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Applying SWAT for TMDL programs to a small watershed containing rice paddy fields

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Abstract

The main objective of this study was to apply the soil and water assessment tool (SWAT) to develop total maximum daily load (TMDL) programs for a small watershed containing rice paddy fields in the Republic of Korea. The total maximum daily load system (TOLOS), based on ArcView SWAT (AVSWAT) using geographic information system (GIS) and remote sensing (RS), was incorporated with the SWAT model to simulate water balance and water quality from irrigated paddy fields. Model parameters related to hydrology and water quality were calibrated and validated by comparing model predictions with the field data collected for 4 years. The results indicated that the simulated runoff and water quality values were acceptably close to the observed data. Water quality parameters also appeared to be reasonably comparable to the field data. The applicability of the system for TMDL development was tested in terms of TMDL allocations and the redistribution of load reductions to 23 sub-areas within the watershed. The results demonstrated that the urbanized subwatershed #2, with residences and other community activities, required the largest allocation of road reduction. TOLOS thus appears to be a useful tool for planning TMDL for a small watershed including rice paddies in Korea.

Keywords: SWAT; Paddy fields; Water quality; Nitrogen; Phosphorus; Suspended solids; GIS; RS

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1. Introduction

In Korea, for the past 30 years population growth and rapid economic development have increased the demand for water and degraded water quality due to waste disposal. As a result, the nation's impaired water bodies have become a threat to public health. In 1999, the Ministry of Environment Republic of Korea (MOE) required local governments to develop a total maximum daily load (TMDL) for each of the major rivers. The National Institute of Environmental Research established guidelines for the development of TMDL programs in 2003 (MOE, 2003).

The United States Environmental Protection Agency (USEPA) has continued to update the TMDL program, which limits the allowable pollutant discharge to water bodies based on their waste-assimilative capacity. This assessment provides the basis for local governments to establish targets for water quality based on recognized pollution control methods (USEPA, 1992). According to the USEPA's guidelines, TMDL is the sum of allowable pollutant loads from point and nonpoint sources, added to the natural background.

In the United States, section 303(d) of the Clean Water Act requires states to develop TMDL to maintain water quality criteria-limited waters where existing or proposed controls do not or are not expected to attain and/or maintain the applicable water quality standards (USEPA, 1992). Implementation of section 303(d) of the Clean Water Act lays a heavy emphasis on the allocation of point source waste loads, which are easily incorporated into National Pollution Discharge Elimination System (NPDES) permits as discharge limits. Nonpoint sources are generally not treated as separate components of the TMDL because of the difficulty in evaluating water quality impacts and the effectiveness of controls. However, controlling point source discharges alone does not necessarily ensure the attainment of water quality standards, especially when nonpoint sources are significant contributors to water quality problems.

The models currently used to simulate water quality can be used to assess the levels of pollution where observed data are insufficient or unavailable, to determine the allowable load for receiving waters with complex interactions among different pollution sources, and to allocate pollutant loads among the identified point and nonpoint pollution sources (Santhi et al., 2001). These models can be very useful in the initial evaluation of water quality, ranking and targeting, TMDL development, evaluation of controls, and program tracking to improve the water quality of impaired water bodies.

Many agencies, universities, and scientists have developed models to simulate water and chemical transport in respond to this legislation (Spuill et al., 2000). The soil and water assessment tool (SWAT) is a physically based, continuous model that simulates the impact of land management activities on water, sediment, pesticide, and nutrient yields. However, SWAT was initially developed for the comprehensive modeling of the impacts of management practices on water yield, sediment yield, crop growth, and agricultural chemical yields in large complex watersheds (Arnold et al., 1998). Although SWAT is generally applied to large river basins, many studies have used it to simulate annual water and sediment yield at both the river basin and small watershed scale (Arnold and Allen, 1996; Arnold et al., 1999; Arnold and Williams, 1987; Harmel et al., 2000). The SWAT ArcView extension is a graphical user interface for the SWAT model (Arnold et al., 1998). ArcView SWAT (AVSWAT) was developed by Texas A&M University in collaboration with the USDA-ARS laboratory in

Temple, Texas (DiLuzio et al., 2002). AVSWAT, as well as the original SWAT model, was recently updated and incorporated into BASINS 3.0 (Better Assessment Science Integrating Point and Nonpoint Sources), which is a software package developed by the USEPA (2001).

Saleh et al. (2000) applied SWAT to assess the effect of dairy production on water quality within the Upper North Bosque River Watershed, Texas. Spuill et al. (2000) evaluated the applicability of SWAT and determined the parameter sensitivities while modeling daily stream flows in a small central Kentucky watershed over a two-year period. King and Balogh (2001) estimated water quality impacts associated with converting farmland and forests to turfgrass using the SWAT model. Fontaine et al. (2002) added a feature capable of simulating hydrologic runoff from a non-agricultural mountainous region by adding a large snowmelt component to SWAT. Harmel et al. (2000) examined several daily precipitation generators in terms of the hydrologic response of SWAT. Culver et al. (2002) analyzed the impact of TMDL allocations on the potential leaching of nitrates to groundwater in the Muddy Creek/Dry River watershed of Virginia. Santhi et al. (2001) applied the SWAT model to evaluate management effects on point and nonpoint source pollution. This research showed that SWAT could be a useful tool for studying the effects of alternative management scenarios for TMDL implementation.

In Korea, the impact of rice paddy fields is of major concern as it provides potential benefits for water quality improvement for various reasons. Rice paddies cover an area of 11,46,000 hectares, 61% of the nation's total cultivated area. Paddy fields retain runoff water so that they can not only reduce soil erosion and sediment yield, but also alleviate downstream flooding. They also release water slowly into the ground and recharge groundwater. However, they occasionally release large amounts of nitrogen (N) and phosphorous (P) to neighboring water bodies, mainly due to the excessive use of fertilizers. At the same time, paddy fields have the potential to remove nitrogen through plant uptake and biochemical reactions in the inundated soil conditions. Better paddy field management can minimize N and P outflow and maximize the nitrogen removal potential of the paddy fields.

For these reasons, paddy fields are being studied as a unique component in the development of TMDL programs for Korea. The objectives of this study are: (1) to monitor hydrology and water quality of a watershed containing rice paddy fields; (2) to develop a TMDL system using geographic information system (GIS), remote sensing (RS), and a water quality model with a paddy field component added to the SWAT model, in order to simulate water balance and water quality from irrigated paddy fields; (3) to calibrate and validate the model for simulating hydrology and water quality by comparing model predictions with field data; (4) to evaluate the applicability of the system for TMDL development through redistribution of load reduction allocations to specific sites within the project watershed.

