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SATEEC GIS System for Spatiotemporal Analysis of Soil Erosion and Sediment Yield

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1. Introduction

In recent years, severe rainfall events have been causing various negative impacts on environment and ecosystem at the receiving water bodies. Especially soil erosion and resulting muddy water problems driven by rainfall-runoff have been hot issues in many countries due to accompanying water quality impacts. Thus various efforts have been made to evaluate soil erosion and sediment yield spatially and temporarily to develop effective soil erosion best management practices. Among those, modeling approaches have been often utilized and many soil erosion models have been developed and evaluated worldwide. In the past couple of decades, these soil erosion models have been integrated with Geographic Information System (GIS) for spatiotemporal analysis of generation and transport of soil erosion/sediments. The Universal Soil Loss Equation (USLE), Water Erosion Prediction Project (WEPP), Soil and Water Assessment Tool (SWAT), European Soil Erosion Model (EUROSEM), Agricultural Non-Point Source Pollution (AGNPS) are widely used for various soil erosion studies. The input requirements for these models vary to some extents. The USLE model has been widely used because its input data are available in most countries and the model is relatively easy to implement. This USLE model has been integrated with GIS for spatiotemporal analysis of soil erosion by many researchers worldwide. The Sediment Assessment Tool for Effective Erosion Control (SATEEC) is one of them with several enhanced modules for sediment yield estimation at a watershed scale with higher accuracies in sediment evaluation. In this chapter, the development history of the SATEEC system and several SATEEC applications for soil erosion and sediment yield estimation will be introduced.

2. Development of SATEEC GIS system

The SATEEC system was developed in 2003 (Lim et al., 2003) and has been upgraded with various enhanced modules incorporated into the system (Lim et al., 2005; Park et al., 2010). It has been applied to various watersheds with diverse purposes (Yoo et al., 2007; Park et al., 2007; Park et al., 2008). In the current SATEEC 2.1 system, the soil erosion is estimated using USLE with time-variant R and C modules. The sediment delivery ratio (SDR) is estimated using area-based SDR module, channel slope-based SDR module, and Genetic Algorithm-based SDR module in the SATEEC system. In addition, several miscellaneous modules are available for various soil erosion and sediment yield applications.

2.1 SATEEC Version 1.0 ~ 1.8

2.1.1 USLE-based SATEEC for soil erosion and area-based sediment delivery ratio modules

The system requiring only USLE inputs was developed with the philosophy of "very limited dataset for reasonable soil erosion estimation accuracy with commonly available GIS interface" and "easy-to-use", To keep the philosophy and provide user with watershed assessment capabilities, the SATEEC version 1.x system utilized are area-based and slope-based SDR methods. The SDR in general is defined as a ratio of the soil which reaches the watershed outlet to soil detached from source area (Yin et al., 2005). The SDR is affected by various watershed characteristics such as watershed area, geomorphologic properties, precipitation pattern, total runoff and peak flow volume, land use properties, physical properties of soil, etc. These characteristics affect it not only with *spatial properties* also *temporal properties*. However, it is not feasible to reflect all of these in estimating SDR due to limited data sets. Empirical regression models to estimate SDR for watersheds were proposed by many researchers; one of them is to estimate SDR using watershed area as shown below (USDA, 1972, Boyce, 1975, USDA, 1972).

$$\mathrm{SDR} = 0.4720 \times \mathrm{A}^{-0.125} \text{ (Vanoni, 1975)} \tag{1}$$

$$\mathrm{SDR} = 0.5656 \times \mathrm{A}^{-0.11} \text{ (Boyce, 1975)} \tag{2}$$

$$\mathrm{SDR} = 0.3750 \times \mathrm{A}^{-0.2382} \text{ (USDA, 1972)} \tag{3}$$

Where, SDR is sediment delivery ratio, and A is watershed area (km^2).

These regression models with only watershed area as an input are useful for a watershed with very limited watershed characteristics data to estimate SDR. These area-based SDR is the first approach in SATEEC system to estimate sediment yield at the watershed outlet.

Yoo et al. (2007) reported that soil reconditioning in agricultural field could affect sediment yield at the watershed significantly. Thus area-based SDR was used to estimate sediment yield and it was found that soil loss could increase by 138.0 % per unit hectare while sediment yield could increase by 59.4 % per unit hectare with various activities in the watershed. It indicates that estimated soil loss and sediment yield may not show identical trend.

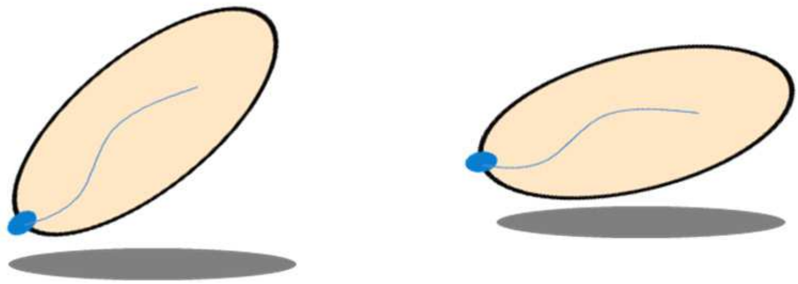
2.1.2 Slope-based Sediment Delivery Ratio modules

Area-based SDR module provides convenience to estimate SDR with limited data collection for a given watershed, The SDR in the watershed is affected by various geomorphologic properties such as average channel slope than watershed area. Thus, slope-based SDR module was incorporated into the SATEEC system to supplement limitation of area-based SDR module.

$$\mathrm{SDR} = 0.627 \times \mathrm{S}^{0.403} \text{ (Williams \& Berndt, 1977)} \tag{4}$$

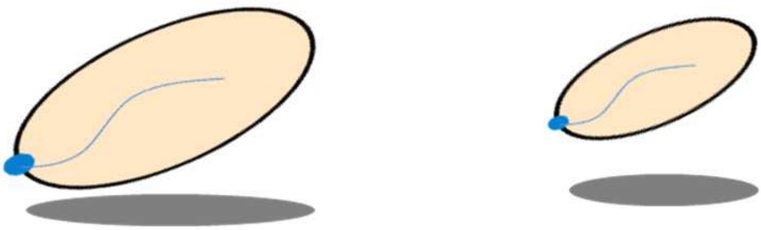
Where, S is slope of watershed.

As indicated above, the SDR could be identical if the area-based SDR is applied to two different watersheds with the same area. Thus, the SATEEC was modified to integrate slope-based SDR module using equation (4). Park et al. (2007) reported that SDRs for 19 small watersheds having identical watershed area were different due to various average channel slope in each watershed, and sediment yields were different by not only USLE factors also estimated SDR for the watersheds. The SDRs by area-based SDR module were calculated as 0.762 for the same size watershed (0.0219 square kilometer). However, the SDRs by slope-based SDR module were from 0.553 to 0.999 with varying slope from 0.73 % to 3.17 %. It indicates that the SDR is one of watershed-specific conditions, thus, better ways to estimate SDR needs to be developed based on various characteristics of watershed and measured data, not just based on single parameter such as only area or only slope. The slope-based SDR module has similar limitation as area-based SDR module does (Figure 1).



Watershed 1
Area = A
Slope = S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Watershed 2
Area = A
Slope = 0.5 S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times (0.5\ S)^{0.403}$



Watershed 3
Area = A
Slope = S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Watershed 4
Area = 0.5 A
Slope = S
$SDR_{area} = 0.472 \times (0.5\ A)^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Fig. 1. Comparison of SDR for watersheds

The research indicated the SDR is not always the most influential and fundamental factor in sediment yield estimations. However it is also one of very important factors to estimate sediment yield which is site-specific/watershed-specific. For instance with Figure 1, watershed areas for Watersheds 1 and 3 with different slope condition, the SDR based on area are identical, but the SDRs based on slope are different. As shown in this comparison, the influence of slope is ignored if SDR is calculated with only their area. In the other way, if the average channel for Watersheds 3 and 4 are the same, while the area of Watershed 3 is greater than that of Watershed 4, the slope-based SDR values are the same while the area-based SDRs are different. From these examples, area-based and slope-based SDR need to be enhanced by incorporating more watershed characteristics affecting generation and transportation of soil erosion and sediment to the watershed outlet.

2.2 SATEEC version 2.0 ~ 2.1

2.2.1 Time-variant SATEEC R and C modules for monthly and yearly soil erosion and sediment

One of highly beneficial modification in SATEEC ver. 2.0 is time-variant soil erosion simulation with temporal USLE factors to reflect surface condition of land and precipitation, represented by USLE C and R factors respectively. Soil loss or sediment yield represented with a single value using long-term precipitation data is not sufficient for various soil erosion studies to develop site-specific Best Management Practices. Soils erosion at the watershed is affected by not only total volume of precipitation but also precipitation intensity or patterns. The SATEEC ver. 2.0 was enhanced to reflect precipitation pattern for soil erosion estimation monthly and annually. Time-variant R module integrated into SATEEC ver. 2.1 derives monthly or yearly USLE R factors using daily precipitation data, using regression models suggested by Jung et al (1983).

$$\text{USLE monthly R factor: } R = 0.0378 \times X^{1.4190} \quad (5)$$

$$\text{USLE yearly R factor: } R = 0.0115 \times Y^{1.4947} \quad (6)$$

Where, X is monthly rainfall amount (mm) and Y is yearly rainfall amount (mm).
With this Time-Variant R module in the SATEEC ver. 2.0, the SATEEC could be used for temporal analysis of soil erosion with USLE input data and readily available rainfall data. In addition to the Time-Variant R module, the Time-Variant C module was developed to reflect crop growth and various management practices such as planting, growth, withering, and kill/harvest at the agricultural fields as well as forest. USLE factor representing land use condition is USLE C factor; they vary depending on land use.

$$C_{USLE} = \exp([\ln(0.8) - \ln(C_{USLE,mn})] \times \exp[-0.00115 \times rsd_{surf}] + \ln(C_{USLE,mn})) \quad (7)$$

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).
SWAT model estimates daily USLE C values for each crop (equation (7)). Instead of adding SWAT USLE C module for dynamic simulation of crop growth in the SATEEC system, the Time-Variant C module was developed in the SATEEC, allowing user to use daily-based USLE C DB containing 30 representative crops and adjust planting date of each crop for watersheds. The USLE C factor values in SATEEC ver. 2.0 represent crop growth well. For instance, the USLE C factor for potato shows the range from 0.370 to 0.659, from 0.644 to 0.784 for watermelon, from 0.491 to 0.689 for cucumber, and from 0.250 to 0.628 for tomato. Simple interface was developed to allow users to adjust a certain schedule of agricultural

activities for each crop so that temporal land use change of the year in the given watershed can be considered. These Time-Variant R and C modules are available in SATEEC 2.0 system (Park et al., 2010). The application of SATEEC with these modules described in following section showed reasonable results, when compared with measured data.

