TECHNICAL NOTE:

ENHANCEMENT OF SWAT-REMM TO SIMULATE REDUCTION OF TOTAL NITROGEN WITH RIPARIAN BUFFER

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ABSTRACT. *In recent years, riparian buffers have become known as one of the most effective best management practices for nonpoint-source pollution. However, establishment of riparian buffer systems with respect to plant species and their position in the buffer zone has not been investigated due to lack of efficient evaluation methods for the analysis of water quality improvement with established riparian buffers. To solve this problem, the SWAT-REMM prototype version was developed by researchers in Canada. In the SWAT-REMM prototype version, many riparian-related input parameters are not directly read from the local input data. Thus, a SWAT-REMM enhancement was developed by improving three major limitations of the prototype version of SWAT-REMM: (1) riparian buffers at designated reaches in the watersheds, (2) riparian buffers using local soil properties at the riparian buffer zone along reaches, and (3) multiple weather stations in a larger-scale watershed. The enhanced SWAT-REMM version was applied to the Bonggok watershed in Korea. This study investigated riparian buffers with different widths (10 m, 5 m, and 1 m) along the slope. Total nitrogen reduction ranged from 14.8% to 54.0% in each catchment for 10 m widths. Total nitrogen reduction ranged from 6.9% to 31.6% in each catchment for 1 m widths. The reduction efficiency was not simply proportional to the width of buffers. This study evaluated the enhanced SWAT-REMM simulation of water quality improvement. Based on this research, the enhanced SWAT-REMM can be used to evaluate water quality improvement by riparian buffers at various watersheds worldwide using local data. In particular, simulation of riparian buffers at user-designated reaches in a watershed enables simulation of riparian buffers in watersheds experiencing frequent flooding where no riparian buffers can be established. It is expected that the enhanced SWAT-REMM can be used to determine economical and environmentally optimum riparian buffer scenarios.*

Keywords. *Modeling, Riparian buffer, SWAT-REMM, Water quality.*

In recent years, various development plans for riparian buffers along streams have been discussed in Korea (Kang, 2009; Han and Jo, 2009). With an increasing focus on the environmentally friendly development of rivers, much attention has been paid to riparian buffer because of their diverse effects on the ecosystem as well as on human life. Some of the most important functions of riparian buffer zones are to: (1) filter and take up pollutants transported by surface and subsurface flow, (2) minimize stream bank erosion, (3) decrease the speed of the intensive growth of aquatic macrophytes by providing shaded areas through tree canopies, (4) improve the microclimate in adjacent fields, and (5) provide habitats at the aquatic-terrestrial ecotones (Lowrance et al., 1997; Woo and Kim, 2000). Riparian buffers, which play important roles in conserving the ecosystems and reducing water quality degradation, have been recommended among the various best management practices for nonpoint-source pollution control (Jobin et al., 2004; Anbumozhi et al., 2005; Dwire and Lowrance, 2006).

Modeling is used to evaluate riparian buffers worldwide (Xiang, 1996; Tucker et al., 2000; Sahu and Gu, 2009). Among the various models that have been applied, the watershed-scale Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has often been used to evaluate the effects of riparian buffers (Parajuli et al., 2008; Kim et al., 2009; Cho et al., 2010), However, SWAT has some limitations in terms of modeling riparian buffers at a watershed scale.

SWAT has been widely used worldwide because of its flexibility in spatial and temporal studies of rainfall-runoff as well as the generation and transport of nonpoint-source pollutants. However, SWAT is a semi-distributed model, and thus runoff and pollutants generated at a field scale within the catchment are assumed to enter the stream directly instead of entering along the riparian buffers in sheet flow form to simulate

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the riparian buffers. Considering this limitation of the model, it is not possible to simulate the effects of riparian buffers on water quality improvement with the current SWAT structure.

For this reason, the SWAT-REMM prototype (Liu et al., 2007) was developed to address these limitations in SWAT riparian buffer simulation. The SWAT-REMM prototype version was developed by integrating SWAT and the Riparian Ecosystem Management Model (REMM) on the GIS platform. The prototype divides riparian buffers into three zones to simulate various canopy scenarios and surface-runoff, lateral flow, and groundwater flow and associated pollutants (Liu et al., 2007). In the SWAT-REMM prototype version, simulated surface and subsurface runoff and pollutants from the buffer drainage (i.e., areas contributing flow and pollutants along the riparian buffer in sheet flow form) are simulated as flowing through the riparian buffer before entering the channel within the catchment, while those from concentrated drainage (i.e., areas flowing directly into a point in a channel within the catchment) are not simulated to flow through the riparian buffer. Discretization of buffer drainage and concentrated drainage in the SWAT-REMM prototype version is a reasonable approach in the evaluation riparian buffers compared with other watershed models, which do not differentiate between the contributing areas to the riparian buffers.

