{n+1} = \mathrm{BOD_{init}}(1 - k_T)(1 - k_T) = \mathrm{BOD_{init}}(1 - k_T)^2\\
&\mathrm{BOD}_{n+2} = \mathrm{BOD_{init}}(1 - k_T)^2(1 - k_T) = \mathrm{BOD_{init}}(1 - k_T)^3\\
&\vdots
\end{aligned}$$

$$\mathrm{BOD_{final}} = \mathrm{BOD_{init}}(1 - k_T)^{l-n+1} \quad (4)$$

where l is the number of total reach segments and n is the segment number which received point source pollution.

If values of k'_T and k_T are the same, the $\mathrm{BOD_{final}}$ for single segment is higher than that for multiple-segments. The other cases can be computed in a similar fashion. As more segments are used, the solution approaches a pattern that looks just like an exponential decay. If we assume that the final concentrations are the same, the k'_T value is:

$$\mathrm{BOD_{init}}(1 - k'_T) = \mathrm{BOD_{init}}(1 - k_T)^{l-n+1}$$

$$k'_T = 1 - (1 - k_T)^{l-n+1} \quad (5)$$

Therefore, the k'_T value is smaller than the k_T value, when the position of the point source loading is in the upper reach.

If all the conditions (e.g., water temperature) are the same and pollutants enter at the nth and mth reaches with BOD_0 and BOD_1 concentrations, respectively, the final concentrations for SSRS and MSRS modeling approach after a model simulation time step follow:

- SSRS modeling approach

$$\mathrm{BOD_{final}} = (\mathrm{BOD}_0 + \mathrm{BOD}_1)(1 - k'_T) \quad (6)$$

- MSRS modeling approach

$$\begin{aligned}
&\mathrm{BOD}_1 = 0\\
&\mathrm{BOD}_2 = 0\\
&\vdots\\
&\mathrm{BOD}_n = \mathrm{BOD}_0(1 - k_T)\\
&\mathrm{BOD}_{n+1} = \mathrm{BOD}_0(1 - k_T)(1 - k_T) = \mathrm{BOD}_0(1 - k_T)^2\\
&\vdots\\
&\mathrm{BOD}_m = (\mathrm{BOD}_0(1 - k_T)^{m-n} + \mathrm{BOD}_1)(1 - k_T)\\
&\qquad = \mathrm{BOD}_0(1 - k_T)^{m-n+1} + \mathrm{BOD}_1(1 - k_T)\\
&\mathrm{BOD}_{m+1} = \mathrm{BOD}_0(1 - k_T)^{m-n+2} + \mathrm{BOD}_1(1 - k_T)^2\\
&\vdots
\end{aligned}$$

$$\mathrm{BOD_{final}} = \mathrm{BOD}_0(1 - k_T)^{l-n+1} + \mathrm{BOD}_1(1 - k_T)^{l-m+1} \quad (7)$$

If we assume that the final concentrations are the same, the $k_T^{'}$ value is:

$$k_T^{'} = 1 - \frac{\mathrm{BOD}_0(1-k_T)^{l-n+1} + \mathrm{BOD}_1(1-k_T)^{l-m+1}}{\mathrm{BOD}_0 + \mathrm{BOD}_1} \quad (8)$$

where BOD_0 is the BOD_5 concentration for point source pollution for *n*th segment and BOD_1 is the BOD_5 concentration for point source pollution for *m*th segment.

If the point source is added at a different position, the k value for a single segment will be changed. Generally, models are used to explore various scenarios. Although the *k* value is adjusted through the calibration process, the predicted value might be in error for a single segment, if an additional point source loading will be input at a different position.

Model description

HSPF-Paddy was developed to simulate pollutant loads from paddy rice fields by modifying HSPF which is a comprehensive model developed by the United States Environmental Protection Agency (Jeon et al. 2007). The behavior of ponded water and nutrients in rice paddy fields can be simulated by adding a function for dike height and a *Dirac delta* function to the HSPF-Paddy model. The schematic diagram of water movement in paddy rice fields in the HSPF-Paddy model is shown in Fig. 2.

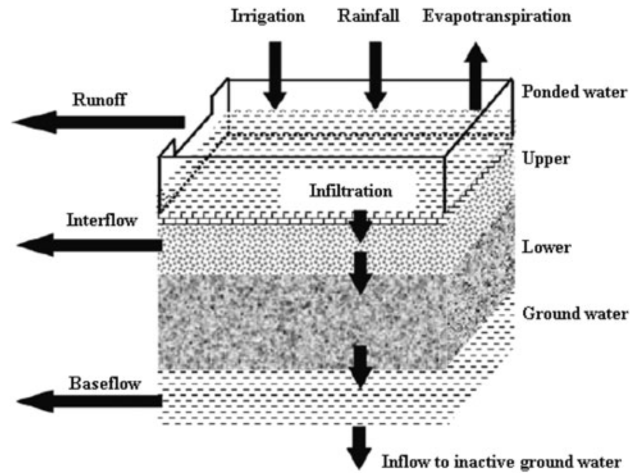

Fig. 2 Schematic diagram of the water balance components in HSPF-Paddy model (Jeon et al. 2007)