2.2.2 Sediment yield estimation using genetic-algorithm-based SDR module

Additional and significant enhancement in the SATEEC is an integration of SDR module considering various watershed characteristics. One of benefits to use the SATEEC is to estimate sediment yield with only USLE factors and SDR; however, the SDRs in SATEEC ver. 1.x had limitation because it only estimated SDR based on either area or average slope. As indicated by Park et al. (2007), the SDR needs to be estimated with various watershed characteristics not with single factor because of complicated sediment yield mechanism. To derive SDR for a given watershed with given data for soil loss simulation, a SDR module was developed with optimization algorithm to determine coefficient and exponents of basic formula with watershed area, average slope, Curve Number as fundamental parameters for a given watershed. The modified SDR module in SATEEC ver. 2.0 estimates the SDR equation using three watershed parameters and four coefficient and exponents, that are watershed area, average slope, and curve number to explain sediment transport processes to the watershed outlet.

$$\mathrm{SDR} = \mathrm{A} \times \mathrm{Area}^{\mathrm{B}} \times \mathrm{Slope}^{\mathrm{C}} \times \mathrm{CN}^{\mathrm{D}} \tag{8}$$

Where, A-D are coefficient and exponents, Area is watershed area (km^2), Slope is average slope of watershed (%), and CN is average curve number of watershed.

The Genetic-Algorithm developed by Holland (1975) was utilized to derive these coefficient and exponents to derive the SDR (Genetic-Algorithm-based Sediment Delivery Ratio: GA-SDR) in the SATEEC system. It is available in the SATEEC 2.0 system. The genetic algorithm has been applied to many scientific studies to solve complex problems, based on the principle of 'survival of the fittest' and setting up a population of individuals.

Figure 2 shows how the GA-SDR module was integrated to SATEEC ver. 2.0; the module requires only the data for soil loss estimation in SATEEC. The basic formula of the module requires watershed area, watershed average slope, and CN, they are derived by Digital Elevation Model (DEM), land use, and soil map data, then the coefficient and exponents are determined by the algorithm, compared measured data.

SATEEC ver. 2.0 was applied to a watershed which has 1,361 square kilometers with the Time-Variant modules and GA-SDR modules, it showed reasonable results represented with 0.721 and 0.720 of determination coefficient (R^2) and Nash-Sutcliff efficiency index (NSE) in calibration, 0.906 and 0.881 of R^2 and NSE in validation (Park et al., 2010).

2.2.3 Daily USLE R modules for daily soil erosion estimation

The latest version of SATEEC through various modifications is the SATEEC ver. 2.1 that allows user to estimate daily soil loss and sediment yield with enhanced R_5 module. The SATEEC ver. 2.0 provides time-variant estimation of soil loss and sediment yield with the Time-Variant C and R modules and GA-SDR module, daily assessment of soil loss and sediment yield at the watershed outlet is in need due to the particularity of precipitation affecting to soil erosion in a single day or a few days, such as typhoon. But deriving USLE R

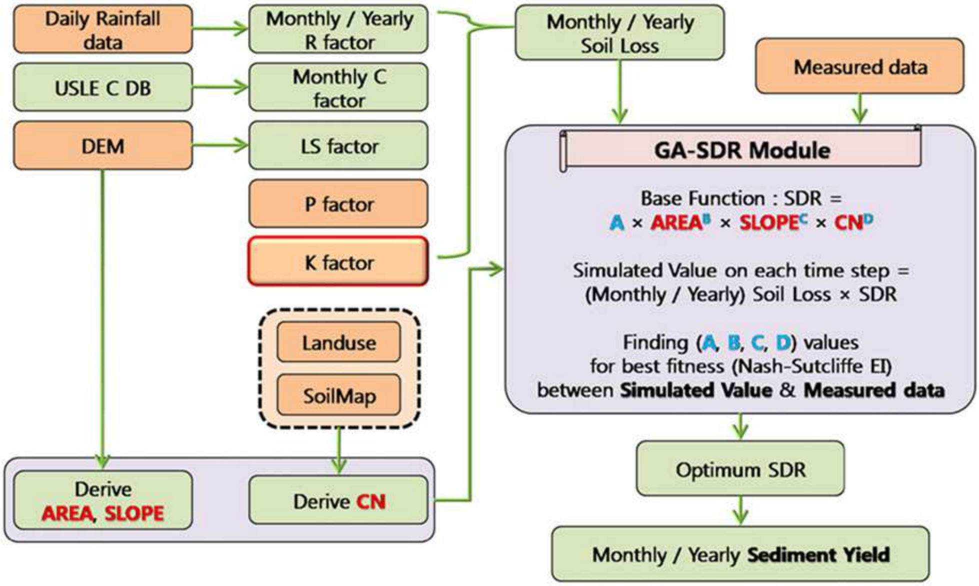


Fig. 2. Overview of SATEEC GA-SDR module (Park et al., 2010)

factor is not deemed as simple process, although daily assessment of soil erosion is strongly suggested to a hydrology model. Another module named R_5 module was integrated to SATEEC for the assessment, the module estimates daily USLE R factor with the process that distributes monthly USLE R factor to each day based on daily precipitation data values. Moreover, the module calculates 5-days antecedent rainfall values with observed daily precipitation data to consider soil moisture condition indirectly (Woo et al., 2010). Eventually, the process to estimate daily USLE R factor with this module can be represented by the equation (9).

$$\text{Daily USLE R factor} = \frac{\text{5 Days Antecedent Precipitation}}{\text{Monthly 5 days Antecedent Precipitation}} \times \text{Monthly USLE R factor} \times 0.172 \quad (9)$$

Woo et al. (2010) applied the SATEEC ver. 2.1 with the module to identical watershed to the watershed used for the application of SATEEC ver. 2.0. The application of SATEEC 2.1 showed more reasonable result represented with 0.776 and 0.776 of R^2 and NSE in calibration, 0.927 and 0.911 of R^2 and NSE in validation. The SATEEC ver. 2.1 allows user to estimate daily, monthly, and yearly soil loss and sediment yield with DEM, land use, soil map, and measured data (Figure 3). SATEEC, operating in ArcView GIS platform, provides various options selectively (Figure 4).

2.2.4 L modules for topography changes

USLE LS factor is derived based on the flow accumulation map and flow direction map which are derived using DEM. DEM represents the elevation of each cell so that hydrologic model estimates direction of flow in a given watershed. However the DEM is not detail enough to represent the forest roads of agricultural canals which affects the flow and soil erosion estimation to some degrees. The segmentation of slope length by human-made roads should be reflected in estimating USLE L factor. Thus a simple module to consider this effect was developed and integrated to the SATEEC system. By considering detailed characteristics such as segmentation of slope length in watershed, the SATEEC model can provide more realistic effects of field slope segmentation on soil erosion.

