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DETERMINING THE EFFECTIVE WIDTH OF RIPARIAN BUFFERS IN KOREAN WATERSHEDS USING THE SWAT MODEL

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Abstract

Riparian buffers play an important role in improving water quality, providing wildlife habitat, and reducing suspended sediments and pollutants entering the water body. The efficiency of pollutant reduction by a riparian buffer is greatly influenced by the width of the riparian buffer. In this study, the Soil and Water Assessment Tool (SWAT) model was applied to the Yudeung Stream watershed, Daejeon Stream watershed, and Gap Stream watershed to determine the most effective width of the riparian buffer. These three largest streams in the Daejeon metropolitan area in South Korea were selected to evaluate the effects on nutrient reduction of various riparian buffer widths ranging from 15 to 1,000 m. The decision criterion for the optimum size of the riparian buffer was a 10% reduction in nutrient load based on the water pollution management plan for Daejeon. Total nitrogen and total phosphorus were reduced by 10% with an 80m deciduous riparian buffer and a 70-m evergreen riparian buffer in the Yudeung Stream watershed. Also, this diminishing was also done with a 70m deciduous and 60m evergreen buffer in the Daejeon Stream watershed, and by 9.8% and 16.3% with a 300m deciduous buffer in the Gap Stream watershed, while a 100m evergreen buffer was needed for 10% reduction. Thus, the effects of riparian buffers on flow and nutrient reduction depend on the type of trees and the width of the buffer, as well as the location of the urban area and land uses in the watershed. These results may be useful in developing economical watershed-specific riparian buffer management practices.

Key words: riparian buffer, South Korea, SWAT, total nitrogen, total phosphorus

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Water quality degradation due to nonpoint source pollutants has become a global challenge. Vegetated riparian buffers are widely acknowledged as a best management practice (BMP) that can reduce sediment and nutrients entering water bodies (Dwire and Lowrance, 2006; Jobin et al., 2004). Riparian buffers remove nitrates through denitrification and assimilation by plants, and can also remove considerable amounts of sediments, phosphorus, and pesticides through filtering, microbial breakdown, and absorption by plants (Cooper et al., 1987). In addition, riparian buffers protect stream banks from

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erosion and provide habitat within aquatic-terrestrial ecotones. Many studies have been conducted on the effects of riparian buffers on the environmental and ecological systems in receiving water bodies. Palfrey and Bradley (1982) suggested that the most appropriate width for buffers (natural vegetation) in coastal areas of Maryland was 91 m, and Roman and Good (1983) suggested a 91-m buffer width for preserving wetlands and waterways based on the regional characteristics of pinelands in New Jersey. Xiang (1993) modified and supplemented the detention-time model of riparian buffers developed by Phillips (1989) and suggested that effective and efficient decision-making can be achieved through the use of a Geographic Information System (GIS) to calculate the appropriate width of a buffer. As an example, an analysis conducted by the Illinois State Natural History Survey (Cooper et al., 1987) suggested that the effectiveness of buffers increased up to 300 m wide. Research in the Chesapeake Bay watershed in Maryland, USA (Lowrence et al., 1995) determined that a 30-m riparian green belt was needed to remove nitrogen and that 50 m was needed to remove sediment and phosphorus. Although various riparian buffer widths have been suggested for pollutant reduction based on local conditions, it is difficult to quantify an optimum buffer width based on these studies. However, 5–47 m for nutrients, 15–53 m for flowing water, 27–95 m for colon bacillus, and 5–110 m for sediment have been suggested (Choi and Lee, 2001).

Riparian buffers have been preserved in many countries for their positive aspects. Castelle et al. (1994) suggested that riparian buffer width should be determined based on neighboring land use, streams, surface cover crops, topography, and hydrology. According to Castelle et al. (1994), water quality cannot be improved by only widening riparian buffers along streams. Fischer et al. (2000) suggested that riparian buffers should be large enough to act as a forested habitat to provide ecological benefits. Dosskey et al. (2011) developed a method for determining the optimum buffer location based on the Digital Elevation Model (DEM) and Soil Survey Geographic Database. Qiu and Dosskey (2012) also suggested that a conservative riparian buffer could be a cost-effective approach to restoring ecosystems in riparian areas. Recognizing the important roles of riparian buffers, the Korean government has designated riparian buffers as an important management practice to improve water quality, repair impaired streams, and restore multiple ecosystem functions (Ministry of Environment of Korea, 2002).

However, despite the importance of riparian buffers, they have been removed or damaged by man-made developments such as cities, roads, and recreational facilities in South Korea. In Korea, there have been very few studies on the effective width of riparian vegetated buffers. Kim (2000) examined the effectiveness of vegetated buffers on water quality along the Neungwoncheon River, a tributary of the Kyeongancheon River, using the Agricultural Nonpoint Source Pollution Model to find an appropriate width, and concluded that 60 m was most effective. Previous studies (Hong, 2000; Kim, 2001; Lowrence et al., 1995; Philips, 1989) have suggested that factors such as land use, condition of the vegetation, ground cover, slope, soil, and regional characteristics also need to be considered when determining the appropriate riparian buffer width.

It is very difficult to consider all of the above factors in a model; however, selection of an appropriate model can be helpful in evaluating the effects of riparian buffers under specific conditions. Generally, small-scale models such as the Agricultural Policy/Environmental eXtender or Water Erosion Prediction Project represent the natural processes of vegetative BMPs in detail using mathematical equations based on validated experiments. In contrast, large watershed models such as the Soil and Water Assessment Tool (SWAT) or empirically based models such as the Universal Soil Loss Equation aggregate many detailed properties and ignore minor processes.