Materials and methods

Study area

The Junju Creek Watershed located in the southwest of the Korean peninsula is used throughout this study for demonstration of methodologies and models developed (Fig. 3). The total watershed area is about 287.6 km^2. Although the majority of the watershed is predominantly forest (167.6 km^2, 58%), it contains considerable urban area (40.8 km^2, 14%) which is the second most common land use. An average of 1286.8 mm of precipitation per year is measured at the Junju weather station. There are several interconnected weirs used to satisfy water use. They drain to the Junju Waste Water Treatment Plant (WWTP) which is located approximately 4.1 km up-stream from the mouth of the Junju Creek, and treated effluent is discharged into Junju Creek. The Junju Creek flows approximately 36.8 km. The main steam of the Junju Creek originates from two small tributaries: Junju Creek and Sam Creek which contain several creeks.

Data source and preparation

The Junju Creek Watershed was segmented into 6, approximately homogenous, sub-watersheds using a 30 m resolution Digital Elevation Model (DEM) obtained from Ministry of Environment (MOE) under the BASINS environment (USEPA 2004) (Fig. 4). Detailed land use data were obtained from the National Geographic Information Institute (NGII) which identities eight general types: upland, barren land, forest land, rice field, urban, water, and others (Table 1). These were subsequently imported into the BASINS environment. Similar hydrologic responses units (HRU) were grouped into a single HRU from combinations of land use groups and land segments.

Hourly historical data related to air temperature, dew-point temperature, cloud cover, wind speed, precipitation, and solar radiation were obtained from the Korea Meteorological Administration (KMA). The meteorological station to which the data belong is located in the city of Junju, named Junju weather station, inside the study area. Potential evapotranspiration was calculated using the Jensen equation (Jensen and Haise 1963), and Penman Pan Evaporation (Penman 1948) was calculated using the minimum/maximum temperature, dew-point temperature, wind speed, and solar radiation, which is part of the USEPA software package WDMUtil (Hummel et al. 2001). Streamflow data were collected by the Ministry of Construction and Transportation (MCT) at the Junju gage station which drains 100% of the study area. Water quality data were collected by the Ministry of Environment (MOE) at Sam Creek 1 (S1) and Sam Creek 2 (S2), Junju Creek 1 (JJ1), Junju Creek 2 (JJ2), Junju Creek 3 (JJ3), Junju Creek 4 (JJ4), Junju Creek 5 (JJ5), and Junju Creek 6 station (JJ6) and summarized in Table 2.

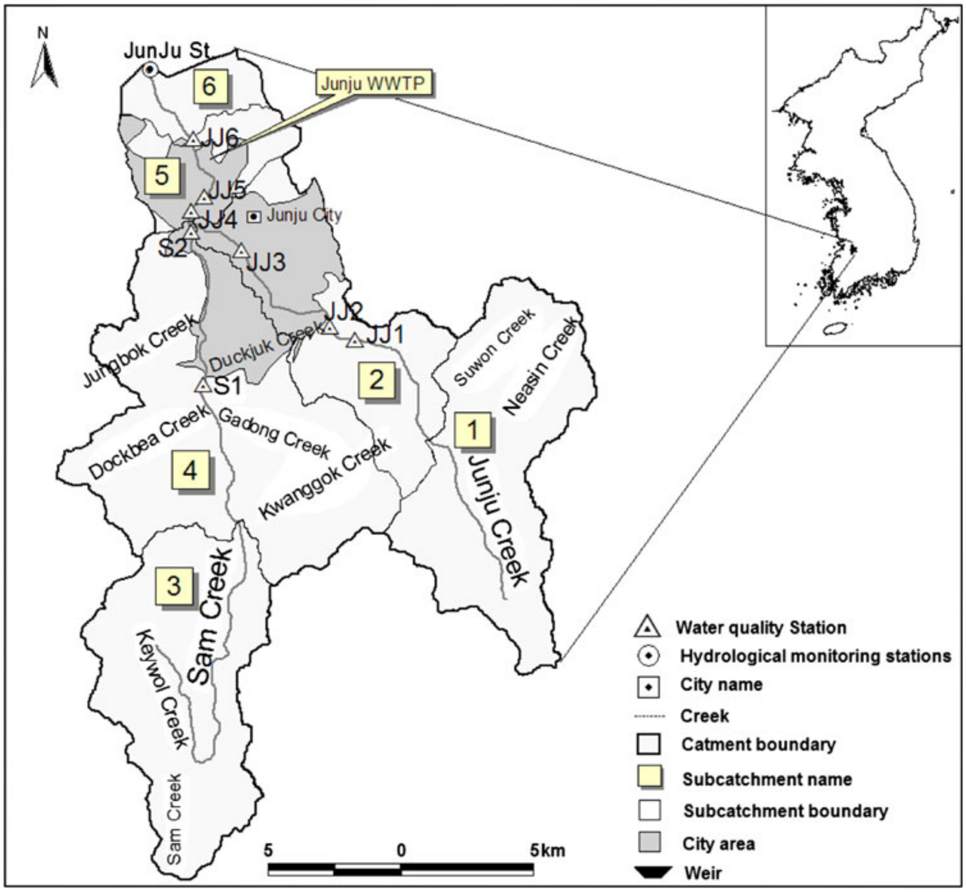

Fig. 3 Junju Creek Watershed with monitoring stations

Preparation of MSRS modeling approach in HSPF-Paddy

The HSPF-Paddy input file (uci) needs to be modified to use a MSRS modeling approach. If one reach is divided into n reaches, the following steps are required.

