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Development of new *R*, *C* and SDR modules for the SATEEC GIS system

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ABSTRACT

Soil erosion is a natural phenomenon, but accelerated soil erosion is occurring with increased construction activities and intensive agricultural cultivation within many watersheds in recent years. To develop efficient soil erosion control best management practices, the soil erosion status in the target areas first needs to be understood spatially and temporally. The SATEEC system has been widely used for soil erosion studies because of its ease-of-use and limited input data requirement. However, SATEEC cannot be used for spatiotemporal analysis of soil erosion studies. Thus, the time-variant *R*, *C*, and GA-SDR modules were developed and integrated with the SATEEC system. The enhanced SATEEC 2.0 system estimated sediment yield values were compared with measured data for the Imha watershed. The R^2 value and the Nash–Sutcliffe coefficient were 0.72 and 0.72, respectively for calibration and 0.91 and 0.88, respectively for validation with the time-variant *R*, *C* and GA-SDR modules. The statistics indicate the enhanced SATEEC 2.0 system with these modules can be used for spatial and temporal analysis of soil erosion and sediment yield with higher accuracy and a limited input dataset, which is the primary philosophy of the SATEEC ArcView GIS system. Since the daily USLE *C* database was obtained from SWAT runs using the climate data and agricultural management data in Korea, the daily USLE *C* database should be adjusted depending on the climate condition and agricultural management when the SATEEC is applied to other watersheds having different climate and agricultural management systems.

1. Introduction

Soil erosion is a natural phenomenon, and accelerated soil erosion is occurring with increased construction activities and intensive agricultural cultivation within watersheds in recent years. Agricultural activities, such as commercial and organic fertilizers, various insecticides, herbicides and fungicides are typically applied to agricultural fields and various tillage is practiced to maximize crop yields. Excessive and accelerated soil erosion cause water quality and ecosystem deterioration in receiving water bodies, as well as social and economic issues in downstream areas. In the last decade, severe sediment-laden water has been the hot issue in Korea and many other countries. It had been assumed that agricultural activities and landslides were the primary causes of these problems in watersheds. To reduce sediment inflow from agricultural activities into watersheds, many best management practices (BMPs) were suggested. In highland agricultural areas of Korea, intensive agricultural cultivation of cash-crops is performed for only 2–3 months of the year. Thus, agricultural fields are left without any surface protection against soil erosion during the rest of the cropping period. Unexpected torrential rainfall events and successive precipitation during the monsoon period are causing excessive soil erosion and sediment inflow into streams, especially when the agricultural fields are left without any surface cover (El-Hassanin et al., 1993). The rainfall patterns are changing rapidly over the years with climate changes worldwide. Thus, characteristics of soil erosion and delivery mechanisms are spatially and temporally changing.

With advances in computer technology, spatiotemporal characteristics of soil erosion have been investigated to a significant extent. There are many soil erosion models available such as Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), Water Erosion Prediction Project (WEPP) (Flanagan and

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Nearing, 1995), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), European Soil Erosion Model (EUROSEM) (Morgan et al., 1998) and others. These models have been developed and enhanced for their application purposes, thus the input requirements vary significantly. Among these models, the USLE model has been widely used in many countries over the years because of its ease-of-use, and extensively available input data. As explained earlier, the nature of soil erosion is essentially spatial; as a result the USLE model has been integrated with GIS by many researchers (Van Remortel et al., 2004; Yitayew et al., 1999; Ouyang and Bartholic, 2001; Lufafa et al., 2003).

One of these USLE-based soil erosion models, the Sediment Assessment Tool for Effective Erosion Control (SATEEC) system (Lim et al., 2005) has been developed in the ArcView 3x platform and has been used for soil erosion and sediment yield estimation studies. The SATEEC has been used for spatial soil erosion and sediment modeling by many researchers worldwide because of its simplicity in preparing input datasets, and its ease-of-use ArcView GIS interface (Lim et al., 2005). This system was developed with the philosophy of "very limited dataset for reasonable soil erosion estimation accuracy with commonly available GIS interface". However, the SATEEC system ver. 1.5 has limitations because it uses only the USLE dataset to estimate soil loss and sediment yield. The USLE and other USLE-based soil erosion modeling systems estimate long-term annual average soil loss. Thus, USLE-based soil erosion modeling systems, such as SATEEC system ver. 1.5, need to be modified and enhanced for practical application in soil erosion related decision making processes because they cannot reflect effects of rainfall patterns and crop growth on soil erosion. Due to these reasons, the time-variant *R* and *C* modules needed to be developed and evaluated for potential use in soil erosion and sediment yield studies in which temporal and spatial variability of erosion are important.

The sediment delivery ratio (SDR) is also important to explain sediment transported to watershed outlets. There are two SDR methods available in the SATEEC system ver. 1.5. One is a watershed area based SDR, and the other is a channel slope based SDR. However, the SDR cannot be simply explained with either watershed area or channel slope. Rather the SDR is affected by many factors, such as watershed runoff potential, watershed topography, watershed area, and many others. Thus, a better SDR estimation module needs to be developed and integrated with the SATEEC system for improved estimation of soil erosion and sediment transported to the watershed outlet.

The objectives of this study were (1) to develop SATEEC time-variant *C*, *R*, and Genetic Algorithm-based SDR modules for monthly and yearly soil erosion and sediment yield estimation and (2) to evaluate the enhanced SATEEC system by comparing the SATEEC simulated results with measured data to assess its applicability in soil erosion and sediment yield decision making processes.