2. Methodology

2.1. TMDL simulation system

A total maximum daily load system (TOLOS) that is capable of estimating and managing TMDL from a small watershed was developed in this study to simulate

TMDL. For the efficient and comprehensive development of TMDL, various aspects of the TMDL behaviors must be estimated and evaluated qualitatively as well as quantitatively. Spatially distributed, parametric TMDL models require topographic, soil, and land use information as input data. Thus, a geographic information system (GIS) and remote sensing (RS) were adopted as useful tools for processing and synthesizing geographic information (Kang, 2002; Kang and Park, 2003). GIS is also used as a pre- and post-processor, linked to the TMDL models. A pre-processor provides formatted input data from the GIS data layers, and a post-processor in used to graphically present simulation results.

As mentioned before, AVSWAT combines the model to simulate hydrology and water quality with a pre-processor, interface and post-processor. TOLOS is based on AVSWAT. It consists of three subsystems: the input processor, based on GIS, the hydrology and water quality model, and the post-processor. The land cover patterns of the study watershed were classified from the Landsat-TM data using an artificial neural network model that adopts an error back propagation algorithm (Rumelhart et al., 1986). The land cover classifier module was added to AVSWAT in the form of an Avenue extension. The water quality model used for TOLOS is the SWAT model, which is a continuous time model, i.e. a long-term yield model.

In this study, paddy field components were incorporated into the SWAT model to simulate water balance at irrigated paddy blocks. Various studies have been conducted on analysis of paddy field using a water balance method. However, there have been few reports of runoff simulation for rice paddies.

A conceptual diagram that shows how TOLOS is integrated with GIS and RS is shown in Fig. 1. TOLOS is an ArcView extension and graphical user interface for SWAT. It was developed as an extension of ArcView GIS for the personal computer environment. The difference between TOLOS and AVSWAT is that TOLOS includes a rice paddy simulation module and a land cover classifier module using RS.

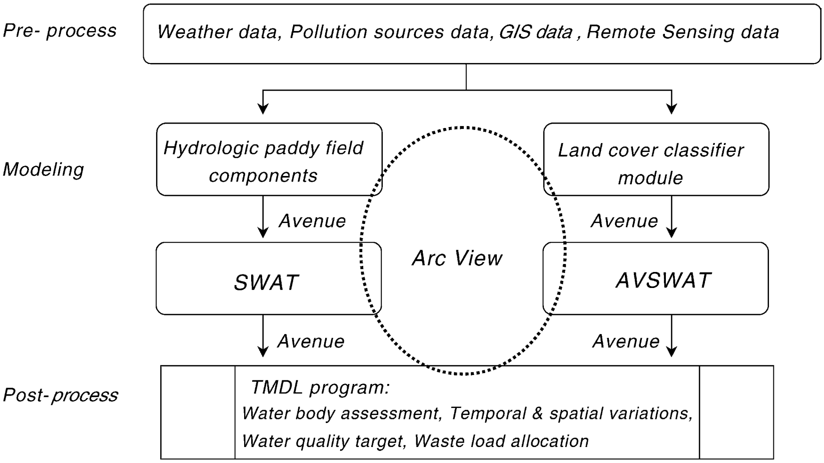

Fig. 1. Conceptual diagram of GIS and RS integrated TOLOS.

2.1.1. SWAT and AVSWAT description

The USEPA's TMDL guidelines provided the criteria for selecting a model for the TMDL applications (TNRCC and TSSWCB, 1999). SWAT was selected in this study as the model that would be used to develop the TMDL program in a complex watershed with various soils, land use and management conditions over a long period of time. Also, the physically based SWAT model uses input data that is readily available, computes efficiently, and makes it possible for users to study long-term impacts (DiLuzio et al., 2002; Neitsch et al., 2002a, 2002b). The model can be used to simulate a single watershed or a system of hydrologically connected multiple watersheds. A watershed must first be divided into sub-basins and then hydrologic response units (HRUs) for each sub-basin evaluated based on the land use and soil distributions (DiLuzio et al., 2002).

AVSWAT was developed as an extension of ArcView GIS entirely in avenue and is dependent on the spatial analyst and the dialog designer extensions. Without leaving the user-friendly ArcView GIS environment, the user can has available a complete set of tools for watershed delineation and definition, enabling the user to edit the hydrological and agricultural management inputs and execute and calibrate the model.

2.1.2. Runoff from rice paddy fields

SWAT is a semi-distributed model partitioned into a number of subwatersheds or subbasins. Runoff is predicted separately for each hydrologic response unit (HRU) using the curve number (CN) method or the Green-Ampt method, and routed to obtain the total runoff at the outlet of watershed (Neitsch et al., 2002a). Rice paddies in SWAT are simulated as impounded and depressional areas and are hydrologically similar to ponded areas.

However, these methods cause some bias when used to calculate the runoff from irrigated paddy fields in Korea (Kim et al., 2003). Runoff from paddy fields thus varies with the heights of the drainage outlets and ponding depths. As a result, the following concept was adopted to simulate the hydrological processes that occur in the irrigated paddy fields.

Rice paddy components were added to the SWAT model to simulate the water balance in irrigated paddy blocks. The hydrologic characteristics of a paddy field are shown in Fig. 2. Paddy fields are characterized by a large number of plots, or fields, separated by low embankments that retain fonding water on the soil surface. Paddy soils have very low infiltration rates and remain inundated between irrigation and/or rainfall events. Overflow occurs when rainfall exceeds the storage capacity of a paddy field, which is the elevation difference between the sill of the check gate and the water level at the time of rainfall.

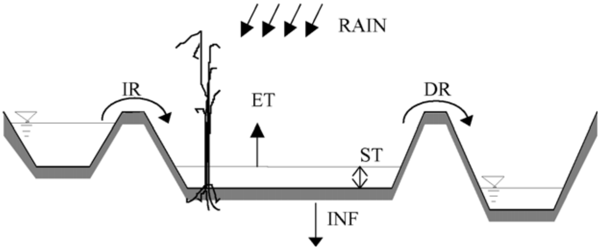

Fig. 2. Hydrologic characteristics of a paddy field.