However, there are several limitations in applying the SWAT-REMM prototype to other watersheds. First, the riparian buffer should be specified along the reaches in every catchment in the watershed, which is not feasible in most cases, particularly for watersheds in Korea where many human-made structures are already installed along the reaches to prevent flooding. Second, the soil properties of the riparian buffers used for the prototype watershed in Canada (Liu et al., 2007) are hard-coded in the SWAT-REMM code; consequently, the prototype version cannot be applied to another watershed without a manual edit of the soil properties for the riparian buffers. Third, only one set of representative weather data can be simulated with the SWAT-REMM prototype version. Usually, riparian buffers are established in large-scale watersheds; therefore, multiple weather data sets should be used in simulating hydrology and water quality.

The objectives of this study are to (1) enhance the SWAT-REMM prototype by addressing the three limitations and (2) simulate water quality improvement with riparian buffers using the enhanced version of SWAT-REMM.

Materials and Method

Study Area

The Bonggok watershed at Gonju-si, Korea, was selected for evaluation of the enhanced SWAT-REMM. The Bonggok watershed is 90.82 ha in size (fig. 1). Forest (81.8%) is the dominant land use, and agricultural fields represent 4.4% of the watershed (fig. 2). The dominant soil is silt loam, which occupies 67.6% of the area (fig. 3). As there are greater percentages of silt and clay, the degrees of soil aeration and soil drainage are not good (Kim, 2007). The Bonggok study watershed was selected to evaluate the generation of agricultural nonpoint-source pollution and the effects of riparian buffers on pollutant reduction. Although this area is primarily forest, a significant portion of the agricultural land contributes to the pollutant load. In addition, the agricultural land runoff is generally not concentrated flow.

Development of Enhanced SWAT-REMM

In the prototype SWAT-REMM system (Liu et al., 2007), catchments are divided into contributing areas (buffer drainage, flowing into riparian buffers in sheet flow form) and concentrated areas (concentrated drainage, flowing into one location in streams) to evaluate the effects of riparian buffers on flow and water quality reduction at the buffer drainage. To divide the catchments into buffer drainage and concentrated drainage, main stream networks where the riparian buffers will be established and fine stream networks into which the flow moves as concentrated flow are needed. The SWAT-REMM GIS interface first delineates concentrated drainage

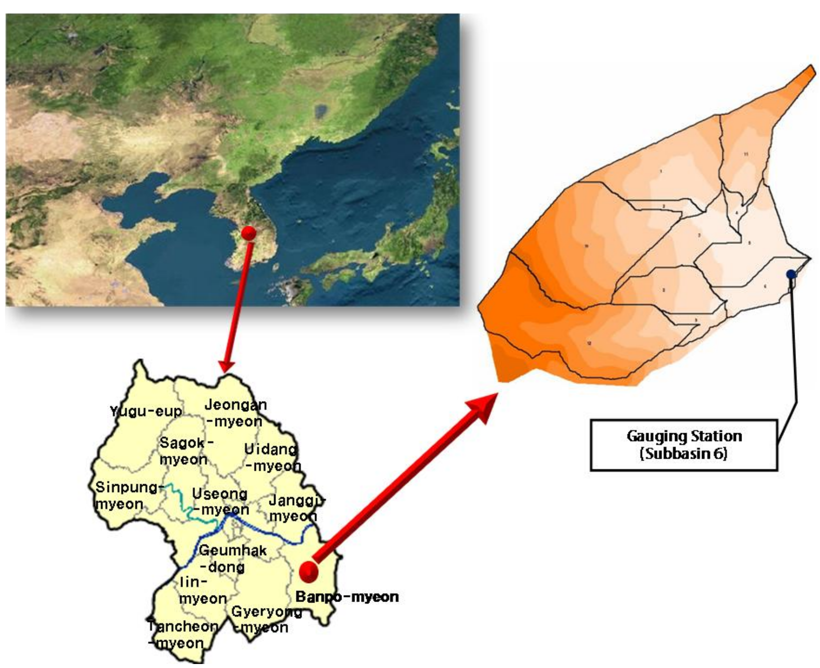

Figure 1. Bonggok watershed, Gonju-si, Korea.