2. Enhancement of the SATEEC system for higher accuracy in estimated values

The SATEEC system ver. 1.5 should only be used for long-term annual average soil erosion and sediment yield estimation. Thus, the time-variant *C* and *R* modules were developed in this study for simulation of temporal changes in soil erosion. Also a Genetic Algorithm-based sediment delivery ratio (GA-SDR) module was developed to simulate sediment delivery to watershed outlets. Fig. 1 shows how the previous version of the SATEEC system ver. 1.5 simulates soil erosion and sediment yield using the USLE input dataset and how the enhanced SATEEC system, developed in this study, simulates monthly and yearly soil erosion and sediment yield with USLE input data, a time-variant *R* module using readily available daily rainfall data, a time-variant *C* database and GA-based SDR modules.

In this study, a time-variant *R* module was developed using long-term daily rainfall databases. The time-variant *C* module was developed for 30 commonly cultivated crops using long-term simulation of SWAT, instead of implementing crop growth, canopy height and crop cover, soil organic matter, crop residue and its decomposition in the SATEEC system, which requires an intensive input dataset that goes against the SATEEC philosophy.

With the time-variant *R* and *C* modules, it would be possible to simulate soil erosion at spatiotemporal scales. However, the amount of sediment transported to the watershed outlet is important from a watershed management perspective. Thus, the SDR is utilized to estimate the sediment transported to the watershed outlet. It is defined as the fraction of net soil erosion that is transported from a watershed. There are many methods to estimate SDR, such as using watershed area and average channel slope. However, the sediment yield varies depending on the SDR methods utilized. The sediment transported to a watershed outlet is affected by watershed-specific factors; therefore those factors affecting the SDR need to be considered for accurate estimation.

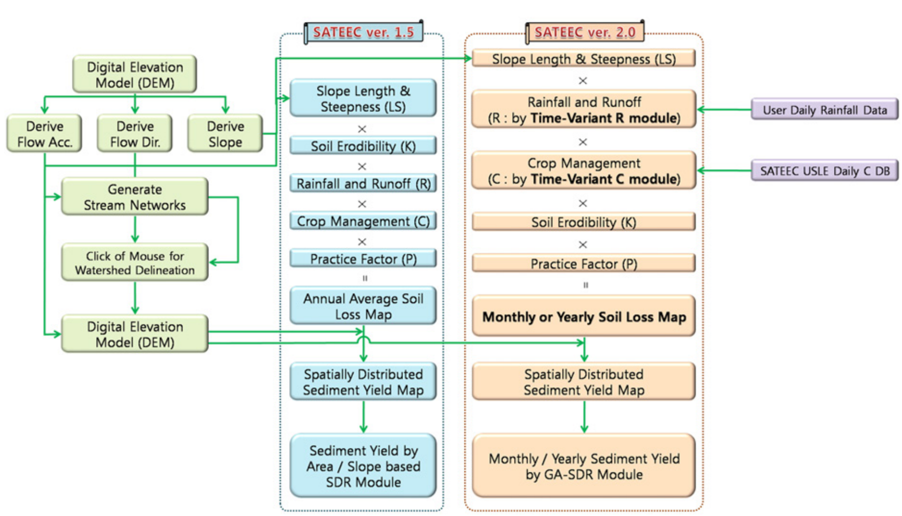


Fig. 1. Overview of previous (ver. 1.5) and enhanced (ver. 2.0) SATEEC GIS system.

The followings sections describe how the time-variant *R* and *C* modules and Genetic Algorithm-based SDR module were developed and integrated with the SATEEC ArcView GIS system.

2.1. Development of time-variant R module in the SATEEC system ver. 2.0

The previous version of the SATEEC system uses the representative single *R* factor value, calculated with at least 22-year long-term rainfall data (Wischmeier and Smith, 1978), for soil erosion and sediment yield modeling. However, rainfall patterns (monthly and yearly total rainfall amounts) change significantly. Thus, the time-variant *R* module was developed and integrated in the SATEEC ArcView GIS system to reflect effects on soil erosion of temporal changes in rainfall. Jung et al. (1983) derived equations to estimate the USLE *R* factor with regional monthly and yearly rainfall amounts. These equations were derived based on 8–21 year long-term rainfall databases. Eqs. 1 and 2 show the monthly and yearly *R* factor equation by Jung et al. (1983).

$$\text{USLE monthly } R \text{ factor}: \; R = 0.0378X^{1.4190} \tag{1}$$

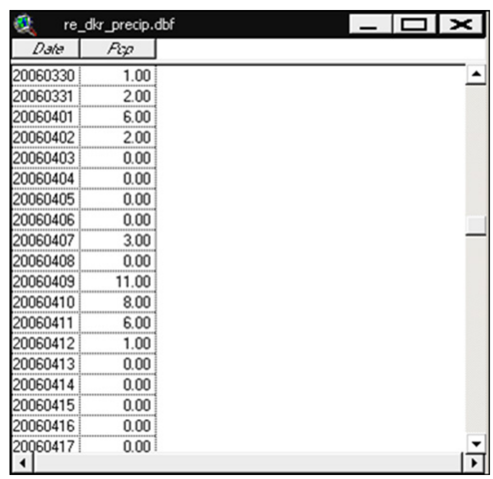
where X is monthly rainfall amount (mm) and R is rainfall and runoff erosivity (MJ mm/ha hr year).

$$\text{USLE yearly } R \text{ factor}: \; R = 0.0115Y^{1.4947} \tag{2}$$

where Y = yearly rainfall amount (mm) and R is rainfall and runoff erosivity (MJ mm/ha h year).