(1) Add the additional reaches in OPN SEQUENCE Block.
(2) Change the reach length in HYDR-PARM1 of RCHES Block.
(3) Copy and paste the FTABLE of a single-reach for as many additional reaches and surface area and volume are disaggregated by the number of multiple segmented reaches in FTABLE Block. Keep the depth and outflow.
(4) Link the point source pollution to specified RCHES in EXT SOURCES Block.
(5) Link between PERLND/IMPRLND and RCHES and among the RCHES in SCHEMATIC Block.

Modeling approach

Land and reach segmentation were performed using the DEM and the BASINS utility. In this process, a single reach receives pollution from one subwatershed. A single-reach was also sub-divided using the multi-segmented reach procedure. The SSRS and MSRS modeling approaches for the study area are shown in Fig. 4. When a single reach is segmented for the MSRS modeling approach, users can divide reaches based on a constant length or a constant number of reaches in each subwatershed. In this study, the constant number of reaches method was employed and each initial reach was segmented by 10 reaches in each subwatershed. The length of single and multiple reaches are shown in Table 3.

Testing the SSRS and MSRS modeling approaches

Reaches 1–10 in the MSRS modeling approach and reach 1 in the SSRS modeling approach are used to evaluate various ideal conditions. Only the RCHES module was used because simulation results of each method were evaluated more clearly. The simulation results of BOD_5 concentration between the two approaches were compared. The various scenarios for model testing were developed as shown in Table 4. First point source was loaded in the first position, which is reach 1, for both the SSRS and MSRS modeling approaches. In case 1, a second point source was loaded at the same position (reach 1) with various BOD_5