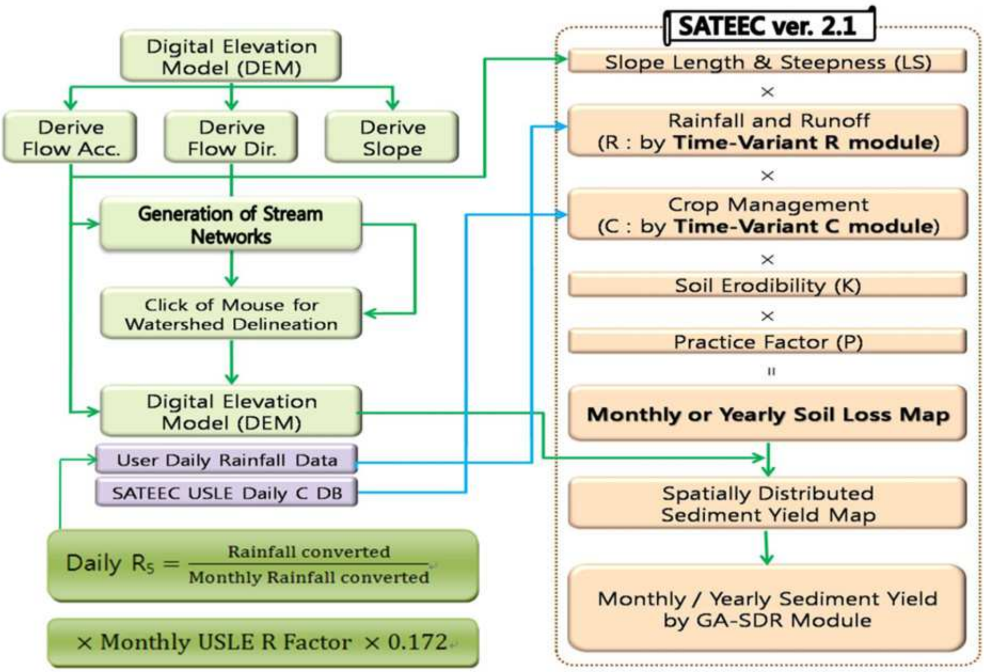


Fig. 3. Overview of the SATEEC ver. 2.1

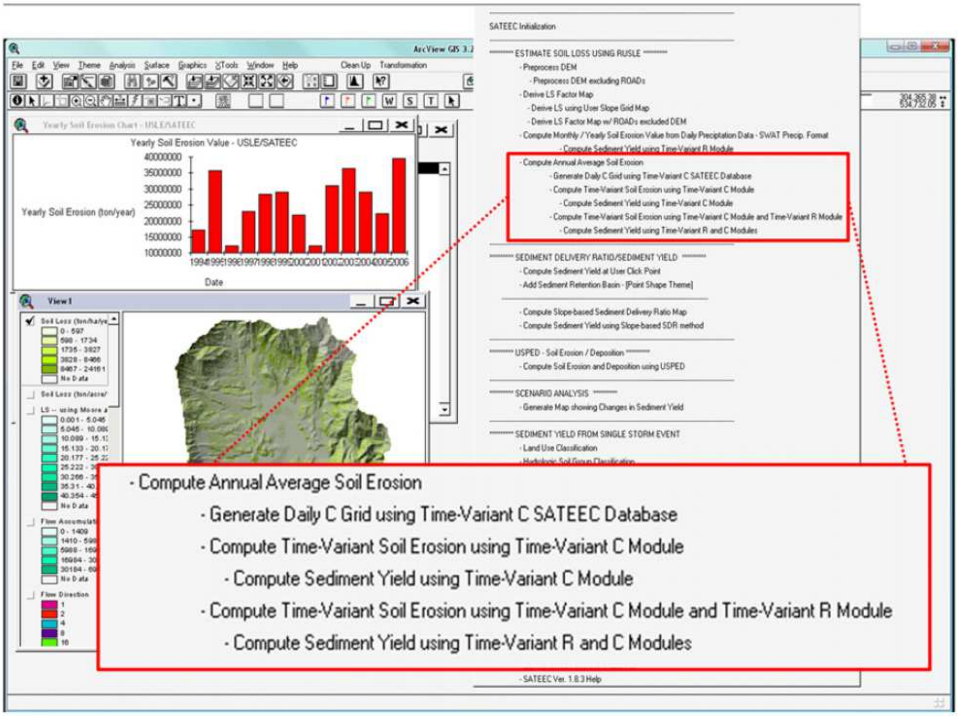
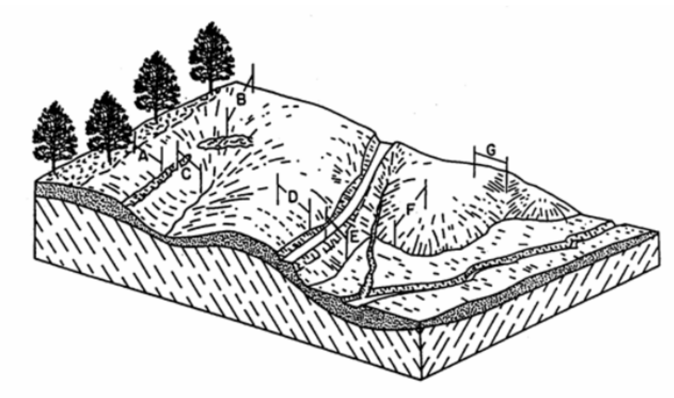


Fig. 4. SATEEC 2.x GIS Interface



(A-G: segmentation of slope length in real fields)

Fig. 5. Field Slope Length at Watershed (Foster et al., 1996)

2.2.5 nLS and USPED in SATEEC

USLE is a field-scale model to estimate soil erosion by sheet and rill erosion, therefore soil erosion estimated by SATEEC represents sheet and rill erosion, excluding gully erosion which is also one of the soil erosion types occurring in a watershed. To estimate soil erosion containing all of the erosion stated above, nLS model (McCuen & Spiess, 1995) for gully head detection and Unit Stream Power-based Erosion/Deposition (USPED, Mitas, L. & Mitasova, 1998; Mitasova et al., 1996) model for gully erosion was integrated with the SATEEC system. The nLS model detects gully head location based on the estimated nLS values, it requires Manning's n coefficient, length of overland flow, and slope (equation (10)) for gully head detection as described below.

$$\text{Gully head} = \frac{3.3 \times n \times L}{\sqrt{S}} \tag{10}$$

Where, n is Manning's n coefficient, L is the length of overland flow, and S is slope (m/m). The L and S parameters for the model are derived using DEM by SATEEC, and the other parameter can be set with Table 1.

Class	Land use	Manning's n coefficient
1	Water area	0.030
2	Urbanization	0.015
3	Eroded land	0.035
4	Marsh	0.050
5	Grassland	0.130
6	Forest	0.100
7	Paddy field	0.050
8	Cropland	0.035

Table 1. Manning's n coefficient for different land uses (Vieux et al., 2004)

The USPED model estimates soil erosion considering erosion and deposition based on tractive force (equation (11), Mitas, L. & Mitasova, 1998; Mitasova et al., 1996), most parameters are available to be defined with USLE input parameters.

$$T = R \times K \times C \times P \times A^m \times (\sin b)^n \tag{11}$$

Where, T is tractive force, R is USLE R factor, K is USLE K factor, C is USLE C factor, P is USLE P factor, A is area in square kilometer, and both m and b are coefficient for types of soil erosion.

The nLS and USPED model are used to estimate soil loss by gully erosion, nLS model defines the points which are gully head, USPED model estimates gully erosion, and then gully erosion map is developed using output with the nLS and USPED models.

3. Application of SATEEC GIS system

The SATEEC system has been applied for various soil erosion studies because it is available in GIS interface and is freely downloadable from the SATEEC website (http://www.EnvSys.co.kr/~sateec). In this chapter, several SATEEC applications will be introduced to give various insights of using SATEEC system to the readers.

3.1 SATEEC ver. 1.5 evaluation using area-based and channel slope-based SDR modules

The comparison of area-based and slope-based SDR modules was performed by Park et al. (2007). The SATEEC provides two SDR modules to estimate sediment yield using soil loss estimated with USLE. The SATEEC was applied to 19 sub-watersheds in South-Korea (Figure 6) which have identical area with various slopes. The study area is located at Chuncheon-si in South-Korea, total area of the watershed is 11.17 square kilometers.

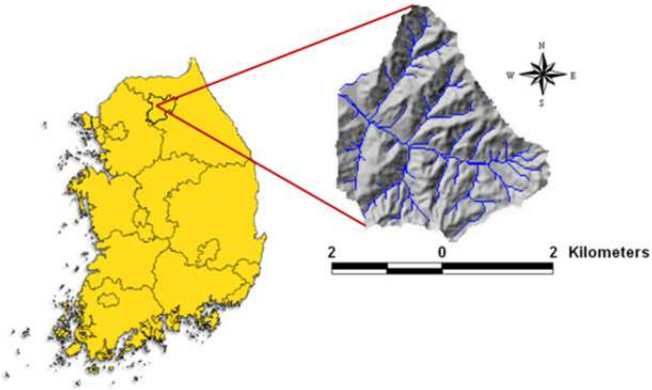


Fig. 6. Location and figure of Sudong watershed (Park et al., 2007)

The USLE R factor suggested by Jung et al. (1999) was used for this study. Table 2 shows USLE R factors of Gangwon province in which Chuncheon-si is located.

Administrative district	R factor	Administrative district	R factor
Kangnung	297	Kosung	250
Samchok	215	Sokcho	255
Yangyang	255	Yongwol	350
Wonju	578	Inje	294
Cheolwon	400	Chuncheon	464
Hwacheon	450	Hongcheon	417
Yanggu	350	Pyongchang	269
Chongson	250	Hoengsung	400

Table 2. USLE R factors for administrative districts in Gangwon province (Jung et al., 1999)

USLE K factor indicating soil erodibility was calculated with equation suggested by Williams (1975), which requires the percentage of sand, silt, and clay (equation (12)).

$$\text{USLE K} = \left[0.2 + 0.3 \times \exp\left(-0.0256 \times \text{SAN} \times \left(1 - \left(\frac{\text{SIL}}{100}\right)\right)\right)\right] \times \left[\left(1.0 - \left(\frac{0.25 \times \text{CLA}}{\text{CLA} + \exp(3.72 - 2.95 \times \text{CLA})}\right)\right)\right] \times \left[1.0 - \left(0.7 \times \frac{\text{SN1}}{\text{SN1} + \exp(-5.51 + 22.9 \times \text{SN1})}\right)\right] \quad (12)$$

Where, SAN is the percentage of sand (%), SIL is the percentage of silt (%), CLA is the percentage of clay (%), and SN1 is (1-SAN/100).

Then the USLE C factor reflects the effects on soil erosion of surface condition of watershed, rainfall drop impact and flow velocity are affected by the surface condition of watershed in real field. Jung et al. (1984) suggested the values of the factor to apply non-crop area such as urbanized area (Table 3). It has the range 0 to 1 as a fraction; lower value indicates that the surface is covered well so that less soil erosion occurs, while higher value indicates that the surface is covered roughly which has higher possibility of much soil erosion.

Land use	USLE C factor
Water	0.000
Forest	0.001
Pasture	0.010
Agriculture	0.260
Urbanization	0.010
Bare Ground	1.000

Table 3. C Factor for Various Land uses (Jung et al., 1984)

USLE P factor represents a conservation or support practice such as contouring, strip cropping, terracing, and etc (Table 4).