However, these equations are not applicable for mountainous areas. Thus, Jung et al. (1999) evaluated the monthly and yearly *R* factor estimation equation suggested by Jung et al. (1983) for various regions in Korea and suggested a regional adjustment coefficient because of significant variations in rainfall intensity. Thus, Jung et al. (1999) suggested a regional adjustment coefficient value of 0.595 for mountainous areas and 1.000 or less for other non-mountainous regions. The monthly and yearly *R* factor estimation equations suggested by Jung et al. (1983) and regional adjustment coefficient values by Jung et al. (1999) were used to develop a time-variant *R* factor module in the enhanced SATEEC system ver. 2.0. As explained before, the SATEEC system was developed for soil erosion and sediment estimation with only USLE input data. Thus, if more intensive input data are needed for a time-variant *R* module in the enhanced SATEEC system, the SATEEC system would not be used worldwide. To meet the SATEEC system development philosophy, only long-term daily rainfall data are required in addition to USLE input dataset for time-variant *R* module in the enhanced SATEEC system ver. 2.0. The ArcView Avenue programs were written to read daily rainfall data for a time-variant *R* module. It calculates monthly and yearly *R* factor values with daily rainfall amount and then generates monthly and yearly soil erosion and sediment yield values spatially and temporally (Fig. 2). To provide auxiliary data to SATEEC users, monthly and yearly *R* factor values were provided in graphical format within the SATEEC ArcView GIS platform and a text file for further analysis.

The long-term daily precipitation needs to be prepared in .dbf file format for the time-variant *R* module. The SWAT long-term daily precipitation format was used for the time-variant *R* module in the enhanced SATEEC system ver. 2.0 because of the wide use of the SWAT model in hydrological and soil erosion modeling worldwide (Fig. 3).


re_dkr_precip.dbf

Date	Pcp
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20060331	2.00
20060401	6.00
20060402	2.00
20060403	0.00
20060404	0.00
20060405	0.00
20060406	0.00
20060407	3.00
20060408	0.00
20060409	11.00
20060410	8.00
20060411	6.00
20060412	1.00
20060413	0.00
20060414	0.00
20060415	0.00
20060416	0.00
20060417	0.00

Fig. 3. Daily rainfall data format in enhanced SATEEC ver. 2.0 system.

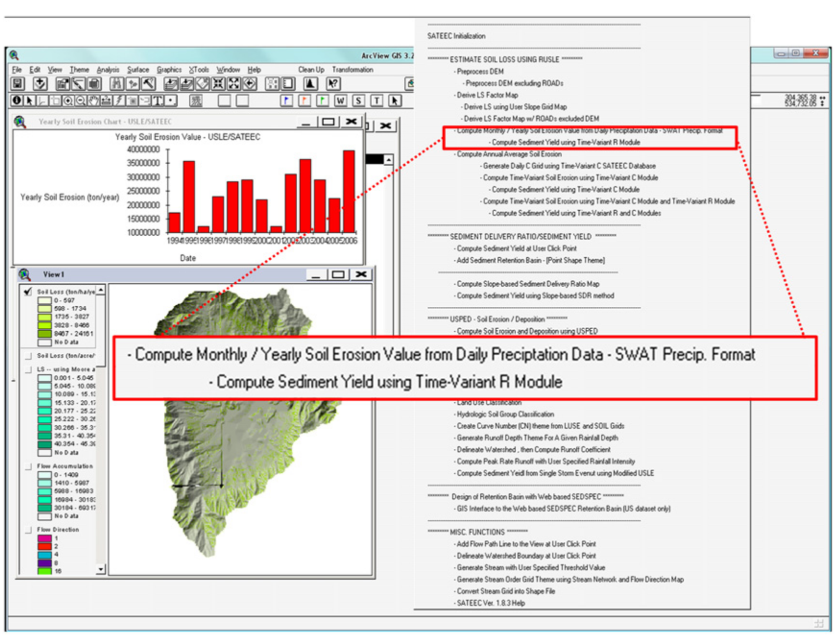

Fig. 2. Time-variant *R* factor module developed for enhanced SATEEC 2.0 system.

The equation used in the time-variant *R* module was derived using the long-term dataset in Korea. Thus, the SATEEC users can easily update these equations in the Avenue script with locally available data. The enhanced SATEEC is now able to be used for time-variant soil erosion characteristics due to precipitation, which were not possible in most USLE-based soil erosion modeling systems.

2.2. Development of time-variant C module in the SATEEC system ver. 2.0

In this study, the time-Variant *R* module was developed to reflect temporal changes in soil erosion with daily rainfall data. However, rainfall is not the only time-variant factor affecting soil erosion. In addition to rainfall amount, surface cover condition with crop growth is important in soil erosion modeling. Thus, the time-variant *C* module was developed and integrated in the SATEEC system. In the previous SATEEC system ver. 1.5, the USLE *C* factor values for representing land cover types, such as forest, agricultural area, urban, pasture, etc., could be simulated. It was not possible to simulate temporal effects on soil erosion of various agricultural crop growths because of lack of temporal USLE *C* data for various crops. To apply the SATEEC system to agriculturally dominant watersheds, the system needs to be expanded and enhanced to reflect temporal changes occurring within the watershed. From an agricultural perspective, crop planting, growth, withering, and kill/harvest need to be considered. Thus, a time-variant *C* module was developed and integrated with the SATEEC system after considering these factors.