However, these models can still be appropriate for evaluating riparian buffers. They are useful in providing an overview and conducting impact analyses of riparian buffers and BMPs for planning purposes without excessive time and labor. In recent years, the SWAT model has frequently been used to estimate the impacts of riparian buffers or filter strips (Bracmort et al., 2004; Bracmort et al., 2005; Chu et al., 2006; Lee et al., 2010; Parajuli et al., 2008). Ryu et al. (2011) enhanced SWAT with the Riparian Ecosystem Management Model (SWAT-REMM) to evaluate the effects of various riparian scenarios on water quality improvements in the watershed.

Local conditions in riparian areas may be critical in determining the most effective riparian buffer width. The efficiency of the riparian buffer is greatly influenced by its width. Smaller widths may not protect water quality, soil integrity, or ecological systems as planned. Sediment- and nutrient-laden high-volume flow caused by intensive precipitation, which occurs often during the summer in Korea, may not have sufficient opportunity for settling or filtration by vegetation if the riparian buffer is not wide enough.

Thus, it is necessary to determine the effective width of a riparian buffer vs. its ability to improve water quality, although land acquisition costs are high in these areas of South Korea.

Therefore, the objectives of this study were to:

(1) model various widths of riparian buffers with different types of trees in three watersheds using SWAT;

(2) assess the removal efficiency of nutrients against a performance criterion of 10% reduction of the total pollutant load;

(3) suggest an appropriate size for the riparian buffer in these watersheds based on water quality standards for the study watershed in Korea.

2. Experimental

2.1. Study area

The study area is shown in Fig. 1. The Hoeduck watershed is located within Daejeon Metropolitan City in Korea and is in the northern area of Keumsan gun in Chungcheongnam-do province, with a population of 1.3 million. The Hoeduck watershed, with a total area of 64,903 ha, includes the Yudeung Stream watershed (16,046 ha), the Daejeon Stream watershed (6,144 ha), and the Gap Stream watershed (42,713 ha). General weather data for this area was obtained from the Daejeon weather station, located at 127°22'28" N and 36°22'09" E at an elevation of 68.3 m above mean sea level. The dominant soil in this area is the Songsan soil series (South Korean soil classification), which is a group of lithosols commonly distributed in mountainous areas. Lithosols consist chiefly of unweathered or partly weathered rock fragments, thus their erosivity is relatively low due to higher permeability.

These three watersheds are characterized by distinct land uses: agriculture is dominant in the Yudeung Stream watershed, urban in the Daejeon Stream watershed, and mixed land use with both agriculture and urban areas in the Gap Stream watershed. While pollutant loads from farmland are known to be primary sources of excessive nutrients, urban areas in Korea have also been recognized as high nutrient loading areas. Thus, these three watersheds were selected for this study to assess the effects of various riparian buffer widths planted along streams. Forests account for over 70% of the area in the Yudeung Stream watershed and the slope of watershed is steep at 17.4%. There are more agricultural lands than in the other watersheds. This area has a large potential to generate non-point source pollution. Forests account for over 60% of the Daejeon Stream watershed and the slope of watershed is also steep. There are many impermeable areas in the watershed and thus, it also has a large potential to generate non-point source pollution. Almost 60% of the Gap Stream watershed is forests and the slope of the watershed is also steep at 15.1%. Urban areas and croplands are relatively well mixed in this watershed. Urban areas are located downstream of Gap Stream and the sewage system is very well established with combined and separated waste/storm water systems throughout the entire city.

2.2. SWAT model

The SWAT model (Arnold et al., 2007) is a watershed scale, long-term, continuous, semi-distributed model for hydrology and water quality. This model can be used to estimate long-term effects on water resources, sediment discharge, and nonpoint pollution source loads associated with various BMPs. The SWAT model can also predict long-term flow and nonpoint source loads by simulating hydrologic processes using input data with various spatial and temporal scales. SWAT divides a watershed into several subwatersheds, and then each subwatershed is further divided into hydrologic response units (HRUs) based on different combinations of soil, slope, and land use. Within each HRU, simulated water and pollutants are directly applied to the assigned stream segments for routing calculations.

The SWAT model is appropriate for accomplishing the objectives of this study, which were to evaluate impacts of riparian buffer width on hydrology and water quality. Thus, the SWAT model was selected to evaluate the hydrology and water quality of HRUs and riparian buffers spatially and temporarily in the study watershed.