The hydrologic cycle within a paddy field may be explained in terms of a water balance (Kang, 2002; Kang and Park, 2003). The ponding water depth (in mm), ST, is determined based on the relationship between the rainfall, evapotranspiration, irrigation water supply, runoff, and infiltration, as given in the following water balance equation:

$$\mathrm{ST}_i = \mathrm{ST}_{i-1} + \mathrm{IR}_i + \mathrm{RAIN}_i - (\mathrm{DR}_i + \mathrm{ET}_i + \mathrm{INF}_i) \tag{1}$$

$$\mathrm{DR}_i + \mathrm{ST}_i - \mathrm{CH}_i \qquad \text{if } \mathrm{ST}_i > \mathrm{CH}_i \tag{2}$$

$$\mathrm{DR}_i = 0 \qquad \text{if } \mathrm{ST}_i \leq \mathrm{CH}_i \tag{3}$$

where IR, RAIN, DR, ET, INF, and CH represent irrigation (mm), daily precipitation (mm), drainage runoff (mm), evapotranspiration (mm), infiltration (mm), and drainage outlet height (mm), respectively. The subscript i denotes day i.

The daily evapotranspiration from paddy fields is determined by the Penman–Monteith method (Monteith et al., 1965; Allen, 1986; Allen et al., 1989). The Penman–Monteith method takes into account solar radiation, air temperature, relative humidity and wind speed. The Penman–Monteith equation combines components that account for the energy needed to sustain evaporation and the strength of the mechanism required to remove the water vapor, along with aerodynamic and surface resistance terms. It is expressed as:

$$\lambda E = \frac{\Delta(H_{\mathrm{net}} - G) + \rho_{\mathrm{air}} c_{\mathrm{p}} (e_z^{\mathrm{o}} - e_z)/r_{\mathrm{a}}}{\Delta + \lambda(1 + r_{\mathrm{c}}/r_{\mathrm{a}})} \tag{4}$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E the depth rate evaporation (mm d^{-1}), Δ the slope of the saturation vapor pressure–temperature curve (kPa $^{\circ}\mathrm{C}^{-1}$), H_{net} the net radiation (MJ m^{-2} d^{-1}), G the heat flux density to the ground (MJ m^{-2} d^{-1}), ρ_{air} the air density (kg m^{-3}), c_{p} the specific heat at constant pressure (MJ kg^{-1} $^{\circ}\mathrm{C}^{-1}$), e_z^{o} the saturation vapor pressure of air at height z (kPa), e_z the water vapor pressure of air at height z (kPa), λ the psychrometric constant (kPa $^{\circ}\mathrm{C}^{-1}$), r_{c} the plant canopy resistance (s m^{-1}), and r_{a} the diffusion resistance of the air layer (s m^{-1}).

Since infiltration from paddy fields occurs under the saturated condition, infiltration is governed by soil type and ponding water depth. Therefore, average daily infiltration rates for paddy fields were used for infiltration estimation instead of applying the soil moisture routing techniques used by SWAT. Table 1 shows the suggested average daily infiltration rate and Table 2 shows the general growth stage of paddy rice in Korea.

2.1.3. Land cover classifier and GIS data

First, all the digital numbers describing seven bands in the image data were normalized into the theoretical range of (0,1). As the sigmoid function is involved, all the data were transformed into the range of (0.05, 0.095). Using the trial and error method, the best

Table 1
Average daily infiltration rate of paddy fields according to the soil types found in the study area (Im et al., 2000)

Soil types	Loam	Sandy clay loam	Silt clay loam	Sandy loam
Infiltration rate (mm/day)	2.7	8.8	5.6	2.2

Table 2
The growth stages of paddy rice (Jin, 1998)

	Date										
	6/10	6/20	6/30	7/10	7/20	7/30	8/10	8/20	8/30	9/10	9/20
Days after transplanting	0	10	20	30	40	50	60	70	80	90	100
Growth stage	Root setting		Tiller			Elongation		Heading		Ripening	

combination model was found to be:

$$\text{Classifier}: O(i) = \text{function}[B(j)] \qquad \text{for } i = 1 \text{ to } 5 \text{ and } j = 1 \text{ to } 7 \tag{5}$$

where $O(i)$ is the digital number in the output layer (class) i, and $B(j)$ is the digital number in the input layer (band) j.

As a direct consequence of Eq. (5), the network used has seven input nodes. The number of nodes in the hidden layer is the only factor that must be determined. The architecture of the artificial neural networks (ANNs) model for land cover classification is shown in Fig. 3. The numbers of input and output nodes were determined using a neural network classifier model. The optimal number of nodes in the hidden layer was found to be eighteen nodes. The image data used for training ANNs and testing the classification accuracy was selected from a section (500 × 1000 pixels) of the Landsat-TM scene (Path116/Row34) showing an area of the republic of Korea. The five categories of land-use classified by ANNs were forest, paddy, upland, urban, and water bodies.

Geographic-spatial information, as well as characteristic data for the watershed, were surveyed and tabulated into GIS databases in the form of basic and thematic maps and their attributes. An interface routine was developed in order to use GIS databases as pre-processing input data for model simulations of spatially varying hydrology and the TMDL. Digital maps extracted from the study site include a digital elevation map (DEM), slope

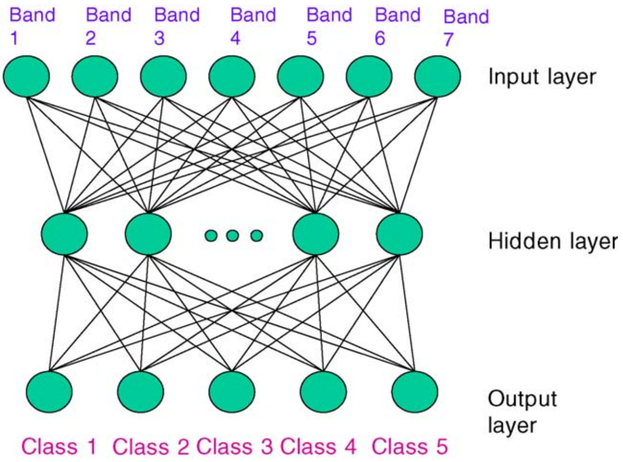

Fig. 3. The architecture of the artificial neural networks (ANNs) model for land cover classification.

distribution map, channel map, sub-watershed boundary map, flow direction map, soil map, and curve number map.

2.2. Model calibration

The parameter values were adjusted after simulation, either manually by the modeler or by using a computerized optimization algorithm, until the 'best fit' parameter set was found. Prediction of other processes that are driven by water runoff, such as erosion and sediment and nutrient transport, depends on the rainfall-runoff models (Beven, 2001; rainfall-runoff modeling).

The calibration tool incorporated in AVSWAT allows the user to perform global changes on input parameters that are commonly modified during the calibration process (Neitsch et al., 2002b). Users can change the value of calibration parameters, run SWAT for the scenario, and then compare the scenario results to those in the original default simulation or those generated by other scenarios.

In this study, the trial-and-error method was adopted for model calibration and the parameter values were varied one at a time to cover all possible combinations of the parameters. Parameter values were adjusted from the initial estimates given in the model within the acceptable ranges shown in Table 3 to achieve the desired proportion.