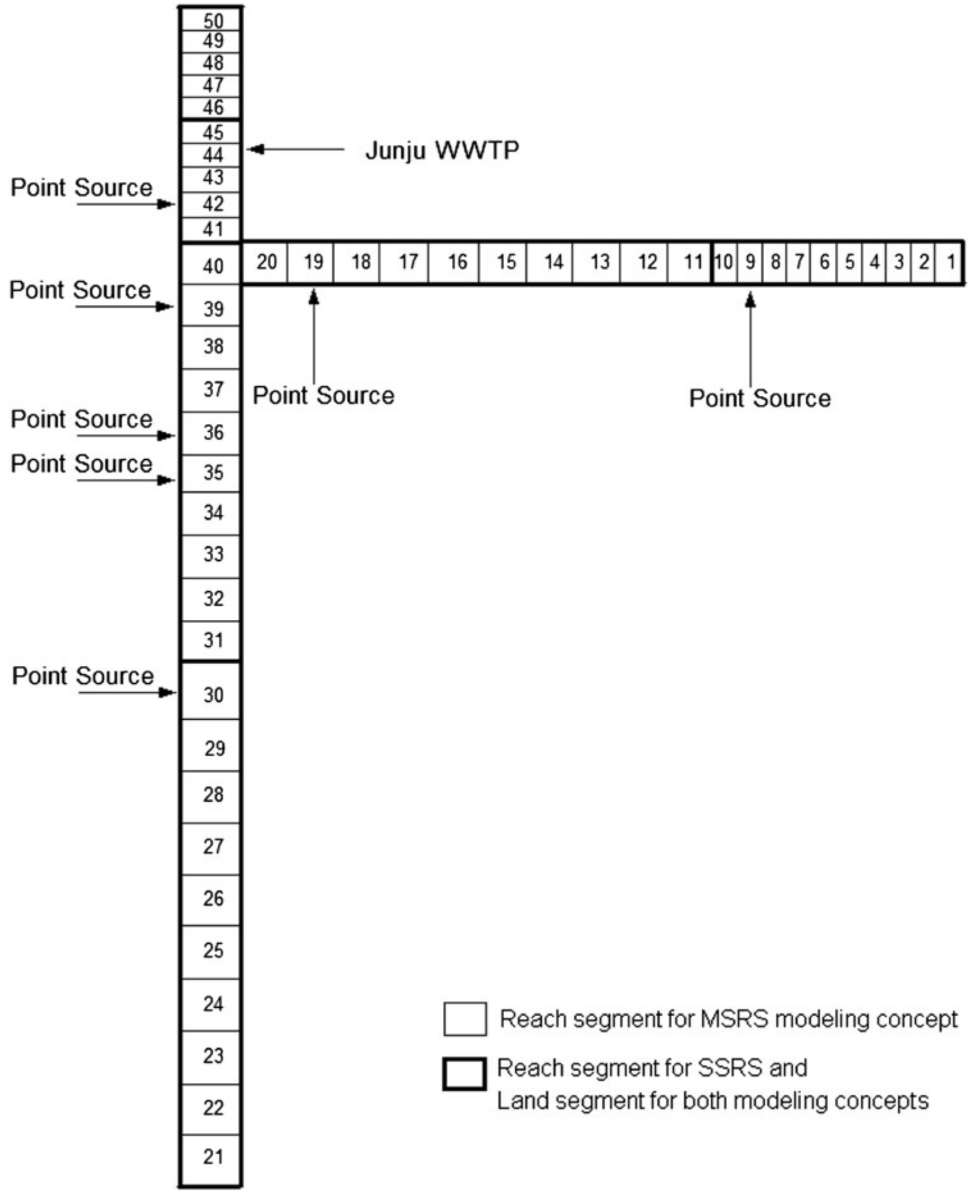

Fig. 4 Schematic of land and reach segmentation for SSRS and MSRS modeling at Junju Creek Watershed

Table 1 Land use classification in Junju Creek Watershed (unit: ha)

Land Use	Subwatershed					
	1	2	3	4	5	6
Forest	5238.3	2216.1	4871.3	4339.5	61.2	36.7
Paddy	120.2	174.0	453.7	1856.7	648.4	388.4
Upland	414.0	318.5	247.7	1056.2	337.4	202.1
Urban	145.7	1457.7	167.5	1330.6	590.7	353.9
Barren	16.5	325.0	13.0	238.5	86.5	51.8
Water	116.6	132.3	256.6	271.1	135.9	81.4
Others	1.3	2.8	3.6	1.9	0.6	0.3
Total	6052.6	4626.5	6013.3	9094.7	1860.6	1114.7

Table 2 Statistical analysis of water quality data for monitoring sites (mg/l)

	S1	S2	JJ1	JJ2	JJ3	JJ4	JJ5	JJ6
Mean	1.74	5.32	1.10	1.11	1.52	2.47	5.39	6.25
Max.	2.86	7.83	2.60	2.60	2.71	3.42	13.40	9.30
Min.	0.69	1.15	0.50	0.40	0.76	1.15	0.30	1.80
STD	0.62	2.19	0.44	0.46	0.35	0.68	3.72	2.56

concentrations from 10 to 19 mg/l and a decay rate from 0.1 to 0.3 day^{-1}. In case 2, a second point source was loaded at various positions for the multiple segmented reach representation, which varied from reach 1 to 10, and

Table 3 Segmentation of sub-reaches and subwatershed

MSRS modeling approach			SSRS modeling approach		
Reach #	Length (km)	Subwatershed	Reach #	Length (km)	Subwatershed
1–10	0.618	1	1	6.18	1
11–20	1.444	2	2	14.44	2
21–30	1.410	3	3	14.10	3
31–40	1.300	4	4	13.00	4
41–45	0.830	5	5	4.15	5
46–50	0.720	6	6	3.60	6

in reach 1 for the SSRS modeling approach. Differences for the concentrations for 2 year averages, and 10 and 90% cumulative frequency between the two modeling approaches were evaluated using relative error as follows:

$$\text{Difference } (\%) = \frac{S_s - S_m}{S_s} \times 100 \quad (9)$$

where S_s is the simulated value for SSRS modeling approach and S_m is the simulated value for MSRS modeling approach.

Application of HPSF using SSRS and MSRS modeling approach

The 2-year simulation period extended from January 1, 2001 to December 31, 2002 for the Junju Watershed. The PERLND, IMPLND, and RCHES modules were used for model application using the two reach concepts described previously, and the simulated BOD_5 concentrations and major parameters for these concepts were compared. Hydrologic calibration was performed using observed instream flow at Junju Station (Fig. 2). Simulated BOD_5 concentration was calibrated at the S1, S2, JJ1, JJ2, JJ3, JJ4, JJ5, and JJ6 stations located at reach 34, 40, 14, 15, 18, 41, 42, and 45, respectively, for the multi-segmented reach representation and at the S2, JJ3, and JJ6 stations located at the outlets of reaches 2, 4, and 6, respectively, for the single segmented reach representation.

Results

Model testing for SSRS and MSRS modeling approach

Figure 5 shows the simulated BOD_5 concentration of the SSRS and MSRS modeling approaches for various loadings upstream. Generally, the simulated BOD_5 concentration for the single segmented reach representation is higher than that of the multiple segmented reach representation as more loadings with higher decay rates are entered in the upstream position. For the 90% cumulative frequency, these differences are much higher than for the 10% cumulative frequency, showing more than a 30% difference.