2.2.1. Daily USLE C factor computation in SWAT model

The Soil and Water Assessment Tool (SWAT) model simulates sediment yield using the Modified Universal Soil Loss (MUSLE) (Williams, 1975) for a given rainfall. The daily *C* value is calculated within SWAT for MUSLE computation. The daily *C* is computed based on crop growth, surface residue and organic matter decomposition, crop-specific data (specified in crop.dat file), growth rate considering water stress, temperature stress and nutrient stresses, as described in the SWAT User's Manual (Neitsch et al., 2001). Eq. (3) shows how daily USLE *C* is computed within the SWAT model.

$$C_{USLE} = \exp([\ln(0.8)\text{-}\ln(C_{USLE,mn})]\exp[-0.00115\,rsd_{surf}] + \ln(C_{USLE,mn})) \quad (3)$$

where $C_{USLE,mn}$ is the minimum value for the cover and management for the land cover and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

The $C_{USLE,mn}$ value is the minimum value for the cover and management for a given land cover, or crop type. The rsd_{surf} is the amount of residue on the soil surface. The rsd_{surf} is calculated based on temporal weather and land surface conditions. It is determined based on biomass and soil organic matter residue, which are a function of weather (daily average temperature, humidity and rainfall amount), soil moisture condition and evapotranspiration at each crop growth stage. Eq. (4), which can be found in SWAT source code, shows how surface residue (rsd_{surf}) is calculated with biomass and residue amounts over the simulation period. Biomass and residue are calculated using crop growth depending on weather conditions such as precipitation, solar radiation, temperature, humidity and wind speed. The module can simulate slow crop growth due to water, temperature, nitrogen and phosphorus stresses.

$$rsd_{surf} = 0.8 \cdot \text{biomass} + \text{residue} \quad (4)$$

where rsd_{surf}: material in the residue pool for the top 10 mm of soil (kg/ha); biomass: land cover, crop biomass (kg/ha) and residue: amount of organic matter in the soil layer (kg/ha).

As explained in this section, the SWAT model calculates daily *C* values internally for sediment yield estimation from its hydrologic response unit, which is the basic computation element in the SWAT model (Arnold and Srinivasan, 1994). SWAT estimated daily USLE *C* values from long-term simulation are extracted externally with modification in the SWAT source codes because it can represent average crop growth and various water, temperature and nutrient stresses, affecting crop growth and daily *C* computation.

2.2.2. Development of daily USLE C factor databases using the SWAT model

To extract daily *C* value for various agricultural crops, the planting and harvesting date, tillage and fertilizer application data were compiled for 30 major crops, and the SWAT model was run using climate data from 1974 to 2005. The SWAT model requires a warming-up period because the model regards land condition as desolate at the initial stage of model runs, i.e., no residue and no organic matter on the surface. Thus, the model simulated results for the first 10 years were dropped in calculating daily *C* values. Therefore, USLE *C* factor values from 1985 to 2005 were used to build the daily *C* database. Fig. 4(a)–(d) shows daily USLE *C* values for 4 crops. Because of the crop residue from the previous year cultivation, the starting USLE *C* values are not that high, as expected. The residue values show a gradual decrease in trend for 30 crops simulated in this study because of organic matter decomposition. The residue value increases sharply right after harvesting, while biomass starts to increase after planting with the crop growth until the maturity period. With changes in both residue and biomass amounts, the daily USLE *C* values increase gradually until planting, decrease until harvesting, increase sharply on the harvest day and increase gradually after harvesting. The modified SWAT daily *C* values show reasonable tendency. Fig. 4 shows daily USLE *C* values for potato, watermelon, cucumber and tomato, simulated in this study. There are large differences in simulated USLE daily *C* values for various crops. For example, maximum and minimum *C* values for potato were 0.659 on the 115th Julian day and 0.370 on the 214th Julian day. However, maximum and minimum values of watermelon were 0.784 on the 170th Julian day and 0.644 on the 232nd Julian day, and maximum of 0.689 and minimum of 0.491 for cucumber, respectively (Fig. 4(a)–(c)). For tomato, there were 0.377 differences between maximum and minimum USLE *C* factor (maximum *C* of 0.628 and minimum *C* of 0.250) (Fig. 4(d)). This result indicates that use of a single USLE *C* factor value for each crop could result in loss of temporal changes in soil erosion patterns.

The daily USLE *C* factor values for 30 crops were compiled and stored in .dbf file to be used in the enhanced SATEEC system, capable of simulating time-variant *C* effects. This database is used to calculate soil erosion on a daily basis with the daily time-variant *C* and monthly time-variant *R* module. The daily USLE *C* values for each crop can be different on the same day depending on the planting date and crop growth. Thus, the "Crop DB Edit" module was developed to allow users to adjust the planting date of each crop in time-variant *C* simulation (Fig. 5).

2.3. Development of SATEEC ArcView GIS interface for time-variant R and C modules

To enable automatic calculation of soil erosion and sediment yield spatially and temporarily from agricultural watersheds with the time-variant *R* and *C* modules simultaneously, ArcView Avenue programs were written and several options are added to the SATEEC ArcView GIS system. Fig. 6 shows the time-variant *C*