Model calibration was accomplished by changing the values of the model parameters that were found to have a significant effect on the output of the model. The model then ran the possible combinations of parameters and calculated model performance. This procedure was repeated until optimal parameter values were found. Calibration was performed by comparing the simulated and observed runoff data. After achieving a satisfactory runoff simulation, the same parameters were used for calibration of the sediment and nutrient yield.

Table 3
Acceptable ranges of model parameters (Neitsch et al., 2002a, 2002b)

Item	Parameter	Definition	Range
Watershed parameters	SMFMC	Melt factor for snow on June 21 (mm H_2O/°C-day)	0–10
	SMFMN	Melt factor for snow on Dec. 21 (mm H_2O/°C-day)	0–10
	SPCON	Linear parameter for calculating sediment	0–0.01
	SPEXP	Exponent parameter for calculating sediment	1–1.5
	NPERCO	Nitrate percolation coefficient	0–1
	PRERCP	Phosphorus percolation coefficient (m^3/mg)	10–17.5
	PHOSKD	Phosphorus soil partitioning coefficient (m^3/mg)	100–200
HRU parameter	ESCO	Soil evaporation compensation factor	0–1
Stream parameter	CH_COV	Channel cover factor	0–50
Groundwater parameters	ALPHA_BF	Baseflow alpha factor (days)	0–1
	GWQMN	Threshold depth for water in the shallow aquifer required for return flow to occur (mm H_2O)	0–5000
	GWREVAP	Groundwater ravap coefficient	0.02–0.2
	REVAPMM	Threshold depth for water in the shallow aquifer for ravap to the deep aquifer to occur (mm H_2O)	0–500
Crop parameter	CN	Initial SCS runoff curve number for AMC	30–100
Soil parameter	SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)	0.02–0.2

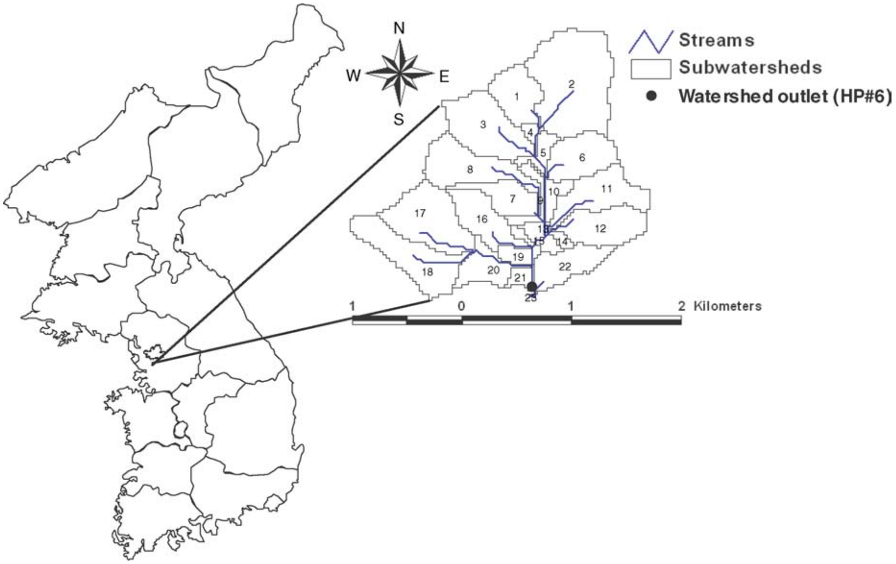

Fig. 4. Location of the monitoring station.

2.3. The study watershed and monitoring

The Baran watershed, 2979 ha in size, is located about 8 km west from Suwon city in Kyunggi province, Korea. Hydrologic and water quality data for the watershed have been collected since 1996 as part of an environmental monitoring and assessment study for the agro-ecological systems (Park, 2000) and used to evaluate the impact of non point source pollutants on the downstream water quality. The watershed monitored by gauging station HP#6 has a drainage area of 384.8 ha and is located in the headwaters of the Baran River, draining into the Namyang sea dike (Fig. 4). The type of land-use in the watershed is mostly forest (51%), followed by urban (20%), paddy (19%), and the remainder consisting of cropland and some water (10%). The geomorphological characteristics of flow length, slope, and shape coefficient of the watershed are 3.088 km, 1.493 m/km, and 1.56, respectively. About 2200 people, about 684 cows, and 38 small-scale industrial units are situated within the watershed. Manure from the livestock was applied to the crop fields.

A monitoring station equipped with two float- and pressure-type water level gauges is located near the channel outlet of watershed HP#6. The measured water levels were converted to stream flow rates using a water level–flow rate relationship regressed from the measured data (Table 4). Stream water was sampled using an automatic water sampler (ISCO 3700) for every rainfall event, in addition to a routine measurement taken once every 2 weeks. Stream water quality data from the project sites were used to estimate daily, monthly, and annual pollutant loadings in the watershed.

Nonpoint source loads were calculated based on the number of animals and the land application amounts of manure and fertilizer. Dry and wet depositions of air-borne pollutant sources were also computed using rainfall quality data collected at the Seoul National University, located 8 km north of the watershed (Park, 2000).

Table 4
Stage–discharge relationships for the HP#6 gauging station

Period	Rating curve	R^2
1996–1998	$Q = 9.2169h^{4.2384}$	0.913
1999–2000	$Q = 13.356h^{3.0625}$	0.979

Q, discharge (m^3/s); h, stage (m)

Test plots of paddy and other land-use types were selected to investigate the crop growth environments and agronomical practices. For paddy test plots, drainage outlet height and ponding depth were measured during crop growth seasons. Paddy fields in Korea are blocked by levees to maintain ponding conditions. Usually, the height of outlet for drainage is managed to be lower than that of the levee. Runoff from paddy fields varies with drainage outlet height and ponding depth. The ponding water depth within paddy field is dependent on outlet height, which is arbitrarily controlled by the farmer according to the growth stages of rice. Thus, the height of the drainage outlet and the ponding depth in the paddy fields varies according to the region and season. To minimize any bias due to these parameters, as many paddy fields were selected as possible. The height of drainage outlet and the ponding depth were monitored in 67 paddy fields, including the seven paddy fields located in subwatershed #22 and 60 paddy fields downstream of the watershed outlet. All the above data were measured on a daily basis during the crop growth seasons for 1996–2000.

The results were used to develop a model to simulate the water balance in the paddy fields. In addition, fertilization data and seasonal variations of nitrogen in the test fields were observed in the plot and study watershed.