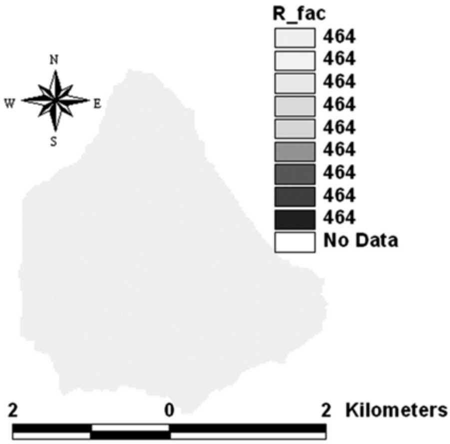
Land use	P Factor	
Paddy land	0.20	
Upland	Slope	P factor
	0 % – 2 %	0.60
	2 % – 7 %	0.50
	7 % – 12 %	0.60
	12 % – 18 %	0.80
	18 % – 24 %	0.90
	24 % – 30 %	0.95
	> 30 %	1.00

Table 4. USLE P Factors for Various Land uses and Slopes

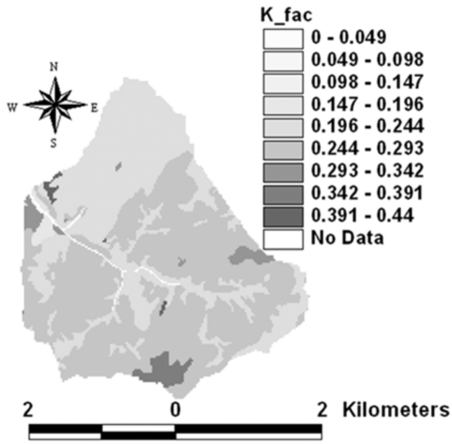
SATEEC computed the LS factor map based on DEM and the method suggested by Moore and Burch (1986, equation (13). The length of hill slope in the USLE experimental plots ranged from 10.7 m (35ft) to 91.4 m (300 ft), thus, it was recommended to use of slope lengths less than 122 m (400 ft) because overland flow becomes concentrated into the rills in less than 122 m (400 ft) under natural condition (Foster et al., 1996).

$$LS = \left(\frac{A}{22.13}\right)^{0.6} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3} \quad (13)$$

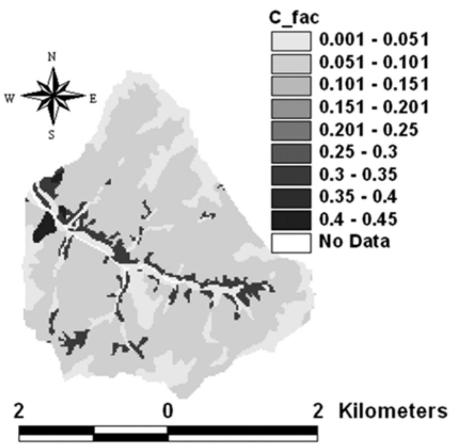
To compare sediment yield by both area-based and slope-based SDRs, which was main purpose of the study, 19 small sub-watershed having 0.0219 square kilometers were selected (Figure 8), they had different watershed characteristics (Table 5). As shown in Table 5, areas of 19 sub-watersheds were identical to investigate effect of different SDR methods. However the slopes for these watersheds ranged from 0.73 % to 3.17 %. The 'Distance (km)' in the table indicates length of the sub-watershed which is from the outlet to the farthest point, and the 'Unity shape factor' indicates a water shape factor which is ratio of the longest distance to the shortest distance in the sub-watershed.



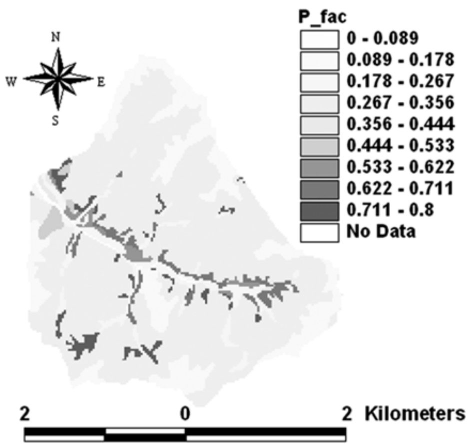
(a) USLE R Factor Map



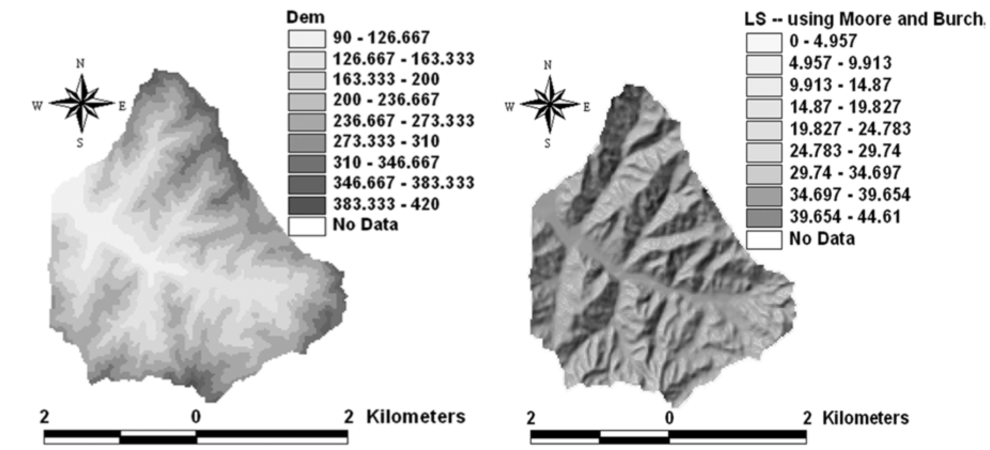
(b) USLE K Factor Map



(c) USLE C Factor Map



(d) USLE P Factor Map



(e) DEM (f) USLE LS Factor Map derived using DEM

Fig. 7. Input data for Soil loss in SATEEC (Park et al., 2007)

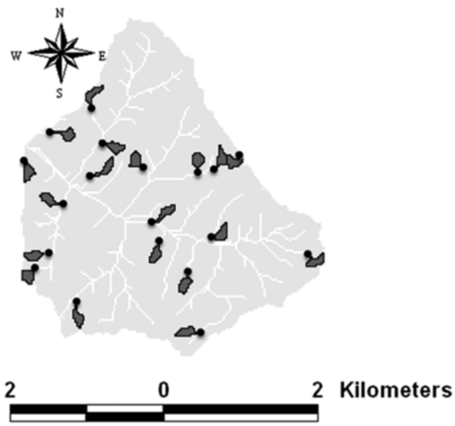


Fig. 8. Location of 19 watersheds in study area (Park et al., 2007)

As shown in Table 6, soil loss for each sub-watershed was different due to different sub-watershed characteristics. However sediment yield estimation was also affected by the SDR methods utilized. Area-based SDRs showed the same results due to identical watershed area, while slope-based SDRs for study watershed ranged from 0.553 to 0.999. The sub-watershed 9 and 11, which are pasture-dominant sub-watershed, showed relatively less soil loss, though, the difference of sediment yield by SDR module was -79.74 %. The difference in percentage ranged from -79.74 % (sub-watershed 11) to 27.45 % (sub-watershed 1), and the difference in 'ton/ha' showed from -89.61 ton/ha (sub-watershed 16) to 73.84 ton/ha (sub-watershed 1).

Sub-watershed	Slope (%)	Area (sq. km)	Distance (km)	Unity shape factor
1	0.73	0.0219	0.207	1.399
2	0.76	0.0219	0.181	1.223
3	0.85	0.0219	0.252	1.703
4	0.86	0.0219	0.216	1.46
5	1.01	0.0219	0.203	1.372
6	1.12	0.0219	0.235	1.588
7	1.21	0.0219	0.252	1.703
8	1.46	0.0219	0.195	1.318
9	1.52	0.0219	0.185	1.25
10	1.58	0.0219	0.309	2.088
11	1.75	0.0219	0.277	1.872
12	2.12	0.0219	0.356	2.406
13	2.49	0.0219	0.302	2.041
14	2.55	0.0219	0.349	2.358
15	2.66	0.0219	0.282	1.906
16	2.67	0.0219	0.285	1.926
17	2.87	0.0219	0.304	2.054
18	3.07	0.0219	0.307	2.075
19	3.17	0.0219	0.251	1.696

Table 5. Subwatershed, slope, area, distance and unity shape factor characteristics (Park et al., 2007)

Sub-watershed	Area (sq. kilometer)	Slope (%)	Soil loss (ton/yr)	Area-Based		Slope-Based	
				SDR	Sediment Yield (ton/yr)	SDR	Sediment Yield (ton/yr)
1	0.0219	0.73	353.125	0.762	268.995	0.553	195.160
2	0.0219	0.76	196.000	0.762	149.304	0.56	109.790
3	0.0219	0.85	311.250	0.762	237.097	0.587	182.551
4	0.0219	0.86	169.688	0.762	129.261	0.59	100.069
5	0.0219	1.01	180.125	0.762	137.211	0.629	113.278
6	0.0219	1.12	100.813	0.762	76.795	0.657	66.227
7	0.0219	1.21	37.375	0.762	28.471	0.678	25.339
8	0.0219	1.46	99.188	0.762	75.557	0.731	72.457
9	0.0219	1.52	1.938	0.762	1.476	0.742	1.438
10	0.0219	1.58	161.938	0.762	123.357	0.754	122.031
11	0.0219	1.75	27.750	0.762	12.139	0.786	21.818
12	0.0219	2.12	354.125	0.762	269.757	0.849	300.581
13	0.0219	2.49	153.438	0.762	116.882	0.905	138.910
14	0.0219	2.55	214.688	0.762	163.540	0.914	196.194
15	0.0219	2.66	134.500	0.762	102.456	0.93	125.121
16	0.0219	2.67	527.250	0.762	401.636	0.932	491.243
17	0.0219	2.87	62.438	0.762	47.562	0.959	59.883
18	0.0219	3.07	141.813	0.762	108.027	0.985	139.652
19	0.0219	3.17	167.938	0.762	127.928	0.999	167.711

Table 6. Soil loss, sediment yield using SDR_A and SDR_S for 19 Sub-watersheds (Park et al., 2007)

This application study indicated that the SDR method could affect sediment yield estimation significantly than the USLE factors do. Thus, soil erosion assessment needs to be performed with not only meticulous collection of USLE input data but also appropriate SDR estimation method.

3.2 SATEEC ver. 1.5 and USPED applications for soil erosion hot spot areas

To determine of soil erosion hot spot watershed, the SATEEC with USPED was applied to a watershed that was referred as requiring BMPs by the Korean government to reduce soil erosion due to severe sediment-laden water problem in the stream. The study watershed is located at Jawoon-ri, Hongcheon-gun in South-Korea, watershed area is 6,906 ha, containing 82.93 % of forest, 12.32 % of agricultural area, 2.02 % of water, 1.62 % of pasture, and 1.09 % of urbanized area.