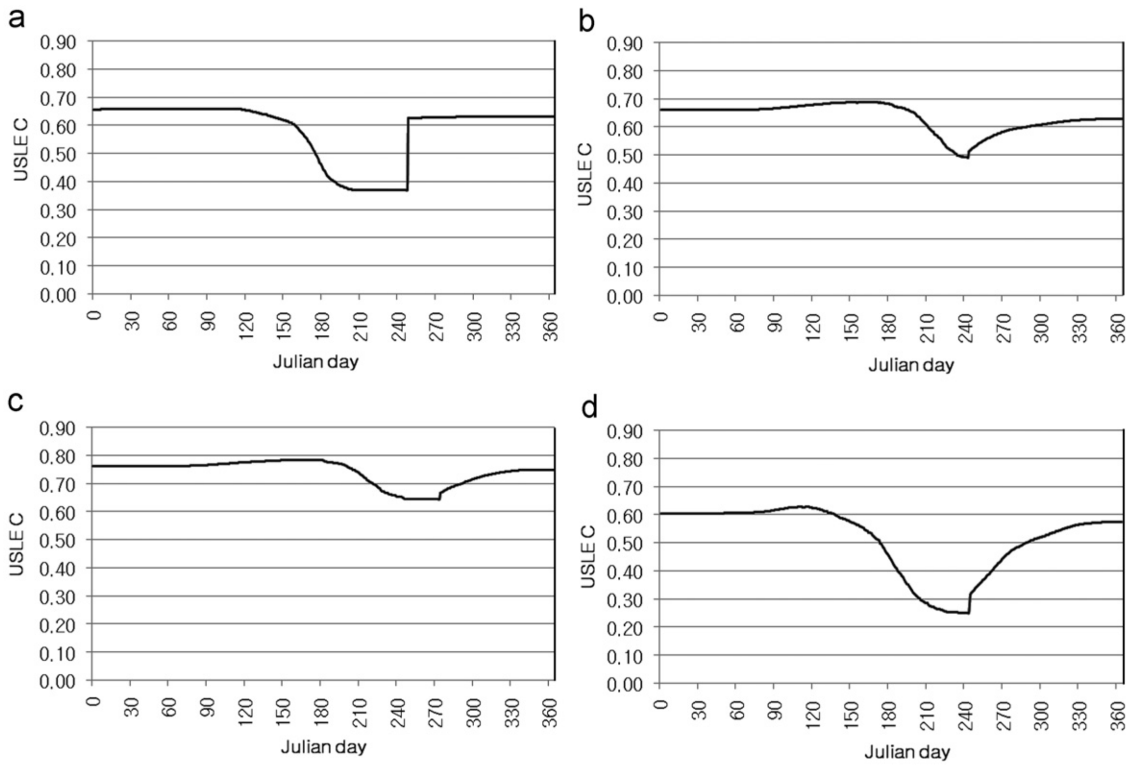

Fig. 4. Daily USLE *C* values for various crops. (a) potato; (b) watermelon; (c) cucumber and (d) tomato.

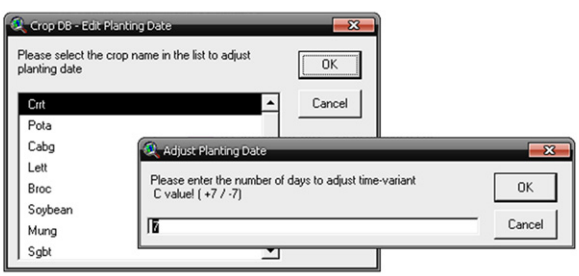

Fig. 5. Function to adjust planting date of each crop.

module coupled with the time-variant *R* module for temporal analysis of soil erosion and sediment yield using USLE input dataset and daily precipitation data, which are both readily available in most countries.

2.4. Development of Genetic Algorithm-based sediment delivery ratio module

With time-variant *R* and *C* modules, the SATEEC system ver. 2.0 estimated monthly and yearly soil loss values reflect temporal rainfall and land cover condition reasonably well from a soil erosion perspective. To develop effective soil erosion management practices at a watershed scale, the sediment transported to the watershed outlet should be estimated in a proper manner. The sediment delivery ratio (SDR) is used to explain the potential deposition of eroded soil in the watershed. It is defined as the fraction of net soil erosion that is transported from a watershed. It can be expressed as

$$\mathrm{SDR} = Y/E \tag{5}$$

where *Y* is average annual sediment yield per unit area and *E* is average annual erosion over the same area.

It estimates the sediment yield that is transported from the watershed to the watershed outlet. It usually has a value between 0 and 1, because of potential deposition of eroded soil when transported to the watershed outlet. There are several methods available in the SATEEC system ver. 1.5 estimate SDR, such as watershed area based SDR (Boyce, 1975; USDA, 1972; Vanoni, 1975; Eqs. (6)–(8)), slope based SDR (Williams, 1977; Eq. (9)) and SDR based on watershed topographic and runoff potential characteristics with watershed area (Williams and Berndt, 1977; Eq. (10)).

$$\mathrm{SDR} = 0.5656\,\mathrm{AREA}^{-0.11} \tag{6}$$

$$\mathrm{SDR} = 0.375\,\mathrm{AREA}^{-0.2382} \tag{7}$$

$$\mathrm{SDR} = 0.472\,\mathrm{AREA}^{-0.125} \tag{8}$$

$$\mathrm{SDR} = 0.627\,\mathrm{SLOPE}^{0.403} \tag{9}$$

$$\mathrm{SDR} = 1.366 \times 10^{-11}(\mathrm{DA}^{-0.0998})(\mathrm{ZL}^{0.3629})(\mathrm{CN}^{5.444}) \tag{10}$$

where, DA and AREA are watershed area (km^2), SLOPE is slope of watershed (%), ZL is relief ratio (m/km) and CN is curve number.