Although the simulated BOD_5 concentration of the single segmented reach representation is higher than that of the multiple segmented reach representation, as the additional point discharges are located more down stream, the simulated BOD_5 concentration of the single segmented reach representation was much lower than for the multiple segmented reach representation (Fig. 6). The differences between single and multiple segmented reach representations were also much more influenced at the 90% cumulative frequency; about 36% relative difference when point source pollution was loaded at the most upstream location and −48% relative difference when point source pollution was loaded at the most down stream location with 0.3 day^{-1}. The maximum differences for the average concentration at the watershed outlet was about 8% for point source loading in the first reach and −30% for

Table 4 Case scenario for comparison of water quality simulation between single and multiple reaches

	First source position[a]	Second source position	k value[c]
Case 1			
Multi-reaches	Reach #1	Reach #1	Varied from 0.10 to 0.3 day^{-1}
		Varied source loading[b]	
Single-reach	Reach #1	Reach #1	
		Varied source loading	
Case 2			
Multi-reaches	Reach #1	Varied from #1 to #10	
Single-reach	Reach #1	Reach #1	

[a] The discharge is 300,000 m^3/day, BOD_5 concentration is 5 mg/l

[b] The discharge is 300,000 m^3/day, BOD_5 concentrations are from 10 to 19 mg/l, increased 1 mg/l for each step

[c] The decay value varied from 0.1 to 0.3 day^{-1} increased by 0.02 day^{-1} for each step

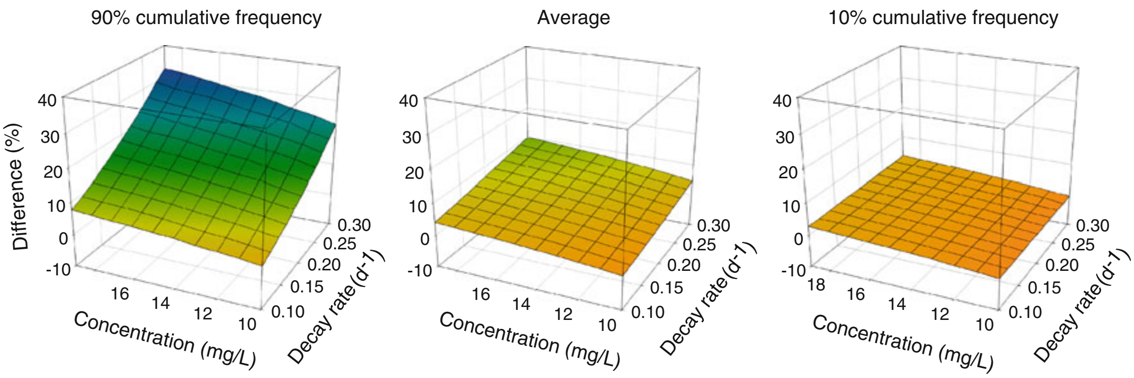

Fig. 5 The percent difference of simulated BOD_5 concentration between single- and multi-reaches in a subwatershed

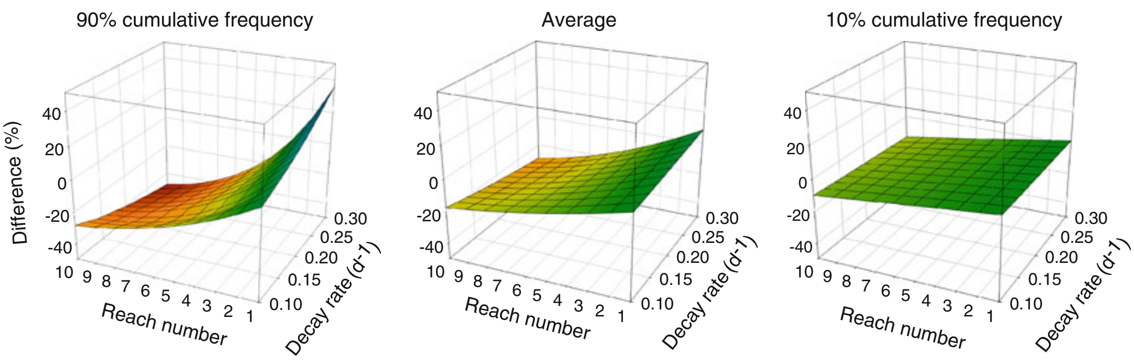

Fig. 6 The difference of simulated BOD_5 concentration between single- and multi-reaches in a subwatershed

loading in the last reach with 0.3 day^{-1} in the multiple segmented reach representation.

Application of SSRS and MSRS modeling approach on study area

Calibration results for stream flow are given in Table 5 and Fig. 7. The calibrated hydrologic parameters are listed in Table 6. Percent differences for the seasonal runoff except spring season and total runoff for the two concepts show "Very Good Agreement" with a 10% difference. A strong correlation was observed between simulated and observed streamflow which results in high model efficiency (Fig. 8). Flow-duration curves for simulated and observed daily flows are similar over the majority of flow conditions. A good fit of HSPF-Paddy using the MSRS modeling approach for streamflow simulation was evidenced by E_f value, slope of regression curve, and determination coefficient for the entire period. There were not significant differences between the single and multiple-segmented reach representation results.

