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Development of Sediment Assessment Tool for Effective Erosion Control (SATEEC) in Small Scale Watershed

소유역의 효과적인 침식조절을 위한 유사평가 툴(SATEEC)의 개발

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Abstract

The Revised Universal Soil Loss Equation (RUSLE) has been used in over 100 countries to estimate potential long-term soil erosion from the field. However, the RUSLE estimated soil erosion cannot be used to estimate the sediment delivered to the stream networks. For an effective erosion control, it is necessary to compute sediment delivery ratio (SDR) for watershed and sediment yield at watershed outlet. Thus, the Sediment Assessment Tool for Effective Erosion Control (SATEEC) was developed in this study to compute the sediment yield at any point in the watershed. To compute spatially distributed sediment yield map, the RUSLE was first integrated with the ArcView GIS and three area based sediment delivery ratio methods were incorporated in the SATEEC. The SATEEC was applied to the Bangdong watershed, Chuncheon, Gangwon Province to demonstrate how it can be used to estimate soil loss and sediment yield for a watershed. The sediment yield using USDA SDR method is 8,544 ton/year and 4,949 ton/year with the method by Boyce. Thus, use of watershed specific SDR is highly recommended when comparing the estimated sediment yield with the measured sediment data. The SATEEC was applied with hypothetical cropping scenario and it was found that the SATEEC can be used to assess the impacts of different management on the sediment delivered to the stream networks and to find the sediment source areas for a reach of interest. The SATEEC is an efficient tool to find the best erosion control practices with its easy-to-use interface.

Keywords : Soil erosion, Sediment delivery ratio, Sediment yield, RUSLE, GIS

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I. Introduction

Land surface has been disturbed by different types of human activities, such as mining, construction, and agricultural activities, which accelerate the natural erosion rates. Soil erosion is a natural process and it refers to processes by which earth materials are entrained and transported across a given surface. Soil loss is the amount of materials that actually removed from a particular slope. Due to the possible on-site deposition of the soil materials in depression on the slope, soil loss is usually less than erosion. Thus, sediment yield is used to represent the amount of soil loss that actually transported at the toe of the slope (Renard et al., 1997). Erosion processes by water result in degradation of soil fertility and water quality on the receiving water bodies due to sediment transportation. The accumulated sediments in the stream need to be dredged to prevent natural disasters such as floods, which cost additional expense. Sediments may carry pollutants, such as phosphorus, into the water system causing significant water quality degradation (Ouyang and Bartholic, 1997) because phosphorus is easily attached to the sediment and transported with them (Glymph, 1975).

If the disturbance of soil structure is inevitable, it would be desirable to develop effective erosion control management practices. Thus, the empirically based Universal Soil Loss Equation (USLE) was developed to predict the potential erosion in the field and to estimate the effects of different control management practices on the soil erosion. The new version of USLE, called Revised Universal Soil Loss Equation (RUSLE) computer program was developed (Renard et al., 1991) and the RUSLE has been modified for accurate estimation of R, K, C, P factors, and soil erosion. The RUSLE has been used/integrated with Geographic Information Systems (GIS) to estimate the soil erosion because GIS helps users manipulate and analyze the spatial data easily, and it also helps the users to identify the spatial locations vulnerable to the soil erosion (Yitayew et al., 1999; Ouyang and Bartholic, 2001; Lufafa et al., 2002). However, these studies didn't consider the sediment delivery ratio to estimate the sediment delivered to the downstream point of interest. The WinGrid system developed by Lin et al. (2002) considered the sediment delivery ratio for a given cell based on receiving drainage length ratio to total drainage length to compute the soil erosion and sediment yield using USLE and sediment delivery ratio. However, this system has separate program components rather than those fully integrated with GIS system. Hence, it is not readily available to soil erosion decision makers because it was developed for research purpose.

To find the best erosion control management practices with RUSLE, one has to run many steps many times with slight modifications in either cropping or management practice data. It will be very tedious and time consuming works. Also, it is not possible to determine the effects of different erosion control managements on the sediment yield of every location within the watershed with RUSLE. Although many GIS integrated system have been utilized in many soil erosion studies, it still requires GIS expertise to operate these systems. To overcome these limitations and provide an easy-to-operate sediment assessment tool, the Sediment Assessment Tool for Effective Erosion Control (SATEEC) was developed in this study.

The objectives of this study were:

1. To develop ArcView interface to sediment assessment tool to compute the spatially distributed soil loss and sediment yield,
2. To demonstrate how the sediment assessment tool can be used to simulate the effects of different erosion control practice on soil loss and sediment yield at a point of interest.

II. SOil Erosion and Sediment Yield

It is necessary to identify the areas vulnerable to the soil erosion and to quantify the amounts of soil erosion for an effective erosion control. The empirically based USLE and newly revised RUSLE have been used in many countries since the late 1960s (Wischmeier and Smith, 1978). It is designed to estimate the long term average annual soil loss for a certain field with specified cropping and management systems as well as rangeland (Renard et al., 1997). The RUSLE estimates annual soil loss per unit area from rill and interill erosion caused by rainfall splash and overland flow, not from gully and channel erosion. The RUSLE does not consider the runoff process explicitly, soil detachment, transport, and deposition individually (Renard et al., 1994). Equation 1 shows how the RUSLE computes the average annual soil loss.

$$A = R\ K\ L\ S\ C\ P \quad \cdots\cdots (1)$$

Where A = average annual soil loss (ton/ac/yr),

R = rainfall/runoff erosivity,

K = soil erodibility,

LS = slope length and steepness,

C = crop management,

P = support practice.