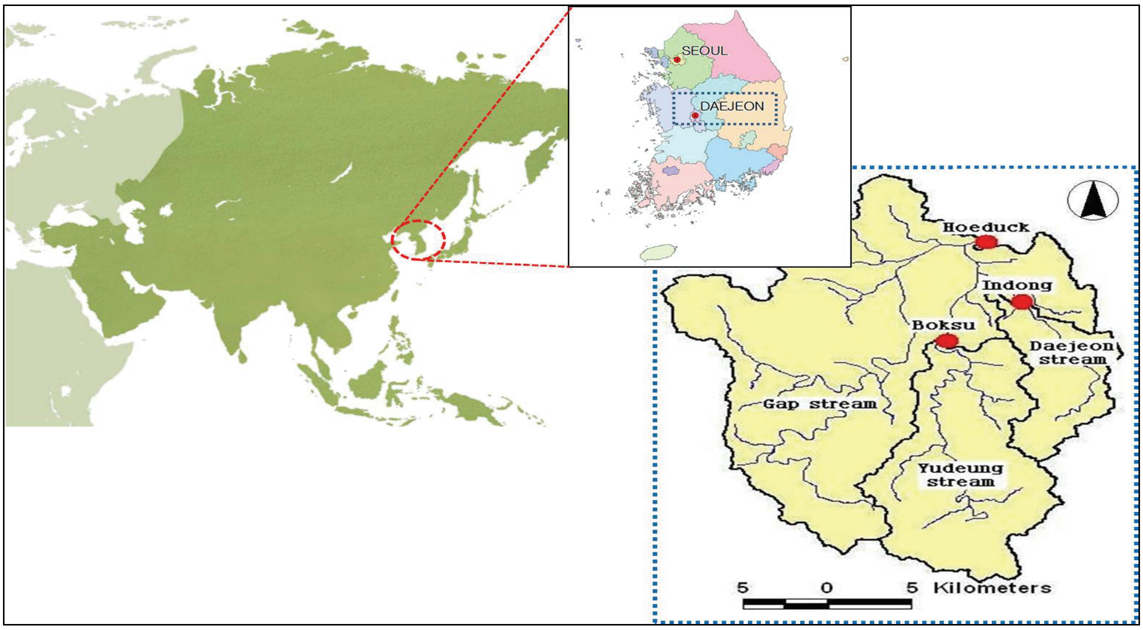


Fig. 1. Location of the Hoeduck watershed, Korea

Table 1. Land use in the Yudeung, Daejeon, and Gap Stream watersheds

Land use	*Yudeung sub-watershed*	*Daejeon sub-watershed*	*Gap sub-watershed*	*Hoeduck watershed*[a]
Urban	4.40	13.72	17.45	18.51
Rangeland	1.22	1.83	3.62	3.73
Water	0.61	0.53	1.16	1.16
Wetland	0.28	0.89	0.43	0.56
Forest – deciduous	28.73	25.75	16.05	20.10
Forest – evergreen	24.04	23.19	21.81	24.00
Forest – mixed	21.45	19.03	23.91	15.15
Hay	0.45	0.13	0.19	0.20
Cropland	10.93	6.98	6.85	7.07
Rice	7.73	3.43	8.04	8.52
Orchard	0.16	4.48	1.44	1.47

[a] *The Hoeduck watershed includes all three watersheds*

The effects of flow in sheet flow form were not simulated; in Korea, most flow and pollutants generated near riparian buffers do not flow into riparian buffers in sheet flow form due to the well-developed drainage system, which is very common in steep watersheds.

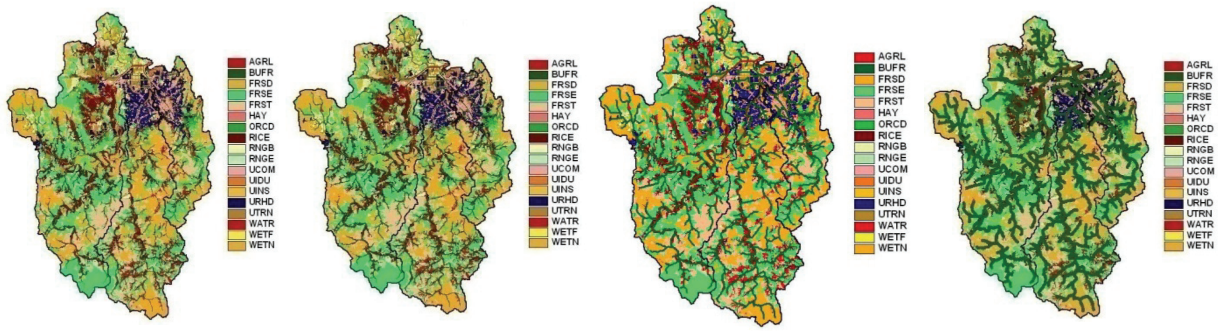
2.3 Simulation of riparian buffers

We did not use the buffer parameter (FILTERW), defined as the width of a vegetative filter strip at the edge of a field, for evaluating riparian buffers in SWAT. Instead, buffers of increasing width were created along streams by replacing the existing land uses with two types of forested areas. Riparian buffers were simulated as forests as suggested by Fischer et al. (2000), and deciduous and evergreen trees were used as buffers to analyze their effect on nutrient reduction. The effects of various widths of riparian buffers were then estimated using the SWAT model for each watershed.

In Korea, riparian buffers have been established along the streams in many watersheds to improve water quality. For example, the Korean government has designated buffers of 500–1,000 m width along four major streams as “riparian buffer areas” to secure ecological and hydrological function. However, flow and pollutants from upland areas flow into the main streams as concentrated flow rather than as sheet flow due to well-developed drainage systems designed to prevent potential flooding during the summer. Thus, land use conversion in riparian buffer areas from current land uses to deciduous/evergreen trees was simulated to evaluate the effects of riparian buffers on flow and nutrient reductions. Using a GIS, the land use data for the riparian buffer areas were replaced with either deciduous or evergreen trees to represent riparian buffers with various widths of 15, 30, 50, 100, 200, 300, 500, and 1,000 m on both sides of the stream (Fig. 2). Overall, we simulated two types of trees and eight buffer widths in three watersheds having various land use compositions and locations of urban areas. Flow, T-N, and T-P reductions were analyzed for the various tree types and buffer widths and the optimum width of the buffer was identified to reach a 10% nutrient reduction goal set by the local government.

2.4. GIS input data

DEM data for the Hoeduck watershed with a resolution of 30 m was obtained from the Korean Ministry of Environment (2002), as was an enhanced land use map (Fig. 3). A soil map (1:25,000) was obtained from the National Academy of Agricultural Science of the Rural Development Administration in Korea, and we used the Korea Institute of Construction Technology SWAT soil database.