The calibration results of BOD are listed in Table 7. The relative errors based on mean annual BOD concentration between observed and simulated values ranged from −26 to 2% for the SSRS modeling approach and from −12 to 5% for the MSRS modeling approach. In the SSRS modeling approach, all monitoring sites can be compared because reaches are more segmented but 3 sites can be compared in the MSRS modeling approach. Based on general calibration/validation tolerances or target for water quality simulation (Donigian 2000), most sites are "good" or "very good". Compared to two different modeling approaches, the simulation results of the MSRS approach are slightly better than those of the SSRS approach.

Another advantage of the MSRS modeling approach is the more detailed spatial distribution of BOD_5 concentration as shown in Fig. 9. Although, predicted BOD_5 concentration was well calibrated for the SSRS modeling approach, there are many uncertainties within the single segmented reach as shown in Fig. 9.

Table 8 shows the key parameters for BOD_5 simulation. Generally, the settling and decay rates for the SSRS modeling approach are smaller than those for the MSRS modeling approach. As a result of model testing under ideal conditions, the simulated concentration by the MSRS modeling approach was higher than that of the SSRS

Table 5 Summary of HSPF model results of simulations of streamflow for entire simulation period

Runoff category	Observed (mm)	Simulated (mm)	Difference (%)	Criterion[d] (%)
Simulation results for multiple reaches in one subwatershed concept				
Total annual runoff	688.1	650.7	−5.4	Very good: <10
Spring runoff	160.9	139.1	−13.6	Good 10–15
Summer runoff	247.5	246.5	−0.4	Very good: <10
Fall runoff	159.5	148.8	−6.7	Very good: <10
Winter runoff	120.3	116.3	−3.3	Very good: <10
Statistical analysis	MAE (%)[a]	RMSE[b]	E_f^c	
	5.43	0.73	0.91	
Simulation results for a single reach in one subwatershed concept				
Total annual runoff	688.1	668.6	−2.7	Very good: <10
Spring runoff	160.9	138.8	−13.7	Good 10–15
Summer runoff	247.5	259.9	5.0	Very good: <10
Fall runoff	159.5	153.1	−4.0	Very good: <10
Winter runoff	120.3	120.3	−3.0	Very good: <10
Statistical analysis	MAE (%)[a]	RMSE[b]	E_f^c	
	23.14	1.02	0.84	

[a] Percent mean absolute error

[b] Root mean square error

[c] Nash–Sutcliffe model efficiency

[d] *Source*: Donigian (2000)

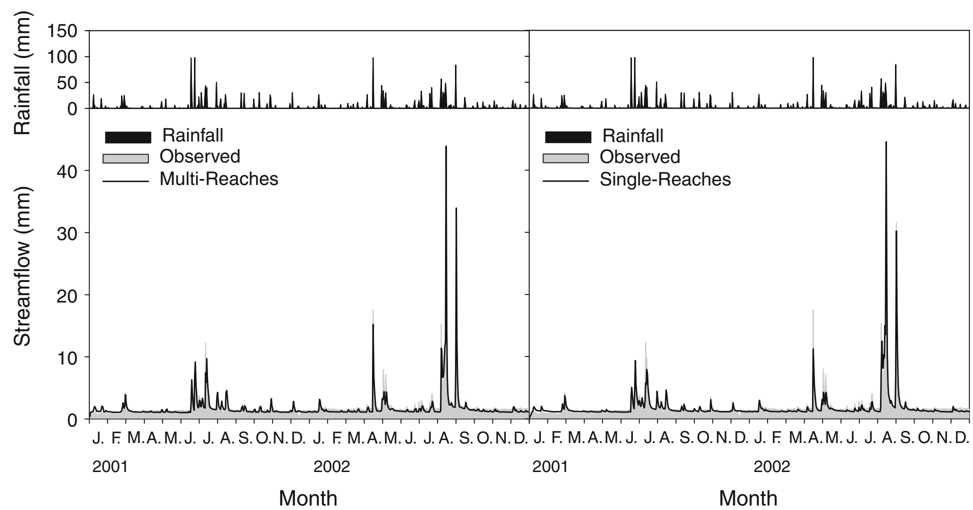

Fig. 7 Stream flow calibration results with single- and multi-reaches for water years 2001 and 2002

Table 6 The calibrated hydrologic HSPF parameters

Parameter	Description	Calibrated values
LZSN	Lower zone nominal soil moisture storage (mm)	635
INFILT	Related to infiltration capacity of the soil (mm/h)	4.57
KVARY	Groundwater recession flow parameter (cm^{-1})	0
AGWRC	Groundwater recession rate (day^{-1})	0.98
DEEPFR	Fraction of groundwater inflow to inactive groundwater recharge	0.8
BASETP	Fraction of remaining ET from baseflow	0.2
CEPSC	Interception storage capacity (mm)	10.2
UZSN	Upper zone nominal soil moisture storage (mm)	50.8
NSUR	Manning's n for overland flow	0.1
INTFW	Interflow inflow parameter	0.85
IRC	Interflow recession parameter	0.95
LZETP	Lower zone ET parameter	0.2