The SDR characteristics of a watershed cannot be simply explained with watershed area or average channel slope (Eqs. (6)–(8) and (9)). Park et al. (2007a) reported that sediment values estimated with various SDR methods (Eq. (6)–(9)) using the same input data were different to some degree. Williams and Berndt (1977) suggested the SDR equation (Eq. (10)) reflecting watershed area, relief ratio and average CN values to explain sediment transport processes to the watershed outlet. However, watershed-specific coefficient and exponent values of the SDR estimation equation by Williams and Berndt (1977; Eq. 10) should be identified for higher accuracy in estimated sediment values. In this study, a Genetic Algorithm-based sediment delivery ratio (GA-SDR) module was developed to derive watershed-specific SDR equation. The GA-SDR module of the SATEEC system ver. 2.0

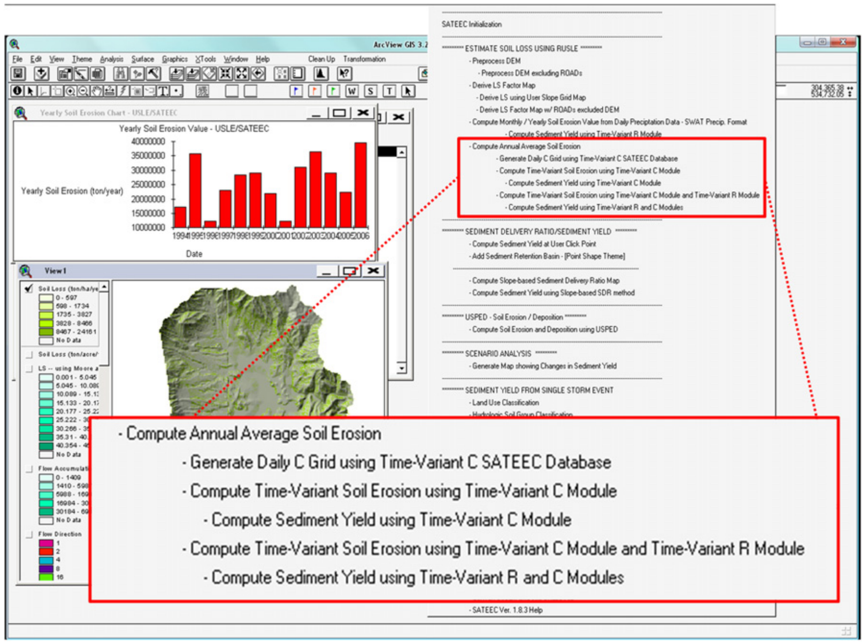

Fig. 6. Time-variant *C* module in the enhanced SATEEC ver. 2.0 ArcView GIS system.

determines coefficient and exponent values of Eq. (11) using watershed area, slope, CN values and measured data at the watershed outlet.

$$\mathrm{SDR} = A\,\mathrm{AREA}^{B}\,\mathrm{SLOPE}^{C}\,\mathrm{CN}^{D} \quad (11)$$

where *A–D* are coefficient and exponent values of the GA-SDR equation, AREA is area of watershed in km^2, SLOPE is average slope of watershed (%) and CN is the average curve number.

The Genetic Algorithm (GA) was developed by Holland (1975) and has been used in many scientific studies. It is based on the principles of 'survival of the fittest'. It sets up a population of individuals to the engineering problem, and strives to create the individual that has 'best fitness'. There are three operators in the GA. The first operator is "Selection". The population is changed from poorer solutions to better solutions to remain. The second operator is "Crossover". It is the procedure where the genetic material of several pairs of solutions and some of their values are traded. It gives better fitness individuals a higher probability of being selected. The third operator is "Mutation". A small percentage of individuals in the population have one or more of their values altered (Holland, 1975; Georgieva and Jordanov, 2009; Wu et al., 2006). Fig. 7(a) shows how the GA-SDR was developed and integrated with the SATEEC system for higher accuracy in estimated sediment values. The GA-SDR module requires the watershed area, average slope and the average CN value for a watershed. These values are extracted from the USLE/SATEEC input dataset automatically (Fig. 7(b)) and rearranged to be compatible with the GA-SDR input format in the SATEEC system ver. 2.0 to provide a simple-to-use interface and accurate estimated sediment values with a limited dataset.

3. Evaluation of SATEEC System ver. 2.0 with time-variant *R*, *C* modules and Genetic Algorithm-based sediment delivery ratio module

To demonstrate the efficiency of the time-variant *C*, *R* and GA-SDR modules in the enhanced SATEEC system ver. 2.0, the Imha watershed, located at Andong, South Korea, was selected because this watershed has been designated as a soil erosion hot spot area due to year-long sediment-laden water problems, mainly from agricultural areas during the monsoon period. Fig. 8 shows the location and land uses in the study watershed, where forest is the primary land use and most agricultural fields are located along the stream. Thus, the soil eroded from these agricultural areas has an increased chance of being transported into the stream, causing severe sediment-laden water problems at the Imha watershed (Park et al., 2007b). The watershed is 1361 km^2 in size. The land uses in this watershed are: forest 79.8%, agricultural areas 16.0%, residential areas 1.4%, water 2.4% and pasture 0.4%.

To estimate the soil loss using the time-variant *C* and *R* modules, the USLE input parameters for the study watershed were prepared. The *K* factor was computed based on the ratio of sand, silt and clay content. The *P* factor was computed based on an adaptation of *P* factor values listed in Wischmeier and Smith (1978). The LS factor was estimated using the LS module in SATEEC. The method developed by Moore and Burch (1986a, 1986b) was used to calculate the LS factor from the Digital Elevation Model (DEM) in the SATEEC system. All DEM pre-processing and map algebra were automated with Avenue programming. According to the RUSLE User's Guide (Foster et al., 1996), the length of hill slopes in the USLE experimental plots ranged from 10.7 m (35 ft) to 91.4 m (300 ft). It was recommended that the use of slope lengths less than 122 m (400 ft) is desired because overland flow becomes concentrated into the rills in less than 122 m (400 ft) under natural condition (Foster et al., 1996). Thus, SATEEC computes the LS factor using the method developed by Moore and Burch (1986a, 1986b) with an upper limit of field slope length.