(a) Buffer width 30 m (b) Buffer width 50 m (c) Buffer width 100 m (d) Buffer width 200 m

Fig. 2. Depiction of riparian buffers by width

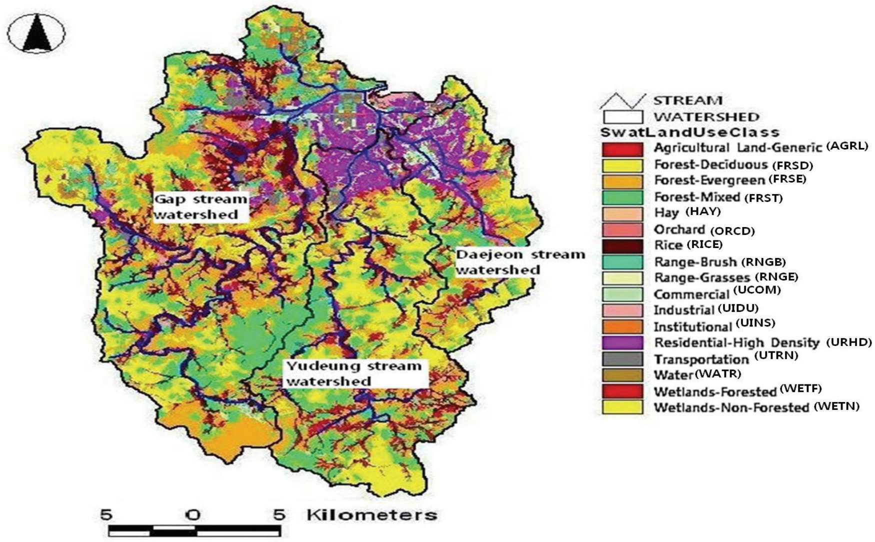


Fig. 3. Land use map for the Yudeung, Daejeon, and Gap Stream watersheds

A topographic map labeled with the streams in the Hoeduck watershed was obtained from the Korea Water Resources Corporation. Daily precipitation data and climate data were obtained from the Daejeon Observatory for January 2002–December 2005. The climate data included temperature (maximum, minimum), precipitation, solar radiation, wind speed, and relative humidity for Daejeon. For Daejeon city, more than 30 years of climate data were available. However, flow and water quality data from 2002 to 2005 were available for the study watershed. Thus, climate data for the period 2002–2005 were used in the modeling. The use of long-term flow and water quality data would be preferable; this is one limitation of our modeling approach.

2.5. Point source pollutants

To evaluate pollutant loads from point and nonpoint sources in the study watershed, point source loads should be included. Thus, point sources discharging in each watershed were estimated by summing the average discharge loads from households, industry, and livestock based on the technological guidelines for managing pollution in the watershed of Daejeon Metropolitan City and Chungcheongnam-do (Table 2) (Daejeon Metropolitan City, 2005; The Province of Chungcheongnam-Do, 2005). Table 2 shows pollutant source statistics for 2002 and 2010 for the Hoeduck watershed. Pollution sources from 2002 to 2005 were estimated by linear interpolation between the data for 2002 and 2010.

2.6. Flow and water quality data

Daily flow data from 2002 to 2005 at Boksu, Indong, and Hoeduck stations were obtained using the stage-flow rating curve suggested in the annual survey of hydrological data and the report on flow in the Geum River basin issued by the Korean Ministry of Land, Transport, and Maritime Affairs. Monthly water quality data for the dry season from 2002 to 2005 were obtained from three stations installed near Boksu, Indong, and Hoeduck stations by the Korean Ministry of Environment. During the rainy season, water quality samples were taken every hour for each storm event and were used to calculate pollutant (Moon and Kim, 2006a).

2.7 Administrative district data for point and non-point source pollutants

The amount of point source pollution in each watershed and subwatershed was estimated based on the amount of pollution for each administrative district provided by the Daejeon government (Daejeon Metropolitan City, 2005). Area-weighted pollutant loads for each watershed were calculated based on data provided by Daejeon Metropolitan City (Total Water Pollution Load Management Plan for Geum River, 2005). Loads in each watershed for 2002 to 2005 were calculated by multiplying the loads generated by the area of each watershed and then used as inputs to the model (Table 3). The Hoeduck watershed was divided into six subbasins for point source modeling (Fig. 4). The average delivery ratio for each watershed in the Hoeduck watershed suggested by Daejeon Metropolitan City was used (The Province of Chungcheongnam-Do, 2005).

In addition, daily discharges generated by the Daejeon sewage treatment plant and wastewater treatment plants in industrial complexes were included in the discharge loads for each administrative district and used as input data for point sources.

Table 2. Pollution source statistics for 2002 and 2010 for the Hoeduck watershed

	BOD5 (kg/day)		***T-N (kg/day)***		***T-P (kg/day)***	
	Generated	***Discharged***	***e***	***Discharged***	***Generated***	***Discharged***
2002	172,624	30,119	32,629	14,431	4,245	1,227
2010	194,705	34,219	37,481	15,083	4,889	1,298

Table 3. Nutrient delivery ratios for the subbasins

Sub-basin (number)	***Nutrient delivery ratio***	
	T-N	T-P
Gap upstream (2)	0.84	0.41
Gap downstream (6)	0.67	0.20
Yudeung upstream (1)	0.48	0.11
Yudeung downstream (3)	0.57	0.15
Daejeon upstream (4)	0.52	0.13
Daejeon downstream (5)	0.52	0.13

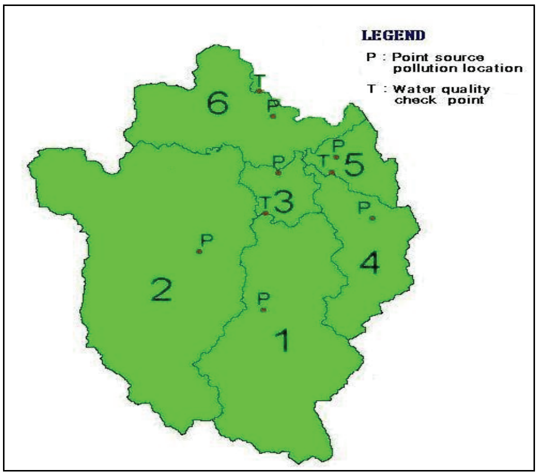


Fig. 4. Water quality sampling sites and point source locations

2.8. Statistical analysis of model performance

The evaluation method primarily used to assess model performance was the Nash–Sutcliffe model efficiency coefficient (NSE; Nash and Sutcliffe, 1970). As a supplemental evaluation index, the coefficient of determination (R^2) was examined, and relative error was used to assess total estimated pollutants and nutrients.