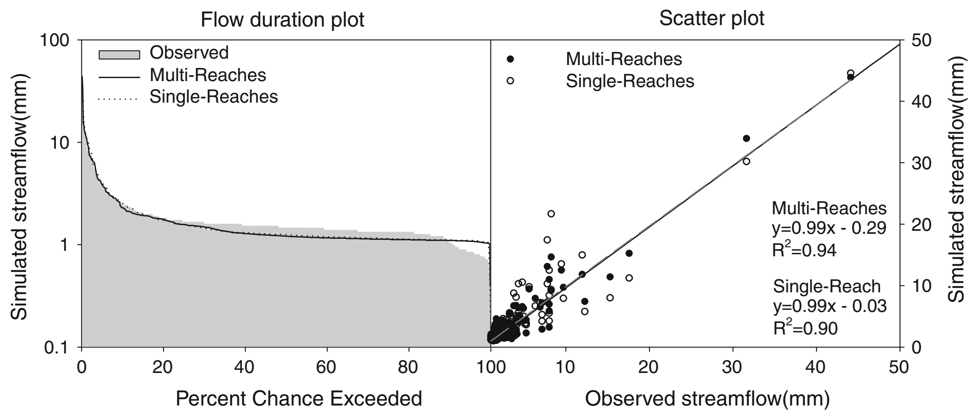

Fig. 8 Flow duration curve and scatter plot for streamflow water years 2001 and 2002

Table 7 The results of BOD calibration

	Observed	SSRS approach			MSRS approach		
	mg/l	mg/l	Error (%)	Level	mg/l	Error (%)	Level
S1	2.1	1.7	−15	Good			
S2	4.6	5.3	15	Good	5.2	−12	Very good
JJ1	0.9	1.1	18	Good			
JJ2	1.1	1.1	2	Very good	1.0	5	Very good
JJ3	1.8	1.5	−13	Very good			
JJ4	3.4	2.5	−26	Fair			
JJ5	5.9	5.4	−9	Very good			
JJ6	6.5	6.3	−3	Very good	6.0	8	Very good

modeling approach when pollution was loaded at various reach positions with the same decay parameter. When the model is calibrated, decay or settling rates for the MSRS modeling approach were higher than those for the SSRS modeling approach.

Discussion

Although, the simulation model is well calibrated using the SSRS modeling approach, the simulated water quality concentration might have potential error if additional point source pollution entered at different loading positions or at different loading rates for predicting future conditions. If additional point source pollution is added at the upstream position, the predicted water quality concentration might be overestimated, as the additional point source concentration is higher using the SSRS modeling concept. This is illustrated in Eqs. 3 and 4 and Fig. 5. These errors are more serious when pollution decays rapidly. If the additional point source pollution enters at a different position for predicting future conditions, the predicted water quality concentration might have significant error (from 7 to −30% of annual average concentration) for a SSRS modeling approach as shown in this study. When the pollution is loaded at the most upper position in a single reach during model calibration processes by the SSRS modeling approach, reacting parameters are calibrated for upstream load conditions and reaction for one continuous stirring tank reactor. For calibration with these conditions, predicted water quality concentration might be underestimated when additional pollution enters somewhere in a single reach because the model always simulates water quality under the assumption which the pollution enters the most upstream position and reacts for the entire reach volume. These errors are also significant when pollution decays rapidly. It is illustrated in Eqs. 6 and 7 and in Fig. 6. Considering the reverse condition, when the pollution is loaded at the most downstream position within the single reach representation during model calibration, reacting parameters are calibrated for the downstream load condition but with reaction for the whole reach. The reacting parameters which reduce concentration are relatively low in compensation for reaction in the whole single reach instead of the actual small volume from the input position to reach outlet. Using this parameter, when additional pollution enters an upper position within a single reach representation, the simulation concentration might be overestimated because the model always assumes that all pollution is loaded at the most downstream location and reacts within the whole single reach with relatively low decay parameters.

Another advantage of the MSRS modeling approach is that the spatial change of water quality along the river length can be simulated in more detail. For developing TMDLs or for water quality control planning, evaluating the source distribution or the effect on a water body is important. The MSRS modeling approach can solve this problem as shown in Figs. 8. Smaller subwatershed delineation could be also considered. However, subwatershed threshold area is limited by DEM resolution using the GIS tool. Delineating watersheds with several hundred meters of river length is not realistic with current DEM quality.