Table 2 shows USLE R factors of Gangwon province in which Hongcheon-gun is located. USLE K factor indicates soil erodibility, was calculated by the equation suggested by Williams (1975). The USLE K map was developed with the soil map for the study. USLE C factor map was developed using the values suggested by Jung et al. (1984) (Table 3), and USLE P factor map was developed based on slope (Table 4). USLE LS factor map was developed with the module in SATEEC using DEM. To determine hot spot area in the watershed and decide the order of priority in BMP implementation, the given watershed was divided into 54 sub-watersheds (Figure 10, Table 7), soil loss for each sub-watershed was estimated with SATEEC and USPED.

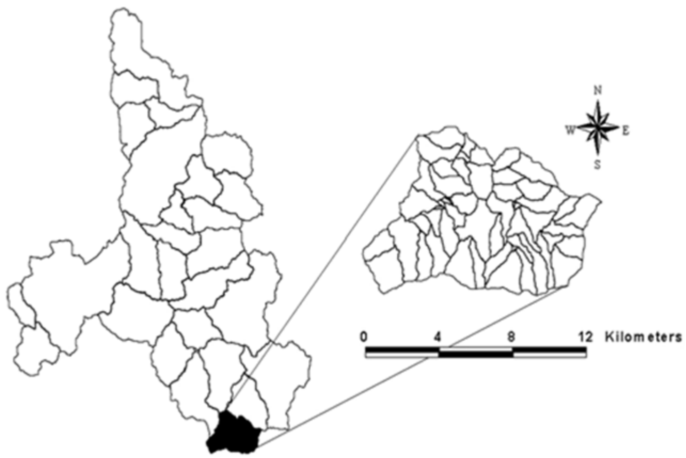


Fig. 9. Location of watershed in Hongcheon-gun (Seo et al.,2010)

The estimated soil erosion values for each sub-watershed are different although these SATEEC and USPED estimate soil erosion with the USLE input data set. However, they showed similar trends for the order of priority in BMP implementation. The soil loss (ton/ha/year) estimated with SATEEC showed higher values in the sub-watershed 2, 1, 25, 21, and 17, the soil loss with USPED considering both erosion and deposition showed higher values in the sub-watershed 2, 1, 7, 35, and 39, and the soil loss by USPED considering only erosion showed higher values in the sub-watershed 46, 2, 3, 1, and 17. The order of priority in BMP implementation is different based on each model, however, both models indicates that BMPs should be applied to reduce soil erosion for sub-watershed 2 and 1.

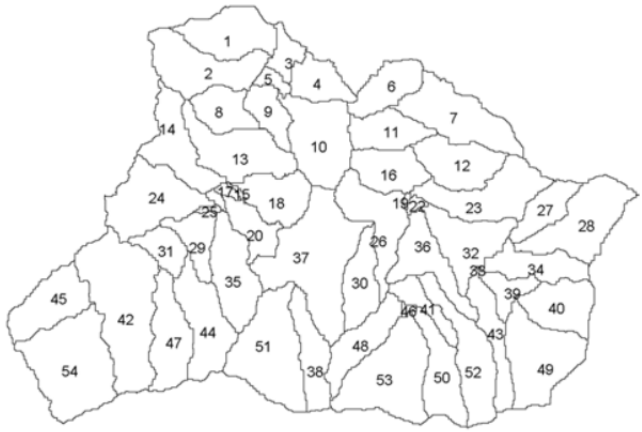


Fig. 10. Location of 54 sub-watersheds at Jawoon-ri Watershed (Seo et al.,2010)

Sub-watershed	SATEEC	Sub-watershed	$USPED_{ED}$	Sub-watershed	$USPED_{E}$
2	265.41	2	3.46	46	28.29
1	199.71	1	3.27	2	24.50
25	167.18	7	2.47	3	18.75
21	153.05	35	2.00	1	18.70
17	87.82	39	1.99	17	18.15

Table 7. 5 Sub-watersheds Requiring BMPs and Soil Loss (ton/ha/year)

3.3 SATEEC ver. 1.8 with USPED, nLS for gully erosion evaluation

It is not possible to estimate gully erosion with USLE model because it estimates sheet and rill erosion. Kang et al. (2010) applied the SATEEC with nLS and USPED to estimate sheet/rill and gully erosion. These models were applied to the study watershed located at Haean-myeon Yanggu-gun in South-Korea (Figure11). Watershed area is 61.78 square kilometers, containing 58.8 % of forest, 37.2 % of agricultural area, 1.9 % of urbanized area, 1.3 % of water, 0.6 % of bare land, and 0.2 % of pasture.

Soil Loss considering sheet/rill erosion and gully erosion can be estimated by the process showed in Figure 12. The processes show how to develop input for nLS and USPED using USLE inputs, determine gully head determined with nLS, gully erosion by USPED, develop gully erosion map combining gully head map by nLS and gully erosion map by USPED, and to combine the map with sheet/rill erosion map by SATEEC.

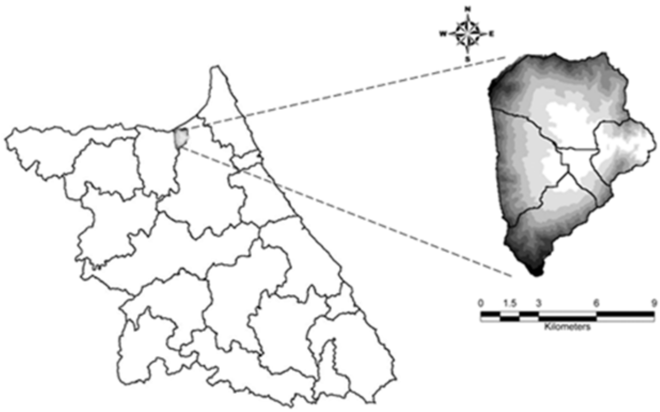


Fig. 11. Location of Haean-myeon watershed (Kang et al., 2010)

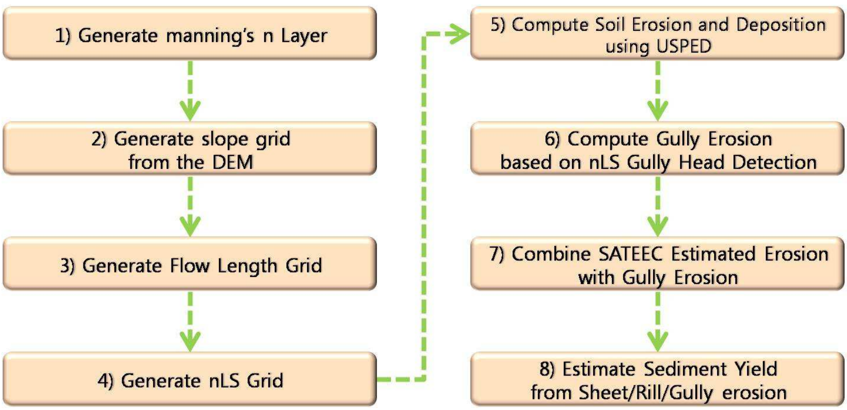
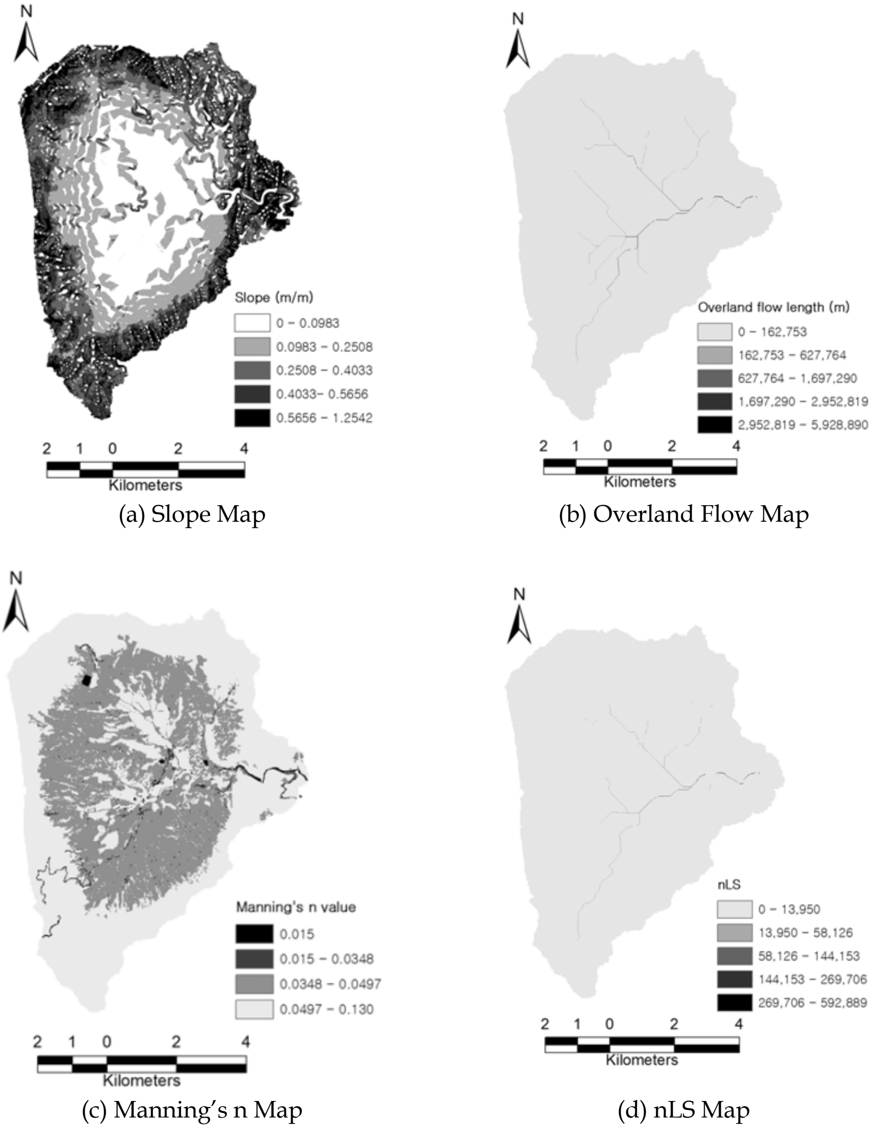


Fig. 12. Modeling process of integrated system using SATEEC, nLS, and USPED (Kang et al., 2010)

USLE input data maps were used for SATEEC and USPED to estimate sheet/rill and gully erosion, the gully head map was developed by nLS model. The nLS map (Figure 13 (d)) was developed using slope map (Figure 13 (a)), overland flow map (Figure 13 (b)), and manning's n map (Figure 13 (c)), the values over 100 in the nLS map indicate gully head.