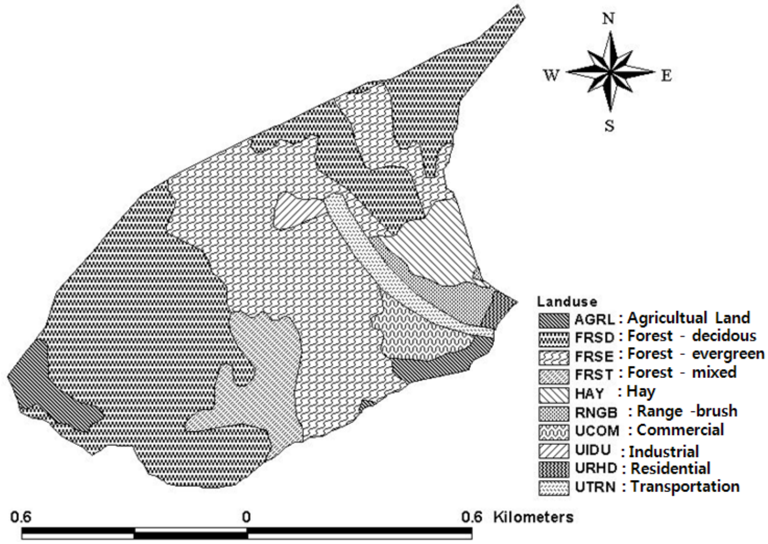

Figure 2. Land uses in the Bonggok watershed.

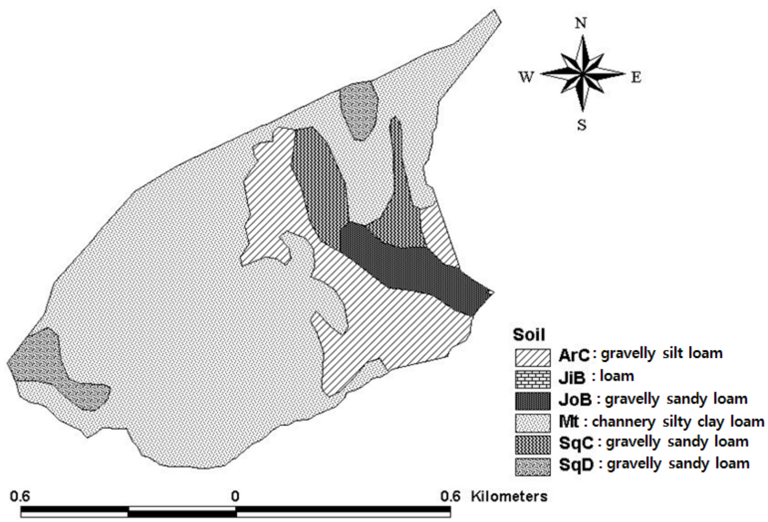

Figure 3. Soil map of the Bonggok watershed.

based on fine stream networks, and then the rest of area for each catchment is defined as buffer drainage, where all flows and pollutants flow into the buffer as sheet flow (Liu and Wang, 2007). However, it is not practically possible to establish riparian buffers at all reaches in watersheds in Korea, and in other countries, because of human-made retaining walls installed along the reaches to prevent flooding. Thus, the SWAT-REMM prototype needs a new module to estimate the effects of riparian buffers in some catchments within the watershed. In this study, a new module was developed to simulate riparian buffers at several catchments within the watershed with a riparian buffer reach segment shape file provided by the users. Buffer drainage and concentrated drainage are delineated for designated riparian buffer catchments. Figure 4 shows the interface of the enhanced SWAT-REMM and the buffer drainage for catchments with user-defined riparian buffer reaches. The shaded parts in each catchment are the areas that contribute flow and pollutants to the riparian buffers.

In the SWAT-REMM prototype, the soil properties at the riparian buffer zone were not directly read from the soil GIS database of the study areas. Since soil properties were originally hard-coded, a preprocessor was written to retrieve the local soil properties of the riparian buffers from the local soil map, as shown in figure 5. In SWAT-REMM, representative soil properties of a single soil type for each riparian buffer can be simulated. Thus, the representative soil type is determined, with areas of the major soil type among the soil types in the riparian buffers after clipping the soil grid with the riparian zone. The soil properties needed for the REMM are retrieved from the SWAT soil database (usersoil.dbf) and written back into the REMM input data format.