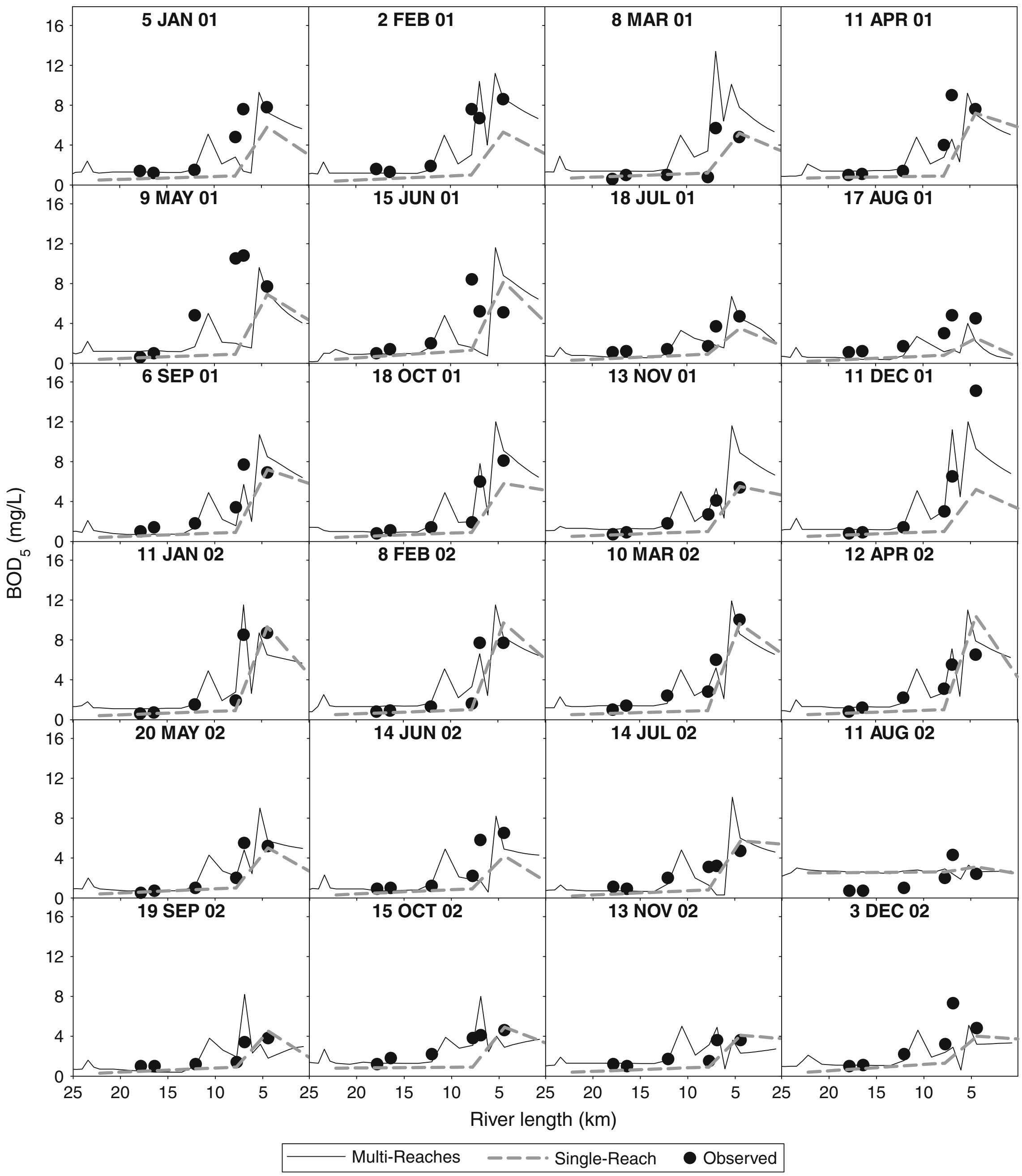

Fig. 9 Monthly BOD_5 variation in Junju Creek during 2001–2002

Table 8 Comparison of calibrated parameters between single- and multi-reaches concepts

Single reach in one subwatershed			Multiple reaches in one subwatershed		
Reach number	Decay rate	Settling rate	Reach number	Decay rate	Settling rate
1	0.010	0.100	1–10	0.01–0.015	0.147–0.187
2	0.015	0.030	11–20	0.007	0.187
3	0.015	0.030	21–30	0.007–0.015	0.107–0.187
4	0.015	0.237	31–35	0.013–0.015	0.257–0.407

Fortunately, the HSPF-Paddy model can apply the MSRS modeling approach with input file modification. In the SCHEMATIC Block of HPSF, the specified area of specified land use can be linked with a specified reach for the MSRS modeling approach. It may also be very useful to link between drainage channels from agricultural land use and reaches.

Conclusions

Reach segmentation can influence the predicted water quality concentration for predicting future conditions, even though the model is well calibrated. Generally, a SSRS modeling approach is used in lumped or semi-distributed watershed models such as HSPF or SWAT. Using a SSRS modeling approach, if a larger point source concentration enters at the same position, the predicted water quality concentration may be overestimated, even though the model is well calibrated. When point source pollution loads occur at different positions, potential error may increase with increasing distance between two loading positions. When the point source pollution which is used for calibrating enters at an upper position within a single reach and an additional future point source enters at a downstream position within a single reach, the predicted water quality concentration might be underestimated. Conversely, when the point source pollution is loaded at the most downstream location within a single reach during calibration and additional pollution enters at downstream positions within a single reach, the predicted water quality concentration might be overestimated. These errors are much more significant when high decay values occur. Large investments may be required for improving river water quality, and thus modelers must minimize the systemic errors from simulation models. The MSRS modeling approach can reduce these systematic errors and be simply applied in HSPF-Paddy by input file modification. The MSRS modeling approach in HSPF-Paddy, including the original HSPF, was demonstrated and showed good agreement with observed data.

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