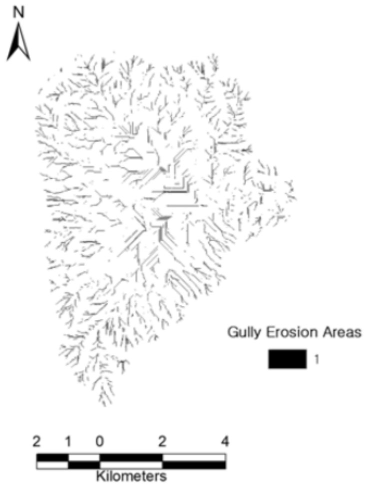


(a) Slope Map (b) Overland Flow Map

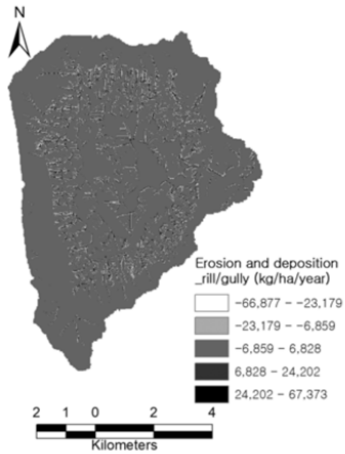
(c) Manning's n Map (d) nLS Map

Fig. 13. Maps to develop Gully Head Map (Kang et al., 2010)

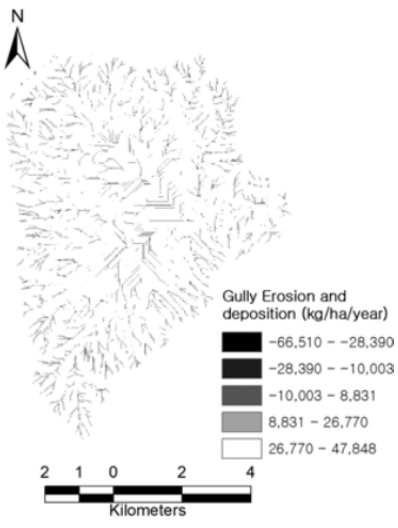
Gully head map (Figure 14(a)) was derived from nLS map (Figure 13 (d)) of which cell values are greater than 100, which indicates potential gully head location. Using the Gully head map and soil erosion map by USPED (Figure 14 (b)), the map representing only gully erosion (Figure 14 (c)) was derived. And then the soil erosion map considering sheet/rill and gully erosion map was derived from gully erosion map and sheep/rill erosion map by SATEEC. The negative values in the maps indicate deposition, and positive values indicate erosion.



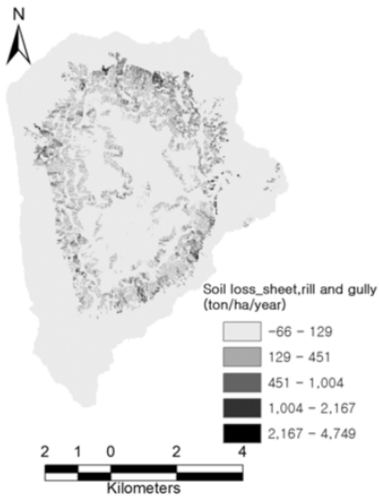
(a) Gully Head Map



(b) Soil Erosion Map by USPED



(c) Gully Erosion Map



(d) Sheet/Rill and Gully Erosion Map

Fig. 14. Soil Erosion Map (Kang et al., 2010)

3.4 SATEEC ver. 2.0 for sediment evaluation using time-variant R and C modules

One of significant modification in SATEEC was development and integration of Time-Variant Modules and GA-SDR modules that are to estimate monthly/yearly sediment yield at the watershed outlet using USLE model which is field-scale. Park et al. (2010) applied the modules to Imha watershed located in South-Korea (Figure 15), the area of the watershed is 1,361 square kilometers containing 79.8 % of forest, 16.0 % of agricultural areas, 1.4 % of residential areas, 2.4 % of water, and 0.4 % of pasture. The watershed is forest-dominant, but much of agricultural areas are located nearby stream, increasing chance of being transported into the stream after soil eroded from the agricultural areas.

Park et al. (2010) set USLE K, P, and LS factor map with similar method and process to previous one in SATEEC, but USLE R factor was estimated using Time-Variant R module with daily precipitation data from Jan/1/1999 to Oct/31/2004 (Figure 16(a)), and USLE C factor was estimated using Time-Variant C module with SATEEC DB (Figure 16(b)) and land use map (Figure 16(c)). To estimate sediment yield at the watershed outlet, GA-SDR module was applied.

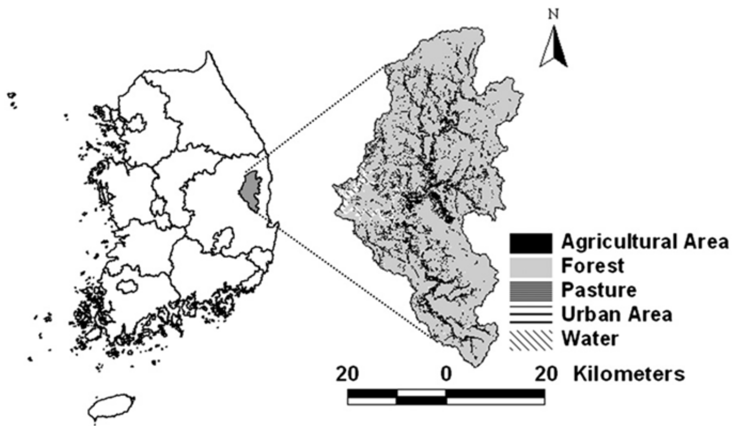
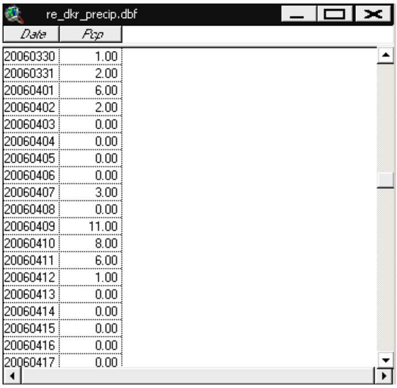


Fig. 15. Location and land-use at Imha Watershed, Gyeongsangbuk-do, South-Korea (Park et al., 2010)

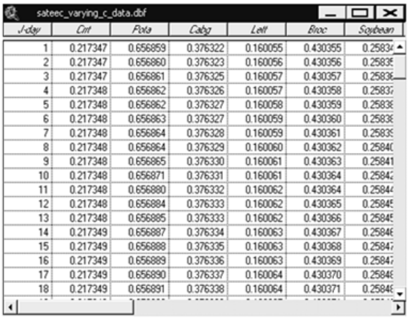
GA-SDR module estimated the coefficient and exponents for the formula to calculate SDR of the watershed (equation (14)), comparing to measured data. SATEEC was calibrated with measured data from 1999 to 2004, was validated with measured data from 2005-2008, it showed 0.721 and 0.720 of R^2 and NSE in calibration, 0.906 and 0.881 for R^2 and NSE in validation (Figure 17).



re_dkr_precip.dbf

Date	Pcp
20060330	1.00
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

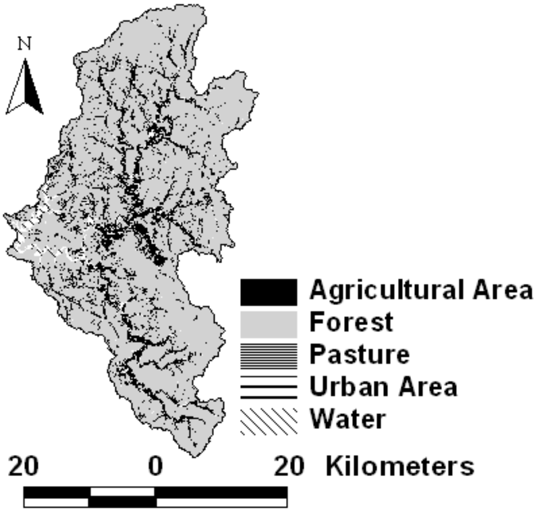
(a) Daily Precipitation Data



sateec_varying_c_data.dbf

J-day	Cnt	Pota	Cabg	Lett	Broc	Soybean
1	0.217347	0.656859	0.376322	0.160055	0.430355	0.25834
2	0.217347	0.656860	0.376323	0.160056	0.430356	0.25835
3	0.217347	0.656861	0.376325	0.160057	0.430357	0.25836
4	0.217348	0.656862	0.376326	0.160057	0.430358	0.25837
5	0.217348	0.656862	0.376327	0.160058	0.430359	0.25838
6	0.217348	0.656863	0.376327	0.160059	0.430360	0.25838
7	0.217348	0.656864	0.376328	0.160059	0.430361	0.25839
8	0.217348	0.656864	0.376329	0.160060	0.430362	0.25840
9	0.217348	0.656865	0.376330	0.160061	0.430363	0.25841
10	0.217348	0.656871	0.376331	0.160061	0.430364	0.25842
11	0.217348	0.656880	0.376332	0.160062	0.430364	0.25844
12	0.217348	0.656884	0.376333	0.160062	0.430365	0.25845
13	0.217348	0.656885	0.376333	0.160062	0.430366	0.25845
14	0.217349	0.656887	0.376334	0.160063	0.430367	0.25846
15	0.217349	0.656888	0.376335	0.160063	0.430368	0.25847
16	0.217349	0.656889	0.376336	0.160063	0.430369	0.25847
17	0.217349	0.656890	0.376337	0.160064	0.430370	0.25848
18	0.217349	0.656891	0.376338	0.160064	0.430371	0.25848