In the SWAT, the nearest weather station in each catchment is selected by computing the distance between the centroid of each catchment and the location of each weather station. This information was used to maintain consistency in SWAT and REMM simulations. Accordingly, the preprocessors of the enhanced SWAT-REMM were written to generate REMM weather input data from SWAT weather data for each riparian buffer zone. With this capability, the enhanced SWAT-REMM can be used for large-scale watersheds, since it can simulate hydrology and water quality using the nearest

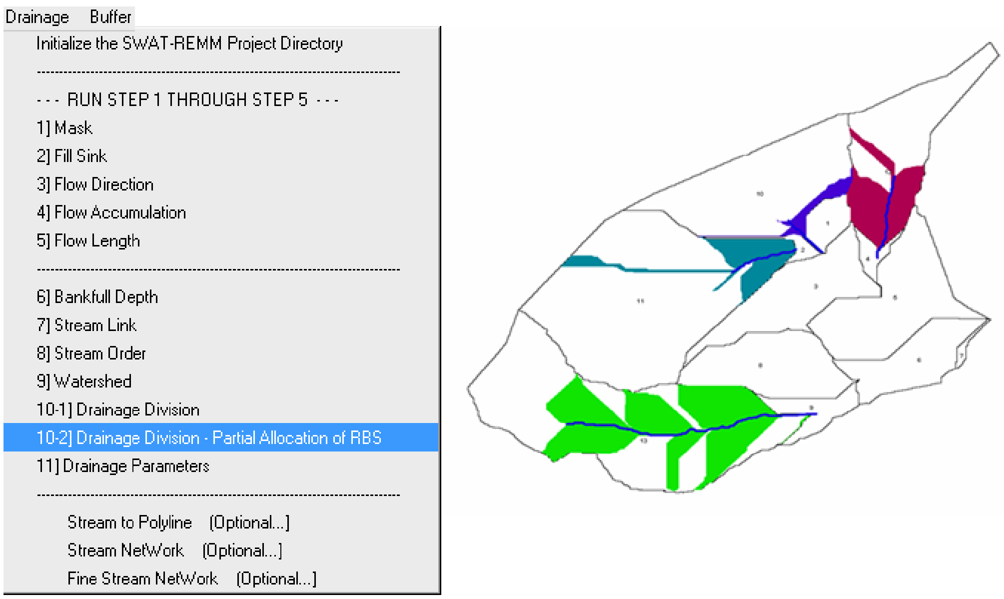

Figure 4. Buffer drainage for several catchments along reaches with enhanced SWAT-REMM.

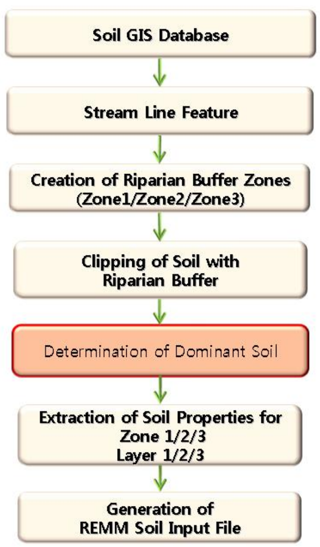

Figure 5. Overview of soil property extraction module in the enhanced SWAT-REMM.

weather data, instead of a single representative weather station, which was the only option available in the SWAT-REMM prototype.

Calibration and Testing of Flow and Total Nitrogen at the Bonggok Watershed

Before analyzing the effects of riparian buffers on water quality improvement, SWAT should be calibrated and tested to simulate streamflow and water quality because SWAT-REMM uses the output of SWAT as input to the REMM. Thus, SWAT was calibrated and tested using observed flow and water quality (Kim, 2007) for the Bonggok watershed. Flow and total nitrogen calibration was from 1 January to 31 December 2005 for daily simulation, and the testing period for flow and total nitrogen was from 1 January to 31 December 2006 for daily simulation.

Three Riparian Buffer Scenarios

To evaluate the effects of riparian buffers on water quality improvement, three buffer scenarios were selected, as shown in figure 6. It was assumed that the same plant types were selected for zones 1, 2, and 3 with different buffer widths (10 m, 5 m, and 1 m on both sides of the stream). In this study, it was assumed that the riparian buffers are installed along the reaches for catchments 10, 11, and 12 (fig. 6).

Results and Discussions

Development of Enhanced SWAT-REMM

In this study, three major improvements were made to create the enhanced SWAT-REMM, and these are described below. First, the modified SWAT-REMM watershed delineation interface allows users to specify the location of buffers within the watershed. With this interface, users can specify the buffer locations for all or several catchments, depending on local conditions along the reaches. Figure 7a shows the buffer drainage delineated using the user riparian buffer zone data with the enhanced SWAT-REMM. The flow and pollutants from all HRUs in buffer drainage are assumed to enter the riparian buffer zone to simulate the effects of riparian buffers on water quality improvement, while the flow and pollutants from all HRUs in concentrated drainage (fig. 7b) are assumed not to enter the riparian buffer zone. Differentiation of flow and pollutants from buffer drainage and from concentrated drainage are key procedures in simulating the riparian buffer zone, particularly for riparian buffer zones at user-designated catchments.