Time-variant *R* and *C* modules, developed in this study, were utilized for *R* and *C* factors. To estimate coefficient and exponent values of the Imha watershed-specific SDR equation, measured sediment values collected from 1999 to 2008 at the Imha watershed were prepared for the GA-SDR module of the enhanced SATEEC system ver. 2.0. The SATEEC system ver. 2.0 with time-variant *R* and *C* modules and GA-SDR module was calibrated using measured data from 1999 to 2004, and validated from 2005 to 2008 to demonstrate the SATEEC system ver. 2.0 applicability in temporal soil erosion and sediment study at a watershed scale. The GA-SDR estimated for the Imha watershed-specific SDR

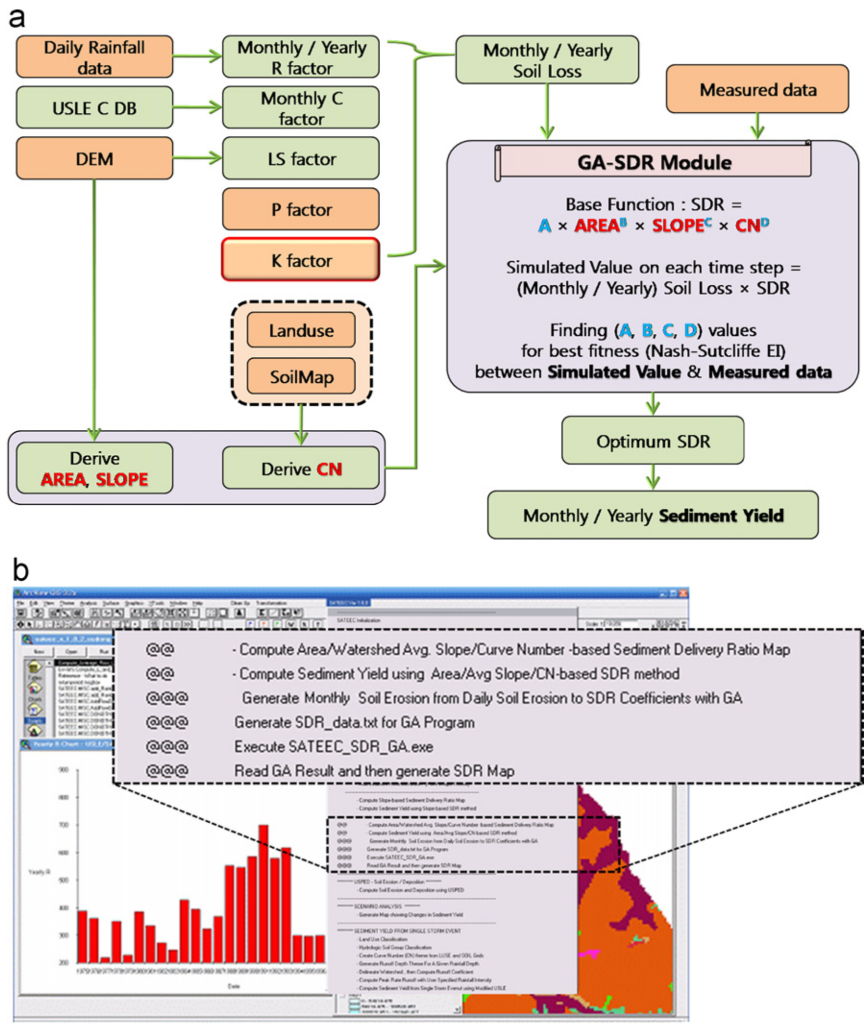

Fig. 7. GA-SDR modules in SATEEC ver. 2.0 System. (a) Overview of the SATEEC GA-SDR module and (b) SATEEC 2.0 ArcView GIS interface to GA-SDR module.

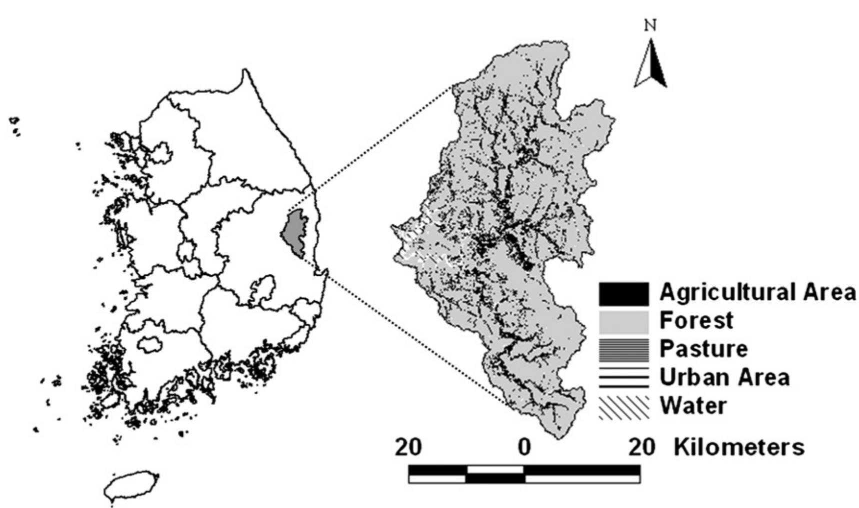

Fig. 8. Location and land-use at Imha Watershed, Gyeongsangbuk-do, South Korea.

equation using measured data for the calibration period is shown in Eq. (12). Eq. (12), the Imha SDR equation, was used to estimate sediment for the validation period at the Imha study watershed and compared with measured data for the validation period.

$$SDR = (6 \times 10^{-4})AREA^{(0.022)}\,SLOPE^{(0.1901)}\,CN^{(0.0267)} \quad (12)$$

where AREA is area of watershed in km^2, SLOPE is average slope of watershed (%) and CN is average curve number.