3. Results and discussion

3.1. Watershed data

Water samples were collected and analyzed according to the TMDL parameters of SS (suspended solid), TN (total nitrogen), and TP (total phosphorus). A total of 76 water samples were taken covering both rainy and sunny days at the gauging station. The maximum and minimum values were 25.4 and 1.2 mg/L for TN and 1.55 and 0.018 mg/L for TP. The average values of TN and TP were 7.3 and 0.387 mg/L, respectively, both of which are higher than the agricultural water quality standards (1.0 mg/L for TN and 0.1 mg/L for TP). Pollutant loads for each parameter were estimated using pollutant load–discharge relationships regressed from the observed data of pollutant loadings and flow rates during the study period (Table 5). The coefficients of determination, R^2, of the relationships were 0.92, 0.93, and 0.93 for SS, TN, and TP, respectively. The rainfall showed average values of TN and TP of 0.952 and 0.036 mg/L with standard deviations of 0.6 and 0.001 mg/L, respectively. The averages and the standard deviations of the groundwater qualities were 1.85 and 1.92 mg/L for TN and 0.021 and 0.014 mg/L for TP.

The application rates of chemical fertilizer to the test paddy were 235 kg/ha for TN and 63 kg/ha for TP. While a greater amount of TN was applied than the standard fertilizer

Table 5
Load–discharge relationships at the gauging station

Item	Load-discharge Relationship	R^2
SS	$L = 0.0001Q^{1.5573}$	0.916
TN	$L = 0.0260Q^{0.8383}$	0.927
TP	$L = 0.0007Q^{0.9212}$	0.933

Q, discharge (m^3/day); L, load (kg/day).

application rate of 100 kg/ha, the TP application rate was similar to the recommended rate of 70 kg/ha. The standard fertilizer application (100 kg/ha) is the nationwide standard advocated by the government. In reality, the amount of applied fertilizer varies by region, and is applied by each farmer arbitrarily. In this study, the actual value monitored in the paddy field was used. Drain outlet height and ponding depth measured at the 67 paddy fields varied much more in the beginning of the irrigation period (June) than later in the season (Table 6).

3.2. Model calibration and validation

The model was calibrated using the observed data from 1996 through 1997 and validated using the data from 1999 through 2000 in terms of runoff, SS, TN, and TP on a daily basis.

The model parameters were determined based on the minimum statistics of RMSE (root mean square error) and RMAE (root mean absolute error). The statistical measures of relative bias (RB), RMSE, RMAE, the Nash–Sutcliffe efficiency index (EI) (Nash and Sutcliffe, 1970) and the coefficient of determination (R^2) were used to evaluate the model simulations (Kang, 2002; Kang and Park, 2003). RB measures any systematic error between the predictions and the observations. RMSE and RMAE measure both systematic and random errors. R^2 is the ratio of the mean square error of the predictions to the total mean square error of the observations. While lower values of R^2 and EI (i.e. those close to zero) mean a poorer model prediction, values closer to 1.0 represent a more accurate prediction (Santhi et al., 2001). Ramanarayanan et al. (1997) suggested that model

Table 6
Inundation and ponding depths for the 67 paddy fields during the irrigation period from 1996 to 2000

Date	Drain outlet height		Ponding depth	
	Mean	Standard deviation	Mean	Standard deviation
The first 10 days of June	80.9	42.8	71.5	38.8
The middle 10 days of June	74.0	24.3	63.2	22.2
The last 10 days of June	57.3	35.3	40.9	27.1
The first 10 days of July	34.6	33.2	14.1	21.8
The middle 10 days of July	72.9	35.1	47.5	33.5
The last 10 days of July	67.2	31.6	49.8	32.0
The first 10 days of August	57.7	24.5	54.3	31.2
The middle 10 days of August	63.4	25.5	48.4	28.6
The last 10 days of August	67.2	33.1	66.3	35.0

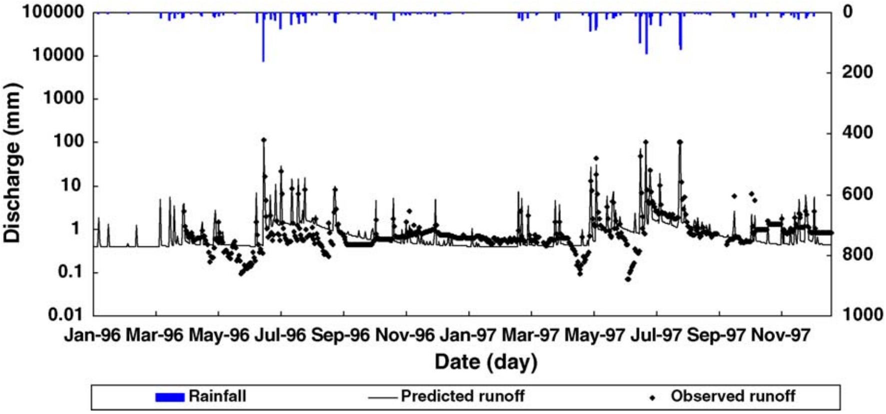

Fig. 5. Comparison of the observed and the simulated runoff for the calibration period.

predictions with the R^2 and EI values greater than 0.6 and 0.5, respectively are acceptable or satisfactory. Although R^2 is a widely used measure of prediction accuracy, care must be taken if an appreciable bias is present, since R^2 evaluates the accuracy of prediction with respect to random error only (Maidment, 1993). For this reason, the prediction accuracy was assessed using a combination of RB, RMSE, RMAE, and EI.

Figs. 5 and 6 compare the observed stream flows with the simulations for the data periods used for the calibration and validation, respectively. The statistics of RB, RMSE, RMAE, EI and R^2 were 0.01%, 2.29 mm/day, 0.40 mm/day, 0.93, and 0.93 for the calibration period and 8.68%, 6.21 and 0.51 mm/day, 0.87, and 0.87 for the validation period, respectively (Table 7). The simulation results showed good agreement with the observed data.

Table 8 notes the comparison of the observed and simulated SS, TN and TP for the study periods. The model was calibrated up to the R^2 values of 0.77, 0.84, and 0.81 and the

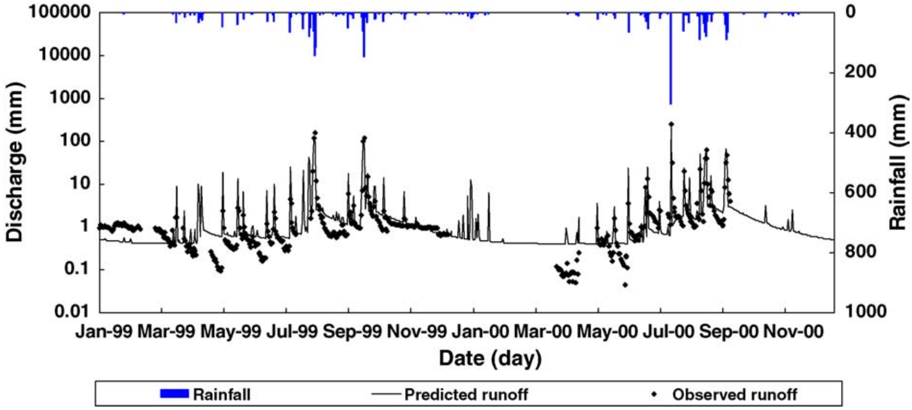

Fig. 6. Comparison of the observed and the simulated runoff for the validation period.