Second, the enhanced SWAT-REMM is now able to read soil properties for the riparian buffer zone from the soil map. Figure 8 shows how the soil properties of the study watershed were automatically entered into the SWAT-REMM input data with the preprocessors developed in this study. In the current enhanced SWAT-REMM, the soil properties of only one representative soil for each riparian buffer zone are used. This could lead to potential errors when the soil properties change spatially within buffers. Thus, to reflect spatially distributed

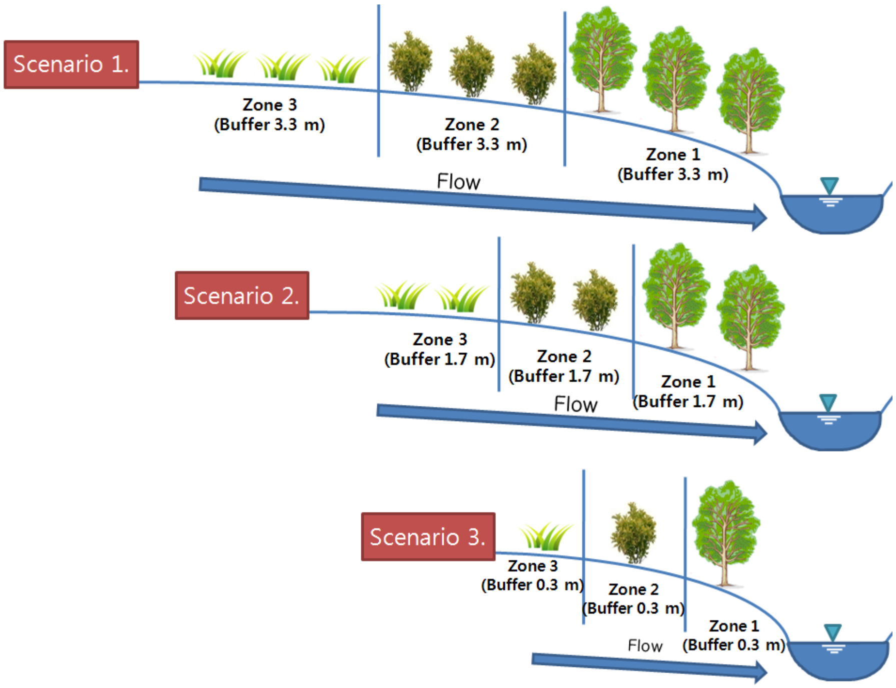

Figure 6. Three riparian buffer scenarios to evaluate water quality improvement.

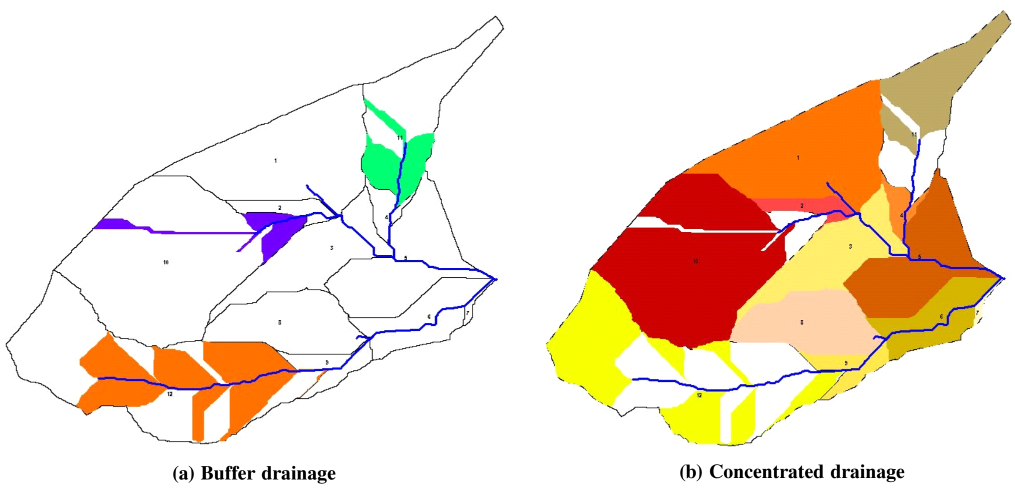

Figure 7. (a) Buffer drainage and (b) concentrated drainage delineated using enhanced SWAT-REMM.

soil properties within the riparian buffers, a new routine capable of considering each soil's properties in the buffers will be added in the next study.

Third, the enhanced SWAT-REMM is able to consider multiple weather stations for a large watershed. With this improvement, the enhanced SWAT-REMM can be used for larger watersheds, where measured weather data are available from multiple stations, to enable more accurate simulation of flow and pollutant generation and transportation.