The NSE is normally applied to evaluate hydrologic behavior models, as follows (Eq. 1):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(\beta_{mi} - \beta_{ci})^2}{\sum_{i=1}^{n}(\beta_{mi} - \overline{\beta_m})^2} \quad (1)$$

where *NSE* is the evaluation coefficient, n is the number of days, β_{mi} is the observed value, β_{ci} is the estimated value, and $\overline{\beta_m}$ is the mean value for the entire period.

NSE ranges, with an ideal value of 1 (*NSE* = , representing a 1:1 ratio between the estimated value and the observed value. If the *NSE* is larger than 0, the relationship between the estimated value and the observed value is positive, indicating that the estimated data can be used as actual data in place of the observed data.

2.9. Model calibration and validation

Model calibration of flow and nutrient data was conducted in previous studies (Moon and Kim, 2006 a,b). In these studies, observed daily flow and nutrient data collected for each storm event during the simulation period were used. Table 5 and Table 5 summarize the optimized parameter values based on flow and nutrient calibration. Parameter optimization for nutrients was conducted for each of the six administrative districts due to their varying values for point sources.

Table 4. Optimized parameters for flow calibration[a]

Parameter	***Watersheds***		
	Indong	***Boksu***	***Hoeduck***
CN	Initial CN + 4	Initial CN + 8	Initial CN + 2
ALPHA FACTOR	0	0.0087	0.0075
GW_DELAY	0	115	132

[a] *Source: Moon and Kim (2006a)*

Table 5. Optimized parameters for T-N and T-P calibration[a]

Parameter	***All 6 subwatersheds***
Phosphorus percolation coefficient (PPERCO)	14
Phosphorus soil partitioning coefficient (PHOSKD)	150
Nitrate percolation coefficient (NPERCO)	0.4

[a] *Source: Moon and Kim (2006b)*

Table 6 and 7 summarize calibration and validation results for daily and monthly flow at each station.

The results of monthly calibration and validation for T-N and T-P loads are summarized in Table 8 and 9.

Table 6. Calibration results for flow (2002–2003)[a]

Station	*Daily*		*Monthly*		*RE*[c]
	NSE[b]	*R^2*	*NSE*	*R^2*	
Indong	0.48	0.51	0.62	0.77	11.0%
Boksu	0.50	0.52	0.74	0.80	22.5%
Hoeduck	0.67	0.69	0.86	0.87	11.0%

[a] *Source: Moon and Kim (2006a);* [b] *NSE: Nash and Sutcliffe efficiency;* [c] *RE: Relative error*

Table 7. Validation results for flow (2004–2005)[a]

Station	*Daily*		*Monthly*		*RE*[c]
	NSE[b]	*R^2*	*NSE*	*R^2*	
Indong	0.45	0.55	0.71	0.74	3.0%
Boksu	0.55	0.57	0.90	0.93	18.0%
Hoeduck	0.80	0.79	0.96	0.97	16.0%

[a] *Source: Moon and Kim (2006a);* [b] *NSE: Nash and Sutcliffe efficiency;* [c] *RE: Relative error*

Table 8. Monthly calibration results for T-N and T-P loading (2002–2003)[a]

Site	*NSE*[b]		*R^2*		*RE*[c]	
	T-N	*T-P*	*T-N*	*T-P*	*T-N*	*T-P*
Indong	0.72	0.78	0.73	0.79	15%	7%
Boksu	0.67	0.70	0.68	0.74	20%	18%
Hoeduck	0.69	0.73	0.73	0.82	11%	16%

[a] *Source: Moon and Kim (2006b);* [b] *NSE: Nash and Sutcliffe efficiency;* [c] *RE: Relative error*

Table 9. Monthly validation results for T-N and T-P loading (2004–2005)[a]

Site	*NSE*[b]		*R^2*		*RE*[c]	
	T-N	*T-P*	*T-N*	*T-P*	*T-N*	*T-P*
Indong	0.79	0.68	0.84	0.67	4%	3%
Boksu	0.69	0.59	0.65	0.80	11%	25%
Hoeduck	0.63	0.73	0.75	0.73	9%	9%

[a] *Source: Moon and Kim (2006b);* [b] *NSE: Nash and Sutcliffe efficiency;* [c] *RE: Relative error*