Fig. 9(a) shows the comparison of the SATEEC estimated and measured sediment values at the Imha watershed for the calibration period. The determination coefficient (R^2) and the Nash–Sutcliffe efficiency index (EI) for the calibration period were

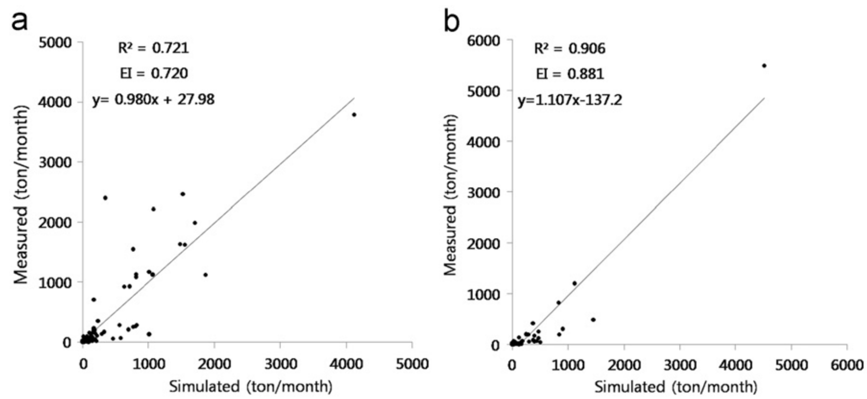

Fig. 9. Comparison of SATEEC simulated and measured values for calibration and validation periods. (a) Calibration period (1999–2004) and (b) validation period (2005–2008).

0.72 and 0.72, respectively. Fig. 9(b) shows the comparison of the SATEEC estimated and measured values for the validation period. The R^2 and EI values for the validation period were 0.91 and 0.88, respectively. The R^2 and EI values for calibration and validation indicate that the enhanced SATEEC system ver. 2.0 with time-variant *R* and *C* modules and GA-SDR module can be used in soil erosion and sediment studies with high accuracies.

4. Conclusion

Because of many limitations in the SATEEC system ver. 1.5 in simulating soil erosion and sediment yield at temporal and spatial scales, the SATEEC system was enhanced in this study by developing the time-variant *R* and *C* modules and Genetic Algorithm-based sediment delivery ratio (GA-SDR) module. These modules were integrated with the SATEEC system to provide an easy to use interface with high accuracy in simulated values. The time-variant *R* module was developed with the equation based on long-term measured rainfall data and ArcView Avenue programming. The time-variant *C* module was developed with modification in SWAT source codes to extract daily *C* values for 30 crops, and Avenue programming. Also, the GA-SDR module was developed for sediment yield estimation at watershed outlets with simple GA codes and Avenue programming to automate the GA-SDR operation within the SATEEC system ver. 2.0 interface. The time-variant *C*, *R* and GA-SDR modules were applied to the Imha watershed to investigate its performance in soil erosion and sediment yield studies. The R^2 and EI values for the calibration were 0.72 and 0.72, respectively, and the R^2 and EI values for the validation were 0.91 and 0.88, respectively. These R^2 and EI values indicate that the enhanced SATEEC system ver. 2.0 with time-variant *R* and *C* modules, and GA-SDR module can be used in spatial and temporal analysis of soil erosion and sediment studies at watershed scales with very limited USLE input data and long-term daily rainfall data, which are available in most countries.

As shown in this study, the enhanced SATEEC system ver. 2.0 has many benefits over the complicated and physically based watershed models in that (1) the enhanced SATEEC system ver. 2.0 requires only USLE input data and commonly available rainfall data and measured sediment values at the watershed outlet and (2) the enhanced SATEEC system ver. 2.0 simulated results match the measured data with R^2 and EI values greater than 0.70 as shown in this study.

The time-variant *R* module generates monthly *R* values, rather than event-based *R* values. Thus, the enhanced SATEEC system ver. 2.0 cannot reflect the magnitude of storm events in soil loss estimation. If the event-based *R* module is developed and integrated with the time-variant *R* and *C* modules and GA-SDR module of the SATEEC system ver. 2.0, the enhanced SATEEC system will become a powerful soil erosion sediment assessment tool with limited input dataset. The daily USLE *C* database was obtained from SWAT runs with climate data and agricultural management data in Korea. The daily USLE *C* database should be adjusted depending on the climate condition and agricultural management when SATEEC is applied to other watersheds having different climate and agricultural management systems. The daily USLE *C* databases were obtained from 30 year SWAT simulation. Therefore, there are discontinuities in estimated USLE *C* values for January 1st and December 31st for most crops, which were not true in reality. Further investigation will be performed to develop USLE *C* databases under various management scenarios for various crops and weather scenarios in the next version of the SATEEC system.

In most SDR estimation methods, the SDR is generally less than 1.0, although the SDR could potentially exceed 1.0 for a watershed experiencing greater channel erosion, gully erosion, and other erosion processes. The SDR should not be used to estimate sediment delivered to the watershed outlet for these watersheds. This is one of the shortcomings of previous version of the SATEEC system ver. 1.5, which estimates the SDR using a regression equation between the SDR and watershed area. The GA-SDR module estimated SDR could be greater than 1.0 because the GA-SDR estimates the SDR equation with measured sediment data, which include sediments from various sources, such as rill/sheet erosion, channel erosion, gully erosion and other erosion processes occurring in the watershed. Although other erosion processes were not explicitly simulated with the current SATEEC system, a SDR greater than 1.0 could explain some of these erosion processes.

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