Calibration and Testing of SWAT

The coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) were used for statistical analysis during the calibration and testing period. The coefficient of determination is defined as the squared value of the coefficient of correlation (Steel and Torrie, 1960), and the NSE (Nash and Sutcliffe, 1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. Figure 9a shows the calibrated daily streamflow at the Bonggok watershed, with R^2 and NSE values of 0.73 and 0.69, respectively. Figure 9b shows the daily streamflow for the Bonggok watershed, with R^2 and NSE values of 0.72 and 0.67, respectively. According to Donigan and Love (2003), the calibration and testing of daily flow simulations could be classified as fair. Figures 10a and 10b show the calibrated and tested daily total nitrogen for the Bonggok watershed, with R^2 and NSE values of 0.67 and 0.62, respectively, for calibration and 0.63 and 0.60, respectively, for testing. These statistics indicate that SWAT, calibrated and tested for flow and total nitrogen, can now simulate flow and pollutant generation from the watershed reasonably well, with an NSE value of 0.60 or greater.

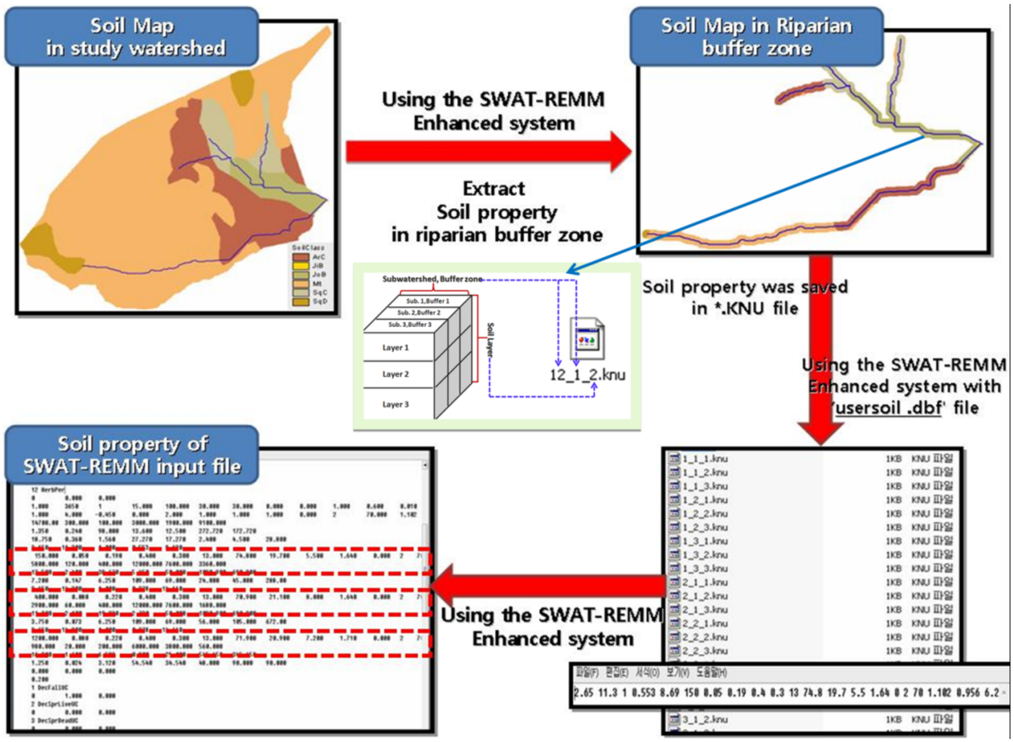

Figure 8. Extraction of soil properties at riparian buffer zone for REMM simulation.