Table 7
Summary of calibration and validation results for daily runoff at the study site

Item	Period	No. of measure (day)	Rainfall (mm)	Runoff (mm)		Ratio of runoff to rainfall		RB (%)	RMSE (mm/day)	RMAE (mm/day)	EI	R^2
				Obs.	Sim.	Obs.	Sim.					
Calibration	1996	274	738	376	425	0.510	0.575	0.01	2.29	0.40	0.93	0.93
	1997	350	1204	863	815	0.717	0.677					
	Subtotal	624	1942	1239	1239	0.638	0.638					
Validation	1999	299	1235	846	943	0.685	0.764	8.68	6.21	0.50	0.87	0.87
	2000	150	1249	784	828	0.628	0.663					
	Subtotal	449	2484	1630	1771	0.656	0.713					

Table 8
Summary of calibration and validation results for daily SS, TN, and TP at the study site

Item	Period	Total period (kg/ha/yr)	Measured period (kg/ha)		RB (%)	RMSE (kg/ha/day)	RMAE (kg/ha/day)	EI	R^2
		Sim.	Obs.	Sim.					
SS									
Calibration	1996	362.12	217.93	330.70					
	1997	753.67	578.56	753.24	39.09	6.37	0.74	0.70	0.77
	Subtotal	1115.79	796.49	1083.94					
Validation	1999	1024.84	802.39	875.18					
	2000	1099.09	829.78	1020.19	16.13	10.08	0.59	0.89	0.89
	Subtotal	2122.93	1632.17	1895.37					
TN									
Calibration	1996	12.76	19.99	11.13					
	1997	24.23	40.32	24.19	41.45	0.15	0.69	0.73	0.84
	Subtotal	36.99	60.31	35.32					
Validation	1999	29.62	36.39	24.38					
	2000	30.34	30.95	27.11	23.54	0.30	0.66	0.65	0.85
	Subtotal	59.97	67.34	51.49					
TP									
Calibration	1996	1.61	1.22	1.38					
	1997	2.77	2.62	2.74	5.69	0.02	0.62	0.42	0.81
	Subtotal	4.38	3.84	4.12					
Validation	1999	3.49	2.45	3.00					
	2000	3.58	2.19	2.84	25.30	0.04	0.67	0.19	0.85
	Subtotal	7.07	4.64	5.84					

RMSEs of 6.37, 0.15, and 0.02 kg/ha/day for SS, TN, and TP, respectively. The model validation resulted in the R^2 values of 0.89, 0.85, and 0.85 and the RMSEs of 10.08, 0.30, and 0.04 kg/ha/day for SS, TN, and TP, respectively, which reasonably well agreed with the observations.

4. TMDL program

4.1. Water body assessment

The water body assessment module defines water quality goals, assesses current water quality and decides the necessity for reduction plans to help achieve a satisfactory TMDL. A water body assessment for the TMDL program was performed using TOLOS in order to estimate the annual pollutant loadings at the project site. The predicted annual pollutant

Table 9
Predicted annual runoff and pollutant loadings during the project period

Year	Rainfall (mm)	Runoff (mm)	Annual pollutant loadings (kg/ha)			Flow-weighted concentrations (mg/l)		
			SS	TN	TP	SS	TN	TP
1996	880	493	362.12	12.76	1.61	73.41	2.59	0.33
1997	1204	824	753.67	24.23	2.77	91.45	2.94	0.33
1999	1512	1104	1024.84	29.62	3.49	92.82	2.68	0.32
2000	1363	1031	1099.09	30.34	3.58	106.56	2.94	0.35
Average	1240	863.22	809.93	24.24	2.86	91.06	2.79	0.33

loadings are summarized in Table 9. The predicted annual average concentrations of SS, TN, and TP ranged from 73 to 107 mg/L, 2.68 to 2.94 mg/L, and 0.32 to 0.35 mg/L, respectively. Note that the predicted TN and TP concentrations were higher than the agricultural water quality standards (1 mg/L for TN and 0.1 mg/L for TP) in Korea. Therefore, appropriate pollutant reduction plans are necessary in order for this watershed to achieve its water quality goals. The necessity of reduction plans justifies the need for the TOLOS model to help achieve a satisfactory TMDL.

Table 10
Land use patterns for the 23 sub-watersheds of the HP#6 watershed

Subwatershed		Land-use (%)				
Number	Area (ha)	Forest	Paddy	Upland	Residual	Water
1	18.7	58.7	0.5	7.2	32.7	1.0
2	60.6	57.1	18.9	4.3	19.3	0.5
3	32.9	52.9	21.1	8.5	17.5	0.0
4	2.7	3.3	13.3	0.0	83.3	0.0
5	6.1	27.9	30.9	5.9	35.3	0.0
6	21.6	64.6	20.4	5.8	9.2	0.0
7	14.5	10.6	10.6	18.6	60.3	0.0
8	28.8	64.1	3.8	9.1	23.1	0.0
9	5.7	4.8	36.5	14.3	44.4	0.0
10	6.6	62.5	8.3	8.3	20.8	0.0
11	24.8	54.9	22.9	15.3	6.9	0.0
12	23.0	57.8	39.8	1.2	1.2	0.0
13	0.5	0.0	60.0	40.0	0.0	0.0
14	2.0	27.3	63.6	4.6	4.6	0.0
15	5.8	12.5	71.9	4.7	10.9	0.0
16	20.1	37.7	23.3	10.3	28.7	0.0
17	34.0	63.5	2.4	15.6	17.2	1.3
18	32.5	67.0	7.8	11.9	13.3	0.0
19	7.3	29.6	40.7	3.7	25.9	0.0
20	14.3	21.4	19.5	20.1	39.0	0.0
21	4.1	6.7	55.6	11.1	26.7	0.0
22	18.3	46.8	31.0	10.3	11.8	0.0
23	0.3	50.0	0.0	0.0	50.0	0.0
Sum	384.8	51.1	18.8	9.4	20.5	0.2