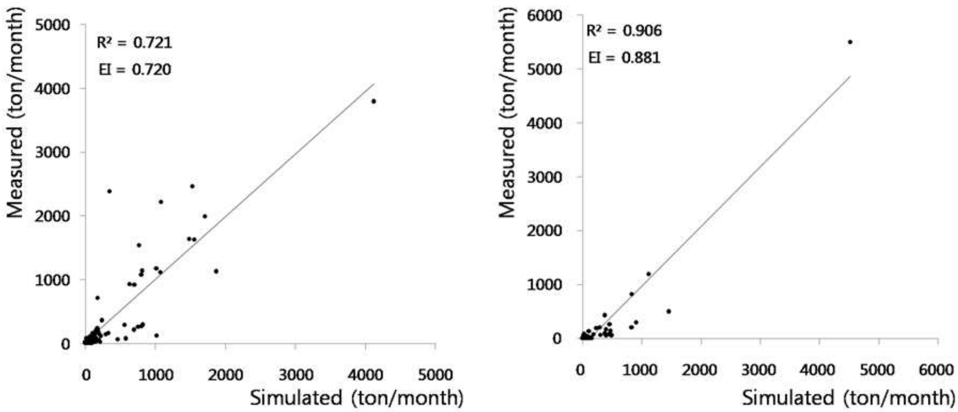
(b) Daily USLE C factor DB



(c) Land use Map

Fig. 16. Data for Time-Variant modules (Park et al., 2010)

$$SDR = (6 \times 10^{-4}) \times AREA^{0.022} \times SLOPE^{0.1901} \times CN^{0.0267} \tag{14}$$



(a) Calibration (1999–2004) (b) Validation (2005-2008)

Fig. 17. Calibration and Validation of SATEEC

SATEEC requires USLE input data, though, it has various modules to estimate time-variant soil erosion and sediment yield at the outlet, and moreover it showed reasonable result.

3.5 SATEEC ver. 2.0 with L modules for topography changes due to forest roads

The application of L module in SATEEC was applied to study watershed located at Haean-myeon Yanggu-gun in South-Korea (Figure 12, Kang et al., 2009). Watershed area is 61.78 square kilometers, containing 58.8 % of forest, 37.2 % of agricultural area, 1.9 % of urbanized area, 1.3 % of water, 0.6 % of bare land, and 0.2 % of pasture. The interference to slope length in the watershed are the boundaries of agricultural areas and roads, the data was built based on Gangwon Development Research Institude's measured data in Haean-myeon watershed (Figure 18).

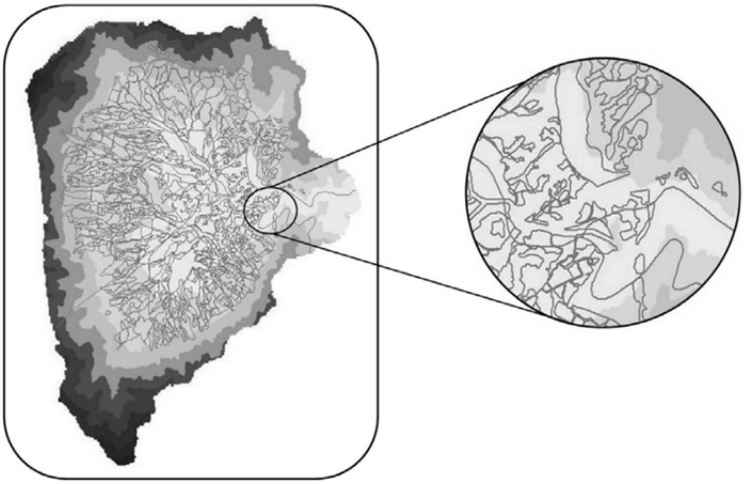
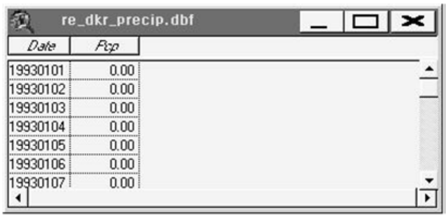


Fig. 18. Slope Length Segmentation due to Agricultural Field Boundaries (Kang et al., 2009)

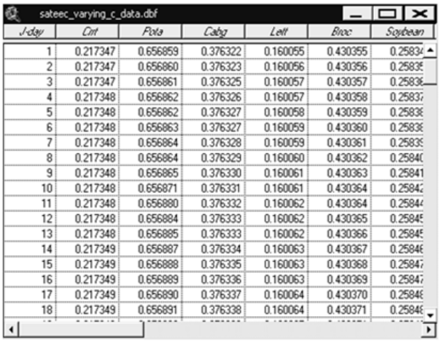
Kang et al. (2009) developed the USLE K and P factor maps with similar method and process to previous one by SATEEC, but USLE R factor was estimated using Time-Variant R module with daily precipitation data from Jan/1/1993 to Jul/31/2007 (Figure 19 (a)), and USLE C factor was estimated using Time-Variant C module with SATEEC DB (Figure 19 (b)) and land use map (Figure 19 (c)).



re_dkr_precip.dbf

Date	Pcp
19930101	0.00
19930102	0.00
19930103	0.00
19930104	0.00
19930105	0.00
19930106	0.00
19930107	0.00

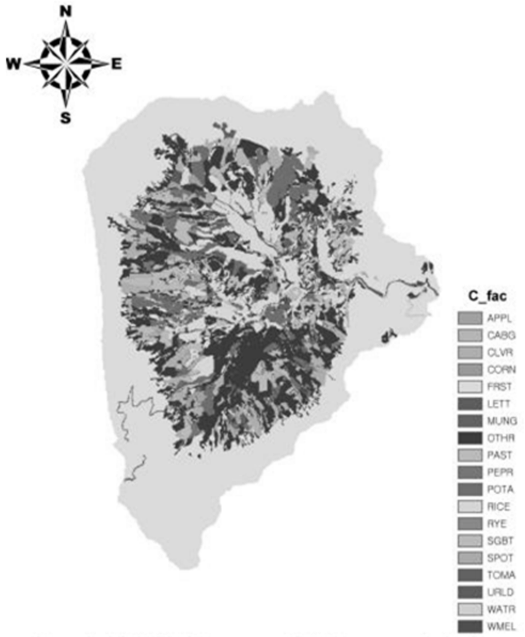
(a) Daily Precipitation Data



sateec_varying_c_data.dbf

J-day	Crrt	Pota	Cabg	Lett	Broc	Soybean
1	0.217347	0.656859	0.376322	0.160055	0.430355	0.25834
2	0.217347	0.656860	0.376323	0.160056	0.430356	0.25835
3	0.217347	0.656861	0.376325	0.160057	0.430357	0.25836
4	0.217348	0.656862	0.376326	0.160057	0.430358	0.25837
5	0.217348	0.656862	0.376327	0.160058	0.430359	0.25838
6	0.217348	0.656863	0.376327	0.160059	0.430360	0.25838
7	0.217348	0.656864	0.376328	0.160059	0.430361	0.25839
8	0.217348	0.656864	0.376329	0.160060	0.430362	0.25840
9	0.217348	0.656865	0.376330	0.160061	0.430363	0.25841
10	0.217348	0.656871	0.376331	0.160061	0.430364	0.25842
11	0.217348	0.656880	0.376332	0.160062	0.430364	0.25844
12	0.217348	0.656884	0.376333	0.160062	0.430365	0.25845
13	0.217348	0.656885	0.376333	0.160062	0.430366	0.25845
14	0.217349	0.656887	0.376334	0.160063	0.430367	0.25846
15	0.217349	0.656888	0.376335	0.160063	0.430368	0.25847
16	0.217349	0.656889	0.376336	0.160063	0.430369	0.25847
17	0.217349	0.656890	0.376337	0.160064	0.430370	0.25848
18	0.217349	0.656891	0.376338	0.160064	0.430371	0.25848

(b) Daily USLE C factor DB



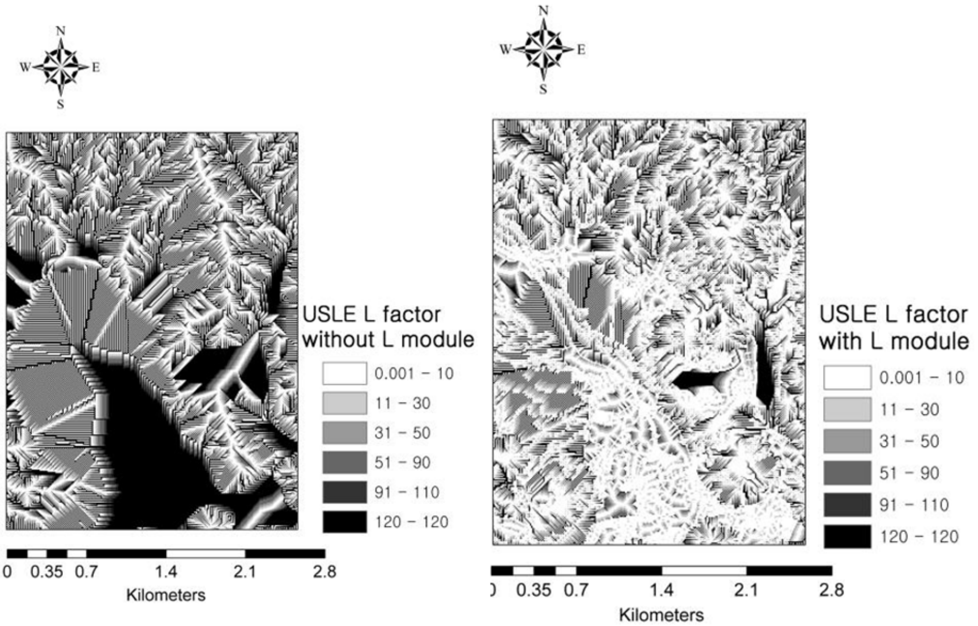
(c) Land use Map

Fig. 19. Data for Time-Variant modules (Kang et al., 2009)

Kang et al. (2009) compared USLE L factor maps without and with SATEEC L module as shown in Figure 20(a) and 20(b). With agricultural field boundaries and roads considered in L factor estimation, flow length segmentation could be considered in soil erosion estimation.