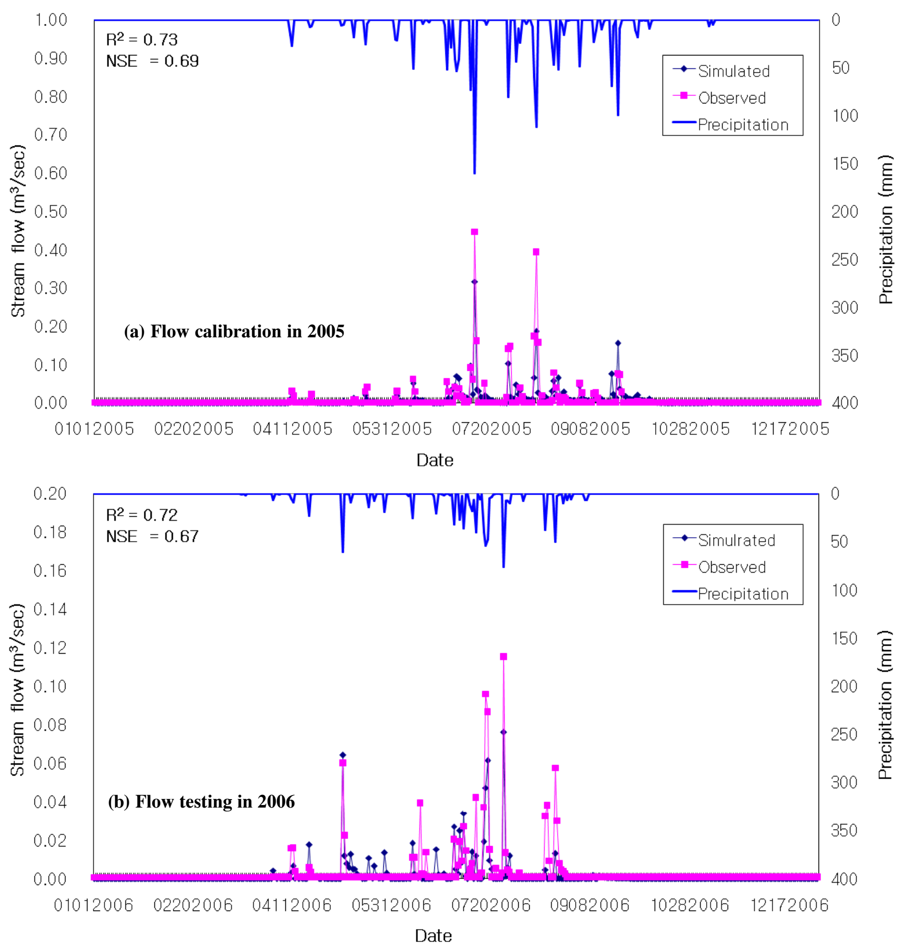

Figure 9. (a) Calibration and (b) testing of daily streamflow for the Bonggok watershed.

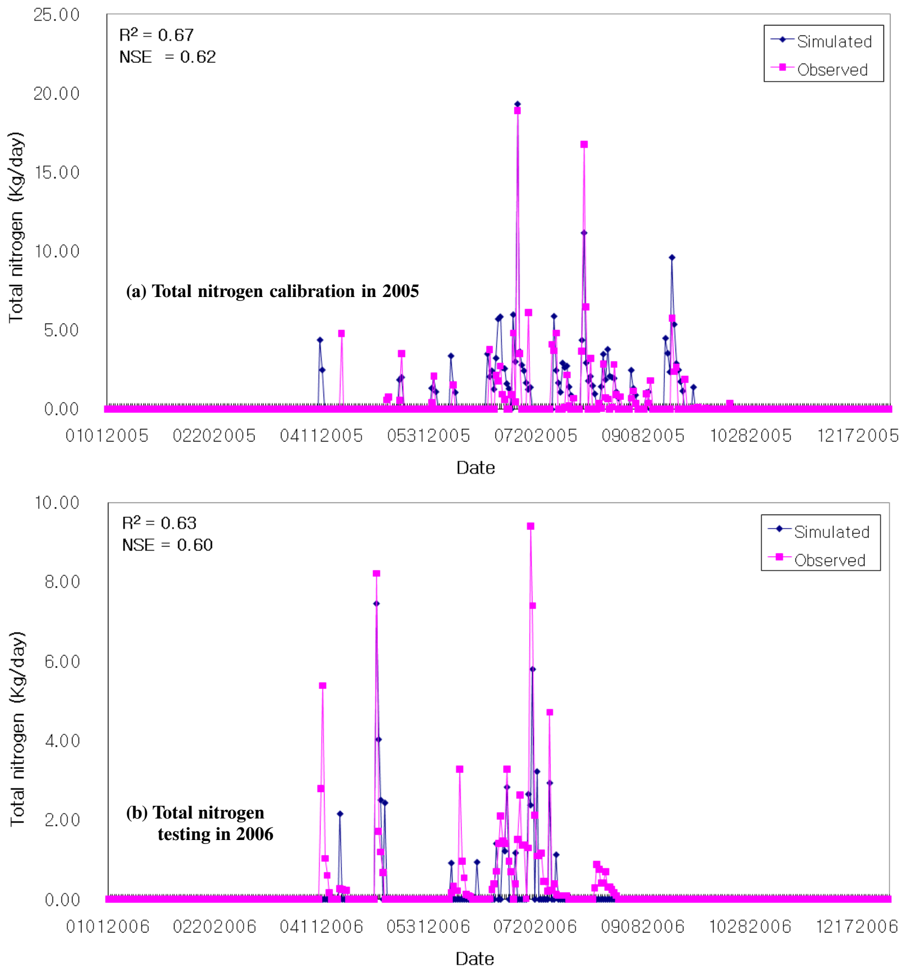

Figure 10. (a) Calibration and (b) testing of total nitrogen for the Bonggok watershed.