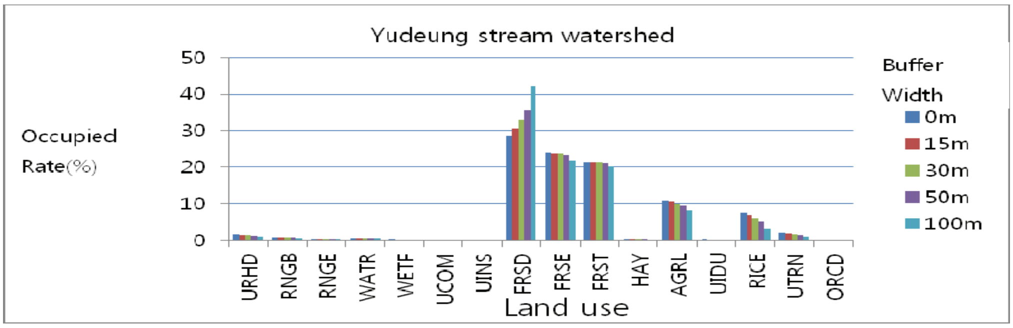


Fig. 5. The riparian buffer width (0–100 m) in the Yudeung Stream watershed

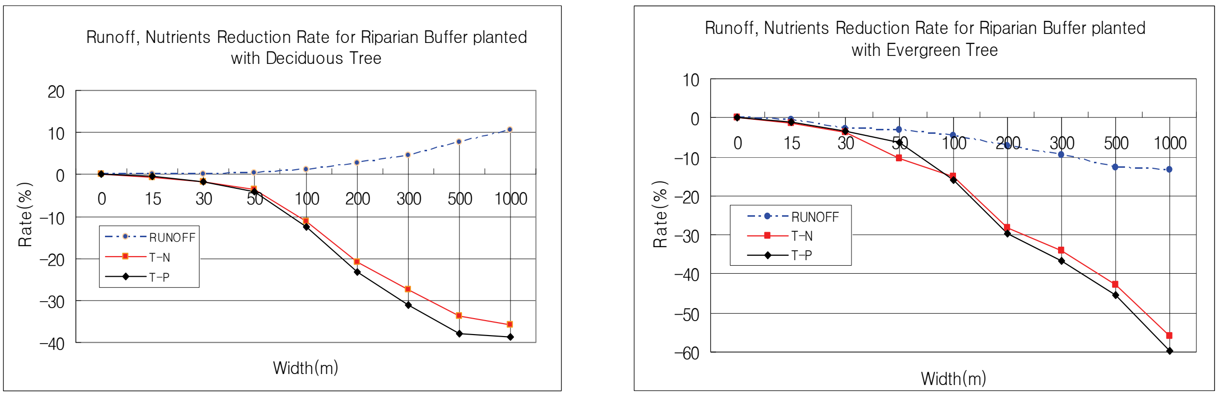


Fig. 6. Changes in flow, T-N, and T-P with riparian buffer width in the Yudeung Stream watershed

3. Results and discussion

The annual pollutant loads with and without riparian buffers were calculated to estimate nutrient reductions for each watershed. The estimated nutrient reductions for each watershed were compared for various buffer widths.

3.1. Yudeung stream watershed

The areas in agricultural land (AGRL) and rice paddies (RICE) decreased with increases in the width of riparian buffers in the Yudeung stream watershed. In addition, buffer widths of 50–100 m produced a more rapid decline in RICE areas (Fig. 5).

Based on the simulations, it was determined that an 80-m riparian buffer of deciduous trees or 70 m of evergreen trees are needed to achieve 10% T-N and T-P load reductions (Fig. 6, Table 10 and Table 11). Changes in the estimated runoff were not observed for thicknesses <80 m.

The runoff increased for deciduous riparian buffers ≥80 m wide, while for evergreen buffers, the runoff decreased as the width of the buffer increased. Paddy and upland areas (18.7%) have the most influence on the optimum width of riparian buffers. Paddies, which occupy 41% of the agricultural areas, have a particularly strong influence.

3.2. Daejeon Stream watershed

Agricultural (AGRL) and rice-paddy (RICE) areas decreased more than other land uses, such as urban (URHD) and orchard (ORCD) areas, with increases in the riparian buffer width in the Daejeon Stream watershed (Fig. 7). The dominant land use types involved in conversion to buffers of 50–100 m width were URHD, AGRL, and RICE.

Based on the simulations, 70-m deciduous riparian buffers or 60-m evergreen buffers are needed to reduce T-N and T-P loads by 10% (Fig. 8, Table 12 and Table 13). Runoff decreased with an increase in riparian buffer width for evergreen trees, but not for deciduous trees. In the Daejeon Stream watershed, paddy and upland areas (10.4%) are the most influential factors in determining the optimum width of riparian buffers. In particular, paddies, which occupy 33% of the agricultural areas, most affect the optimum width of riparian buffers for 10% nutrient reduction.

3.3. Gap Stream watershed

For the Gap Stream watershed, the RICE area decreased substantially more than did the URHD, AGRL, or UTRN areas..

Table 10. Reduction rates (%) for deciduous riparian buffers

Buffer width (m)	15	30	50	100	200	300	500	1000
Runoff	0.1	0.1	0.3	1.1	2.7	4.7	7.7	10.5
T-N	-0.7	-1.8	-3.6	-11.2	-20.8	-27.4	-33.7	-35.7
T-P	-0.6	-1.9	-4.0	-12.5	-23.3	-31.2	-38.0	-38.7

Table 11. Reduction rates (%) for evergreen riparian buffers

Buffer width (m)	15	30	50	100	200	300	500	1000
Runoff	-0.4	-2.7	-3.2	-4.7	-7.2	-9.6	-12.7	-13.3
T-N	-1.3	-3.6	-10.5	-15.1	-28.2	-34.1	-42.9	-55.9
T-P	-1.1	-3.4	-6.4	-15.9	-29.8	-36.6	-45.6	-59.6