Annual soil erosion with and without SATEEC L module were shown in (Figure 21). The average annual soil loss estimated without L module was 91,714.71 ton, while the average annual soil loss estimated with L module was 68,469.49 ton. The application indicates that soil erosion could be overestimated if the flow segmentation was not considered with the SATEEC L module.

In addition, the estimated sediment yields with SATEEC were compared with SWAT monthly simulation since no measured sediment values available. The R^2 and NSE were 0.729 and 0.719 for calibration period, 0.818 and 0.800 of R^2 and NSE for validation period, when the module was not applied. Sediment yield estimated with the L module showed 0.730 and 0.720 of R^2 and NSE in calibration, 0.818 and 0.800 of R^2 and NSE in validation.



(a) USLE L factor without L module (b) USLE L factor with L module

Fig. 20. Comparison of USLE L factor with L module and without L module (Kang et al., 2009)

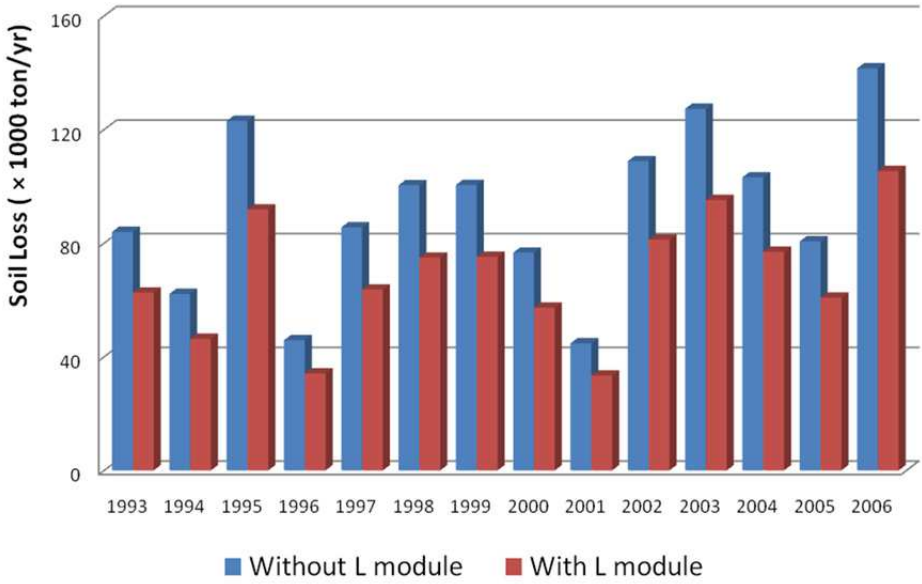
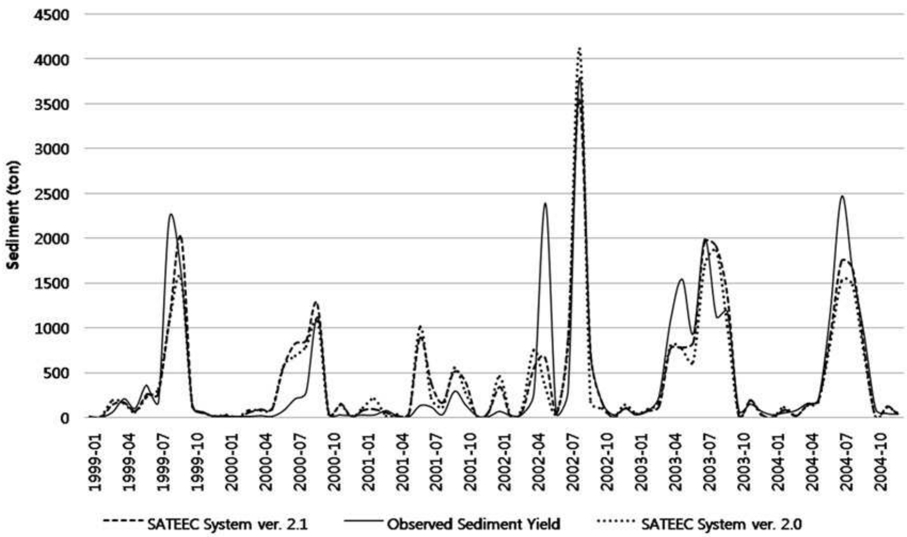


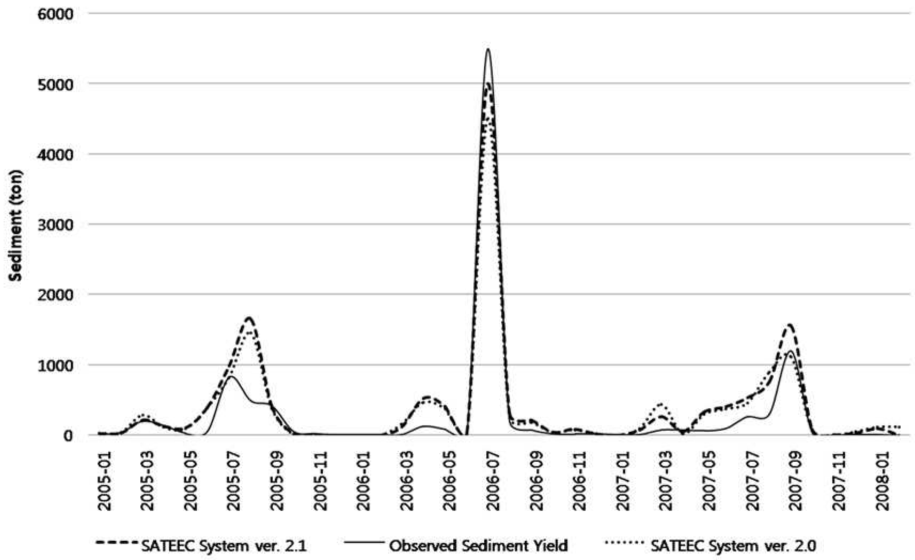
Fig. 21. Comparison of Annual Soil Erosion using SATEEC 2.0. with L Module and without L Module (Kang et al., 2009)

3.6 SATEEC ver. 2.1 for daily sediment estimation using daily USLE R modules

Although, with integration of Time-Variant C and R modules, the SATEEC allows user to estimate monthly/yearly soil erosion and sediment yield, daily assessment of soil loss and sediment yield at the watershed outlet is in need due to the particularity of precipitation affecting to soil erosion in a single day or a few days, such as typhoon. Woo et al. (2010) applied SATEEC with R_5 module to estimate daily USLE R factor to Imha watershed stated above (Figure 16). Most of input data was set with identical method to Park et al. (2010), but R_5 module was applied to estimate daily USLE R factor, and to validate the module. As shown in Figures 22 (a) and (b), the estimated sediment yield by SATEEC ver. 2.1 using R_5 module showed less difference than the estimated sediment yield by SATEEC ver. 2.0 using Time-Variant R module, compared to measured data in both calibration and validation periods.



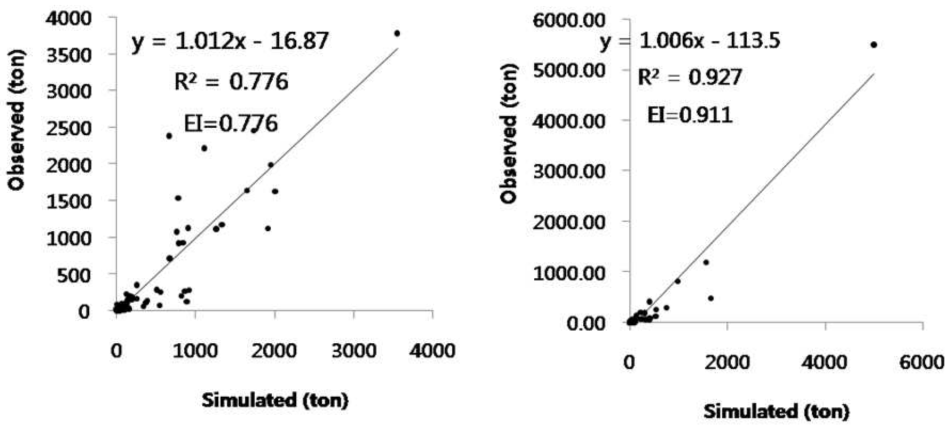
(a) Calibration Period (Jan/1999 – Dec/2004)



(b) Validation Period (Jan/2005 – Dec/2008)

Fig. 22. Comparison in Time-Series Plot

R^2 and NSE of the sediment yield by SATEEC ver. 2.1 were 0.776 and 0.776 in calibration, and 0.927 and 0.911 in validation (Figure 23). Compared to the criteria of SATEEC ver. 2.0 results, SATEEC ver. 2.1 showed more reasonable values for both R^2 and NSE in calibration and validation, it is deemed as SATEEC ver. 2.1 allows the estimation considering more detailed precipitation characteristics.



(a) Calibration (1999–2004) (b) Validation (2005-2008)

Fig. 23. Calibration and Validation of SATEEC ver. 2.1

4. References

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Foster, G.R., Renard, K.G., Yoder, D.C., McCool, D.K. and Weesies, G.A., (1996). RUSLE User's Guide. Soil and Water Cons. Soc.

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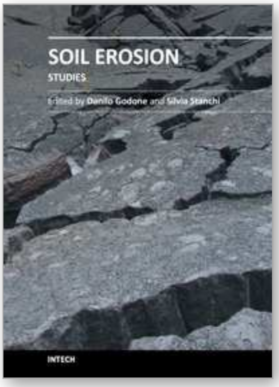

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Soil erosion affects a large part of the Earth surface, and accelerated soil erosion is recognized as one of the main soil threats, compromising soil productive and protective functions. The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena. The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems, ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering). The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.).

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