Table 11
Predicted annual pollutant loadings, water quality targets and reduction rates of SS from the sub-watersheds

Subwatershed number	Annual pollutant loadings (kg)				Water quality targets (kg)				Allocation rates of load reductions (kg)			
	1996	1997	1999	2000	1996	1997	1999	2000	1996	1997	1999	2000
1	8460	16767	23141	25643	8284	14420	19738	18101	176	2347	3403	7542
2	31128	64064	94317	106896	25591	45132	64289	60330	5537	18931	30028	46566
3	10772	24463	31673	31235	16629	27559	36697	35055	0	0	0	0
4	888	1654	1861	1865	1274	2168	2804	2453	0	0	0	0
5	1083	2464	2963	2833	2713	4867	6475	6026	0	0	0	0
6	11252	24444	34391	37105	9209	16538	23070	21923	2043	7906	11321	15182
7	7186	13442	15188	15313	6843	11617	15038	13148	343	1825	150	2165
8	631	1028	1272	1147	18324	27360	35243	32513	0	0	0	0
9	187	418	460	356	2648	4679	6092	5670	0	0	0	0
10	1649	3322	4764	5294	2852	4995	6920	6378	0	0	0	0
11	14551	32192	44851	47392	10598	19038	26468	25214	3953	13154	18383	22178
12	13154	29760	40923	42090	9917	17867	24661	23632	3237	11893	16261	18458
13	333	656	874	973	205	370	480	460	129	285	394	513
14	174	467	594	568	854	1595	2131	2071	0	0	0	0
15	28	263	220	22	2542	4809	6290	6187	0	0	0	0
16	11077	23355	28723	28436	9667	16418	21830	20377	1410	6937	6894	8059
17	542	976	1332	1389	21421	32153	40834	37715	0	0	0	0
18	452	834	1175	1229	20470	30394	38410	35374	0	0	0	0
19	517	1259	1496	1347	3228	5827	7795	7312	0	0	0	0
20	21077	38289	50631	57667	6795	11516	15288	13744	14283	26773	35343	43923
21	36	104	110	44	1892	3393	4445	4239	0	0	0	0
22	4164	9787	13395	14083	7777	14225	19603	18746	0	0	0	0
23	3	5	6	3	120	209	281	253	0	0	0	0
Sum	139344	290012	394359	422930	189851	317148	424883	396920	31110	90052	122177	164586

Table 12
Predicted annual pollutant loadings, water quality targets and reduction rates of TN from the sub-watersheds

Subwatershed Number	Annual pollutant loadings (kg)				Water quality targets (kg)				Allocation rates of load reductions (kg)			
	1996	1997	1999	2000	1996	1997	1999	2000	1996	1997	1999	2000
1	283.0	518.7	671.4	717.1	82.8	144.2	197.4	181.0	200.2	374.6	474.0	536.1
2	868.5	1663.2	2276.2	2508.0	255.9	451.3	642.9	603.3	612.6	1211.9	1633.3	1904.7
3	385.1	769.9	895.2	857.7	166.3	275.6	367.0	350.5	218.8	494.3	528.2	507.2
4	45.9	81.3	103.6	100.8	12.7	21.7	28.0	24.5	33.2	59.6	75.5	76.3
5	60.3	123.1	142.3	133.0	27.1	48.7	64.8	60.3	33.1	74.4	77.5	72.7
6	302.4	641.9	827.4	858.1	92.1	165.4	230.7	219.2	210.3	476.5	596.7	638.9
7	294.7	540.5	681.5	675.4	68.4	116.2	150.4	131.5	226.3	424.4	531.1	543.9
8	213.3	290.9	338.7	355.8	183.2	273.6	352.4	325.1	30.1	17.3	0.0	30.7
9	36.8	72.0	79.6	72.0	26.5	46.8	60.9	56.7	10.3	25.3	18.6	15.3
10	68.1	121.8	158.8	169.0	28.5	49.9	69.2	63.8	39.6	71.9	89.6	105.3
11	362.4	800.8	1023.3	1036.4	106.0	190.4	264.7	252.1	256.4	610.4	758.6	784.2
12	319.8	737.7	923.6	903.7	99.2	178.7	246.6	236.3	220.7	559.0	677.0	667.3
13	13.3	24.9	28.7	30.1	2.0	3.7	4.8	4.6	11.3	21.2	23.9	25.5
14	12.2	29.3	30.5	28.1	8.5	15.9	21.3	20.7	3.7	13.3	9.2	7.3
15	25.1	67.8	59.1	48.6	25.4	48.1	62.9	61.9	0.0	19.7	0.0	0.0
16	359.0	726.5	877.9	848.1	96.7	164.2	218.3	203.8	262.4	562.3	659.6	644.3
17	208.7	291.7	309.5	323.7	214.2	321.5	408.3	377.1	0.0	0.0	0.0	0.0
18	165.3	240.7	251.1	266.5	204.7	303.9	384.1	353.7	0.0	0.0	0.0	0.0
19	49.5	103.5	113.5	104.3	32.3	58.3	78.0	73.1	17.3	45.2	35.6	31.2
20	649.0	1065.9	1128.2	1166.2	67.9	115.2	152.9	137.4	581.1	950.7	975.3	1028.7
21	22.0	47.1	46.3	41.0	18.9	33.9	44.5	42.4	3.1	13.1	1.9	0.0
22	163.1	362.3	428.7	427.3	77.8	142.2	196.0	187.5	85.3	220.0	232.6	239.8
23	1.9	2.8	3.2	3.0	1.2	2.1	2.8	2.5	0.7	0.7	0.4	0.5
Sum	4909.7	9324.2	11398.2	11673.8	1898.5	3171.5	4248.8	3969.2	3056.4	6245.7	7398.7	7860.0

4.1.1. *Water quality goal*

According to the USEPA's guidelines, TMDL is defined as the sum of allowable loads from point as well as non-point sources to water bodies (USEPA, 1999; Novotny and Olem, 1994). In this study, the TMDL was estimated based on the water quality goals, which are the agricultural water quality standards (100 mg/L for SS, 1.0 mg/L for TN, and 0.1 mg/L for TP) in Korea.

The water quality goal was applied to each of the 23 sub-watersheds that contribute to the main stream. Table 10 summarizes the areas and the land-use patterns of the 23 sub-watersheds of the HP#6 watershed, which range from 0.3 to 60.6 ha in size. Sub-watershed #2, located in the upper stream, is the largest (60.6 ha) and sub-watershed #23, at the watershed outlet, is the smallest (0.3 ha).