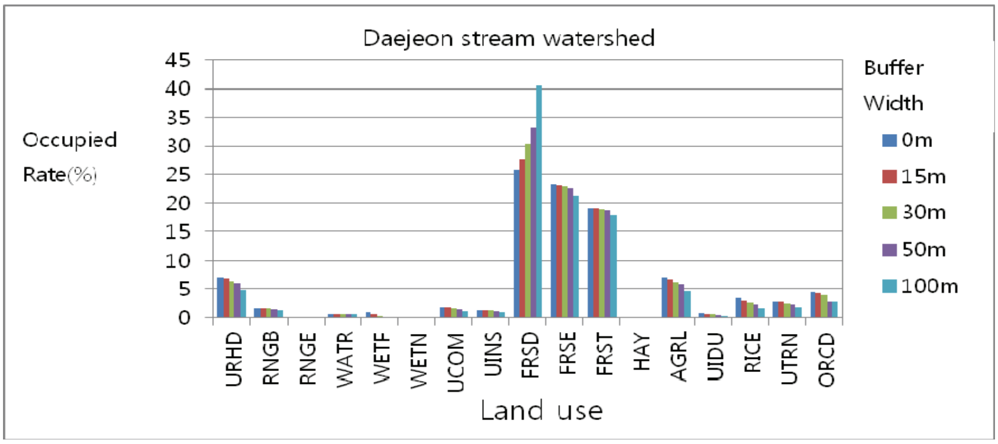


Fig. 7. Land use change with riparian buffer width (0–100 m) in the Daejeon Stream watershed

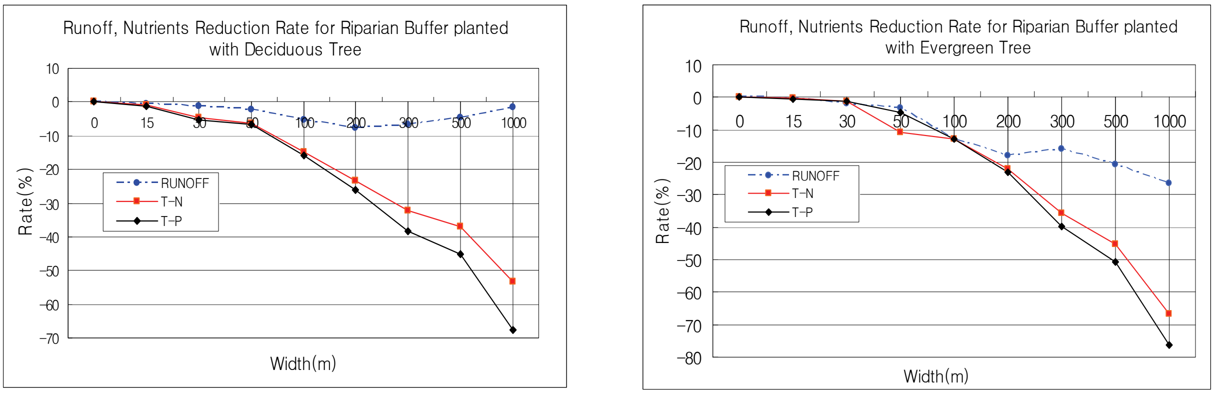


Fig. 8. Changes in flow, T-N, and T-P with riparian buffer width in the Daejeon Stream watershed

Table 12. Reduction rates (%) for deciduous riparian buffers

Buffer width (m)	15	30	50	100	200	300	500	1000
Runoff	-0.5	-1.3	-2.4	-5.3	-7.7	-6.6	-4.5	-1.4
T-N	-0.8	-4.7	-6.2	-14.9	-23.2	-32.1	-36.8	-53.4
T-P	-1.4	-5.4	-6.8	-15.9	-25.9	-38.3	-45.2	-67.7

Table 13. Reduction rates (%) for evergreen riparian buffers

Buffer width (m)	**15**	**30**	**50**	**100**	**200**	**300**	**500**	**1000**
Runoff	-0.2	-1.8	-3.4	-13.0	-17.8	-16.0	-20.5	-26.6
T-N	-0.2	-1.2	-10.8	-12.9	-22.0	-35.7	-45.1	-66.9
T-P	-0.7	-1.3	-4.5	-12.9	-23.0	-40.0	-50.5	-76.3

Similar to the Yudeung Stream watershed, RICE is the predominant land use that would need to be converted to achieve a 100-m wide riparian buffer (Fig. 9). To reduce the T-N and T-P loads by 10%, 300-m deciduous buffers or 100-m evergreen buffers would be needed. Deciduous buffers were less effective than evergreen buffers. Runoff did not change for deciduous buffers regardless of width, while runoff decreased for evergreen buffers as the width increased (Fig. 10,

Table 12 and Table 15).

As for the other watersheds, paddy and upland areas (15.2%) had the most influence on the optimum width of riparian buffers. Similarly, paddies, which occupy 63% of the agricultural area, most affected the optimum width. Table 16 shows the optimum width of riparian buffers for each watershed to meet 10% nutrient reduction goals.

We found that paddy areas within each watershed most affected the optimum width of the riparian buffers due to the greater nonpoint source potential from agricultural areas, although complex interactions between rainfall-runoff, sediment, and nutrients affect the efficiency and optimum width of buffers.