Application of Enhanced SWAT-REMM

The calibration and testing of the enhanced SWAT-REMM was used to evaluate the effects of riparian buffers on water quality improvement. In this study, it was assumed that riparian buffer zones are established in catchments 10, 11, and 12, but not in the entire watershed. Table 1 shows that annual runoff was reduced slightly with riparian buffers. The enhanced SWAT-REMM simulation for scenario 1 showed a streamflow reduction for each catchment ranging from 4.7% to 23.1%, scenario 2 showed a reduction within each catchment ranging from 4.3% to 18.5%, and scenario 3 showed a reduction within each ranging from 2.1% to 10.2%, depending on the percentage of the riparian buffer contributing areas, the flow from these areas, and the physical characteristics of the riparian buffers. Runoff could be reduced, to some degree, with a riparian buffer. Reductions in flow rate from catchments 11 and 12 were more apparent since the buffer drainage areas were larger. As expected, as buffer width decreased, runoff reduction decreased.

A similar trend was found for total nitrogen reduction with riparian buffers, as shown in table 2. These trends and reductions were related to the percentage of buffer drainage in catchments 10, 11, and 12, the physical characteristics of the riparian buffers, and the nutrients transported from the upland areas. The enhanced SWAT-REMM simulated a total nitrogen reduction (scenario 1) within each catchment ranging from 14.8% to 54.0%, while reduction within each catchment in scenario 2 ranged from 10.5% to 35.7%, and scenario 3 ranged from 6.9% to 31.6%. As shown in this study, the enhanced SWAT-REMM can be used to determine and design the optimum width of a riparian buffer zone along the slope for a target nutrient reduction.

Table 1. Estimated streamflow reduction with three riparian buffer scenarios.

Catchment	Area of Drainage Buffer (%)	Streamflow for Each Catchment: Before Buffer ($m^3\ s^{-1}$)	Scenario 1 (10 m buffer): After Buffer ($m^3\ s^{-1}$)	Scenario 1 (10 m buffer): Reduction (%)	Scenario 2 (5 m buffer): After Buffer ($m^3\ s^{-1}$)	Scenario 2 (5 m buffer): Reduction (%)	Scenario 3 (1 m buffer): After Buffer ($m^3\ s^{-1}$)	Scenario 3 (1 m buffer): Reduction (%)
10	9.6	8.7	8.3	4.7	8.4	4.3	8.6	2.1
11	33.2	3.5	2.8	18.7	3.0	14.5	3.2	6.9
12	46.5	7.8	6.0	23.1	6.3	18.5	7.0	10.2

Table 2. Estimated total nitrogen reduction with three riparian buffer scenarios.

Catchment	Area of Drainage Buffer (%)	Before Buffer (kg year^{-1})	Scenario 1 (10 m buffer) After Buffer (kg year^{-1})	Scenario 1 (10 m buffer) Reduction (%)	Scenario 2 (5 m buffer) After Buffer (kg year^{-1})	Scenario 2 (5 m buffer) Reduction (%)	Scenario 3 (1 m buffer) After Buffer (kg year^{-1})	Scenario 3 (1 m buffer) Reduction (%)
10	9.6	86.6	73.7	14.8	77.5	10.5	80.6	6.9
11	33.2	18.3	10.5	42.4	12.6	31.3	13.8	24.5
12	46.5	75.8	34.8	54.0	48.7	35.7	51.9	31.6

Total Nitrogen Load for Each Catchment

Summary and Conclusions

The SWAT-REMM prototype was enhanced with three major improvements, and then total nitrogen reduction efficiency was evaluated with established buffers at the Bonggok study watershed. The enhanced SWAT-REMM was able to simulate established riparian buffers at user-selected catchments with local soil properties for the riparian buffer zone at buffer drainages. In addition, the enhanced SWAT-REMM used multiple weather stations. Three riparian buffer scenarios with different buffer zone widths (10 m, 5 m, and 1 m) and different canopies were used to evaluate the enhanced SWAT-REMM. It was found that total nitrogen reduction efficiency ranged from 14.8% to 54.0% in each catchment in scenario 1, which was an established riparian buffer with a 10 m width. Total nitrogen reduction efficiency ranged from 6.9% to 31.6% in each catchment in scenario 3, which was an established buffer with a 1 m width. The reduction efficiency was not proportional to the width of the buffer. As shown in this study, the enhanced SWAT-REMM could be used to evaluate the effects of various riparian buffer scenarios on water quality improvement.

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