The TMDLs for each sub-watershed were determined by multiplying the water quality standards by the runoff volume (Tables 11–13). The TMDLs for SS, TN, and TP ranged from 120 to 60,330 kg, 1.2 to 642.9 kg, and 0.1 to 64.3 kg, respectively. Sub-watershed #2 and sub-watershed #23 produced the greatest and the smallest TMDLs, respectively, probably because their areas and stream runoff rates are the largest and the smallest of the sub-watersheds.

Table 13
Predicted annual pollutant loadings, water quality targets and reduction rates of TP from the sub-watersheds

Subwatershed number	Annual pollutant loadings (kg)				Water quality targets (kg)				Allocation rates of load reductions (kg)			
	1996	1997	1999	2000	1996	1997	1999	2000	1996	1997	1999	2000
1	49.8	83.3	104.1	110.4	8.3	14.4	19.7	18.1	41.5	68.9	84.4	92.3
2	83.5	136.2	194.3	214.2	25.6	45.1	64.3	60.3	57.9	91.1	130.0	153.9
3	34.2	64.3	78.8	71.6	16.6	27.6	36.7	35.1	17.5	36.8	42.1	36.6
4	12.7	22.3	27.9	29.2	1.3	2.2	2.8	2.5	11.4	20.2	25.1	26.7
5	10.8	18.7	23.0	22.8	2.7	4.9	6.5	6.0	8.1	13.8	16.6	16.8
6	29.2	54.1	72.3	73.6	9.2	16.5	23.1	21.9	20.0	37.5	49.2	51.6
7	93.7	169.2	209.6	219.3	6.8	11.6	15.0	13.1	86.8	157.6	194.5	206.2
8	20.3	21.5	29.1	31.4	18.3	27.4	35.2	32.5	2.0	0.0	0.0	0.0
9	5.5	8.0	10.8	10.6	2.6	4.7	6.1	5.7	2.9	3.3	4.7	4.9
10	8.7	13.2	17.9	19.0	2.9	5.0	6.9	6.4	5.9	8.2	11.0	12.6
11	34.8	68.7	90.3	89.1	10.6	19.0	26.5	25.2	24.2	49.7	63.9	63.9
12	31.1	64.5	82.8	78.1	9.9	17.9	24.7	23.6	21.2	46.6	58.2	54.5
13	0.9	1.4	1.8	1.9	0.2	0.4	0.5	0.5	0.7	1.1	1.3	1.4
14	1.4	2.3	2.8	2.5	0.9	1.6	2.1	2.1	0.6	0.7	0.7	0.5
15	3.3	4.9	5.6	4.6	2.5	4.8	6.3	6.2	0.8	0.1	0.0	0.0
16	80.4	151.6	186.1	188.6	9.7	16.4	21.8	20.4	70.7	135.2	164.3	168.2
17	20.2	20.7	26.7	27.2	21.4	32.2	40.8	37.7	0.0	0.0	0.0	0.0
18	19.2	19.5	25.3	25.8	20.5	30.4	38.4	35.4	0.0	0.0	0.0	0.0
19	8.2	13.1	16.6	16.3	3.2	5.8	7.8	7.3	5.0	7.3	8.8	8.9
20	51.2	82.0	93.7	98.4	6.8	11.5	15.3	13.7	44.4	70.4	78.4	84.6
21	2.7	3.4	4.6	4.3	1.9	3.4	4.4	4.2	0.8	0.0	0.2	0.0
22	17.2	29.9	38.4	37.3	7.8	14.2	19.6	18.7	9.4	15.7	18.8	18.6
23	0.2	0.2	0.3	0.3	0.1	0.2	0.3	0.3	0.1	0.0	0.0	0.0
Sum	619.1	1053.1	1342.8	1376.3	189.9	317.1	424.9	396.9	431.7	764.1	952.0	1002.1

4.1.2. Allocations of load reductions for TMDL program

The amounts of annual pollutant loadings over TMDLs must be reduced to achieve the target water quality. The required load reductions were allocated to the 23 sub-watersheds in proportion to the pollutant loads of each sub-watershed.

Tables 11–13 present the predicted annual pollutant loadings, water quality targets, and the load reduction requirements for each sub-watershed. Predicted annual pollutant loadings of SS, TN, and TP ranged from 3 to 106,896, 1.9 to 2276, and 0.2 to 214 kg, respectively. The per unit area values ranged from 0.01 to 277.80, 0.01 to 6.52, and 0.001 to 0.57 kg/ha, respectively. Sub-watershed #2 showed the greatest annual pollutant loading levels. This is because sub-watershed #2 is not only the greatest in size, but also the most concentrated in terms of residences and other community activities.

As shown in Tables 11–13, most of the sub-watersheds failed to meet TMDL goals for both TN and TP. The annual average requirements of load reduction of SS, TN, and TP during the study periods were 101,981, 6140, and 789 kg, respectively. However, sub-watersheds #16 and #17 did satisfy the TMDLs for all water quality items. As expected, the urbanized sub-watershed #2 has the greatest load reduction requirement.

5. Conclusions

A TOLOS system based on AVSWAT was used to evaluate and develop TMDL for the study watershed in the republic of Korea, which is 385 ha in size and contains rice paddies. A component to simulate the water balance in irrigated paddy fields was incorporated into the SWAT model.

The model was calibrated and validated on a daily basis using the observed water quality data for the periods (1996–1997 and 1999–2000). Calibration and validation resulted in R^2 values of 0.77–0.93, and positive EI values for all the water quality parameters. The simulated runoff and water quality values also agreed well with the observed data.

The TMDLs for each sub-watershed were determined by multiplying the water quality standards by the runoff volume. Sub-watershed #2 and sub-watershed #23 exhibited the greatest and the smallest TMDLs, respectively, largely because the area and stream runoff rate of sub-watershed #2 is the largest of those studied.

The pollutant load reduction requirements were determined according to the amounts of annual pollutant loadings in excess of the TMDLs and allocated to each sub-watershed based on its pollutant loads. Sub-watershed #2, which is the most and urbanized, showed the greatest annual pollutant loading. Most of the sub-watersheds failed to meet the TMDL goals for both TN and TP. Only two sub-watersheds, #16 and #17, satisfied the TMDLs for all water quality items. The urbanized sub-watershed #2 has the greatest load reduction requirement.

The assessment method used for this study was able to identify TMDLs quantitatively as well as qualitatively for various sources of pollution that are spatially dispersed. The significance of this study is that it provides an assessment of the impact of Best Management Practices (BMPs) on the water bodies studied, allowing the TMDL program to be complemented more effectively. In conclusion, the TOLOS system based on

AVSWAT can be a useful tool for developing and evaluating TMDL for small watersheds containing rice paddies in the Republic of Korea.

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