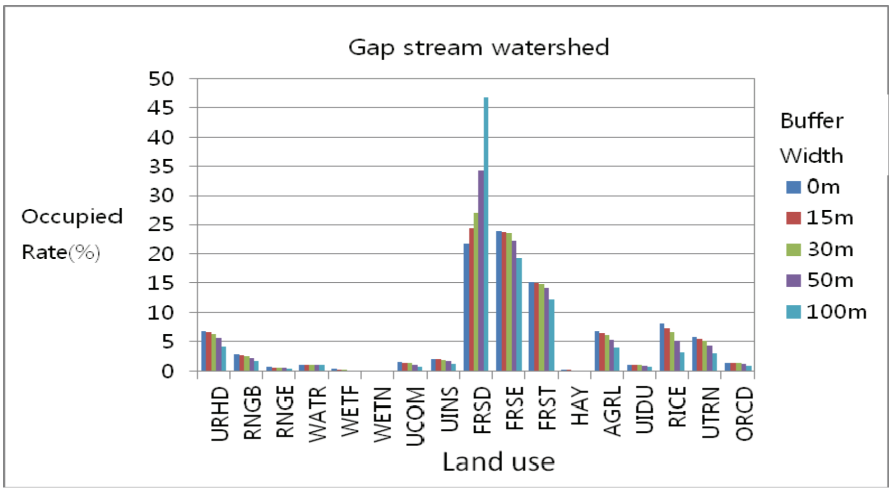
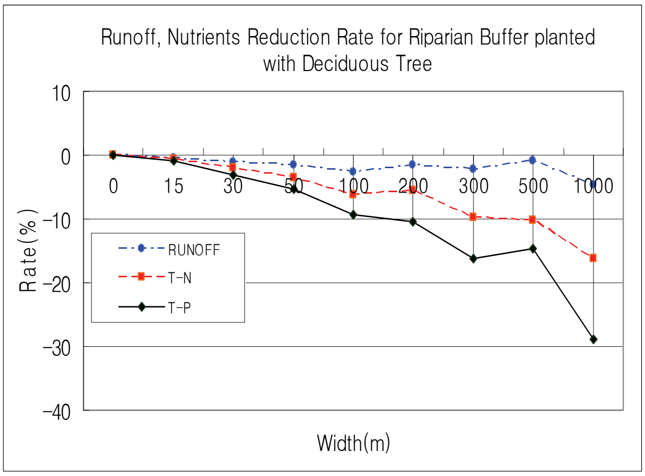


Fig. 9. Land use change with riparian buffer width (0–100 m) in the Gap Stream watershed



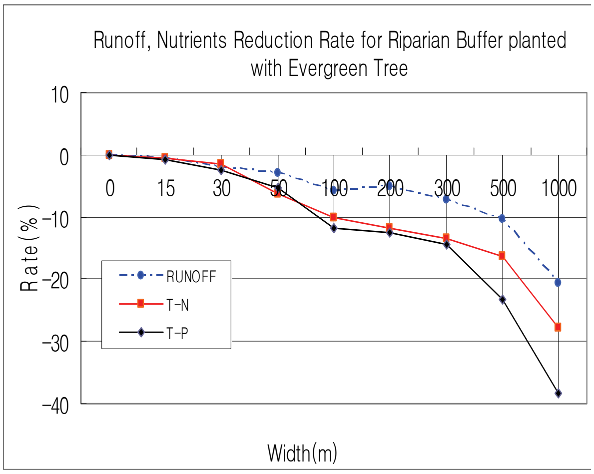


Fig. 10. Changes in flow, T-N, and T-P with riparian buffer width in the Gap Stream watershed

Table 14. Reduction rates (%) for deciduous riparian buffers

Buffer width (m)	15	30	50	100	200	300	500	1000
Runoff	-0.4	-1.0	-1.6	-2.6	-1.6	-2.2	-0.8	-4.6
T-N	-0.6	-2.0	-3.6	-6.1	-5.5	-9.9	-10.2	-16.2
T-P	-0.9	-3.1	-5.4	-9.2	-10.4	-16.3	-14.6	-29.0

Table 15. Reduction rates (%) for evergreen riparian buffers

Buffer width (m)	15	30	50	100	200	300	500	1000
Runoff	-0.4	-2.0	-3.0	-5.9	-5.0	-7.2	-10.2	-20.6
T-N	-0.4	-1.6	-6.2	-10.2	-11.9	-13.5	-16.3	-27.7
T-P	-0.7	-2.5	-5.4	-11.9	-12.5	-14.4	-23.3	-38.4

Table 16. Optimum width of riparian buffers to meet the 10% nutrient reduction goal for each watershed compared to agricultural and paddy areas

	Agricultural areas (%)	***Paddies in agricultural areas (%)***	***Optimum width to meet 10% nutrient reduction goal (m)***	
			Deciduous	***Evergreen***
Yudeung Stream watershed	18.7	41	80	70
Daejeon Stream watershed	10.4	33	70	60
Gap Stream watershed	14.9	54	300	100

3.4. Effects of slope

Researches on the effects of riparian buffers on nutrient reduction have primarily been focused on land use conversion in riparian areas. Instead of simulating nutrient reduction with sheet surface flow and subsurface flow at the buffers, the approaches used in this study may be more appropriate for areas such as Korea where the slope of watershed ranges from 8 to 20%. Many previous studies have reported that riparian buffer zones can mitigate negative effects of pollutants loads from watersheds with slopes of 5–7%, while have lesser impacts for slopes >15%. Typical precipitation during the summer (May–September or October) in Korea results in surface runoff that can be more than 20-fold that during the dry season. For these reasons, Korea has well-developed drainage systems (in urban, rural, or mountainous regions), suggesting that the sheet flow is not typical. When heavy rainfall exceeds drainage capacities, then overflows may begin. However, the filtering function of the riparian buffer cannot accommodate the amount of overflow generated. In addition, many existing hydrological models continue to have limitations in simulating the filtering effect of riparian buffers on watershed scales. Thus, we suggest that the SWAT model is able to simulate the impacts of HRU-based land use changes at these larger spatiotemporal scales. This model can be used to assess long-term riparian buffer effects at mesoscale field sites (>5 km^2).

4. Conclusions

The following conclusions can be drawn:

- Deciduous buffer widths of 70–300 m or evergreen buffer widths of 60–100 m are needed to meet 10% nutrient reduction goals.

- Deciduous buffers are less effective than evergreen buffers in reducing nutrients and do not reduce runoff volumes.
- The area of rice paddies within the watershed has the greatest effect on the effective width of the buffer; land use and the location of urban areas also affect nutrient reduction.
- The SWAT model is appropriate for assessing areas with steep slopes such as in Korea.

This approach can be used to develop economical watershed-specific riparian buffer management practices in Korea or other countries with similar weather patterns, land uses, and soils.

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