The R factor in the RUSLE software is composed of total storm kinetic energy (E) times the maximum 30 min intensity (I_{30}), and the numerical value of R is the average annual value for storm event for at least 22 years (Wischmeier and Smith, 1978; Renard et al., 1997). Hence, the RUSLE can not be used to estimate the soil erosion and sediment yield for a single storm event. Thus, the Modified Universal Soil Loss Equation (MUSLE) has been widely used to estimate the sediment yield from a single storm event (Williams and Berndt, 1977). The Equation 2 shows how the MUSLE computes sediment yield from a single storm event.

$$Y = 11.8\ (Q \times q_p)^{0.56}\ K\ C\ P\ L\ S \quad \cdots\cdots (2)$$

Where, Y = sediment yield from a single storm event (ton),

Q = storm runoff volume (m^3),

q_p = peak runoff rate (m^3/s),

K = soil erodibility,

LS = slope length and steepness,

C = cover management,

P = support practice

The RUSLE is a field scale model, thus it cannot be directly used to estimate the amount of sediment reaching downstream areas because some portion of the eroded soil may deposit while they travel to the watershed outlet, or point of interest in the downstream areas. To account for these processes, the Sediment Delivery Ratio (SDR) for a given watershed should be used to estimate the total sediment transported at the watershed outlet. The SDR can be expressed as follows (Equation 3).

$$SDR = SY / E \cdots\cdots (3)$$

Where, SDR = Sediment Delivery Ratio,
SY = Sediment Yield,
E = Gross Erosion for Entire Watershed.

As stated before, the RUSLE only estimates the soil erosion from rill and interrill erosion. However, gross erosion (E) in Equation 3 includes the erosion from gully and channel erosion as well as rill and interrill erosion (Ouyang and Bartholic, 1997). According to the study by Wade and Heady (1976), the soil losses from rill and interrill erosion in the Great Lakes Basin area are responsible for more than 67% of gross erosion. Thus, the use of Equation 3 in the SATEEC is valid if there is no significant amount of erosion from gully and channel. Simanton et al. (1980) applied the USLE for four watersheds and found USLE estimated soil losses matched reasonably for two watershed having no gullies or significant alluvial channels, while didn't match well for two watershed with significant gullies and channels. These result indicate USLE should be not be applied to large scale watersheds, experiencing gully and channel erosion.

Erskine et al. (2002) compared the RUSLE estimated soil loss with the measured sediment yield for 12 subwatersheds in Australia. The coefficient of determination is 0.88 for this comparison although it didn't consider the sediment delivery ratio in the estimated soil erosion using RUSLE. This is because the average areas for 12 subwatersheds is around 5 ha, and 3 ha for 10 subwatersheds. Thus, the SDR for these small size watersheds are high and no significant deposition occurred in the small size watershed. The SDR decreases with the size of watersheds, thus, the SDR needs to be considered when RUSLE is applied for a large scale watershed.

Many researches have been performed to estimate the SDR. It was found that the SDR is related to the watershed size. The relationship for the SDR and watershed size is known as the SDR curve (USDA, 1972). The SDR curve based on watershed size is widely used because of its simplicity. A power function (Equation 4) was derived from the data at 300 watersheds in the world to develop a generalized SDR curve (Vanoni, 1975). Boyce (1975) and USDA ARS (1972) also developed the SDR curves, (Equations 5 and 6).

$$SDR = 0.4724\ A^{-0.125} \cdots\cdots (4)$$

Where, A = watershed area (km^2)

$$SDR = 0.3750\ A^{-0.2382} \cdots\cdots (5)$$

$$SDR = 0.5656\ A^{-0.11} \cdots\cdots (6)$$

Fig. 1 shows the SDR curves for different size of watershed. The SDR curves developed by Vanoni (1975) and USDA (1972) are similar, compared with the SDR curve by Boyce (1975). For the accurate estimation of the sediment yield for a given watershed, use of the watershed specific SDR curve is desirable although it is not

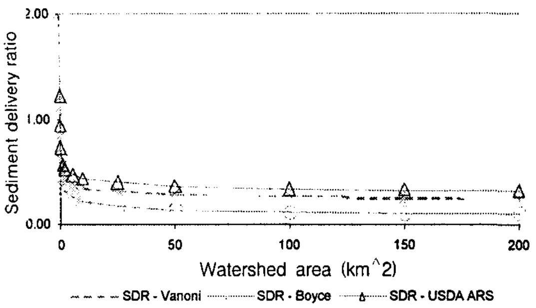

Fig. 1 Sediment delivery ratio (SDR) curves

easy to obtain watershed specific SDR curve.

The USLE has been linked with GIS because of advantages of using GIS for large quantities of spatial data. Hession and Shanholtz (1988) used GIS for non-point source agricultural pollution modeling with USLE for the computation of sediment loading to streams. Spanner et al. (1983) and Blaszczynski (1992) used RUSLE GIS to extract slope length and steepness from Digital Elevation Model (DEM). Yitayew et al. (1999) developed the Arc/Info RUSLE system to computes the combined slope length and steepness factor from DEM using two different algorithms, one is with Spanner's algorithm (Spanner et al., 1983) and the other with Moore's algorithm (Moore and Wilson, 1992). It was found that the LS factors using two algorithms with the same source data are nearly double that of the order (Yitayew et al., 1999). The comparison of the RUSLE GIS estimated soil erosion with the measured sediment yield data indicates the sediment delivery ratio depending on watershed size needs to be considered in the comparison as possible explanation for the difference in RUSLE GIS estimated erosion and measured sediment yield (Yitayew et al., 1999). Ouyang and Bartholic (2001) developed Web-based GIS interface to the RUSLE model. It provides the soil erosion index map to the client web browser with the input information provided by the users. However, this system does not consider the SDR for sediment yield estimation. Lin et al. (2002) developed WinGrid system to extract the slope length factor for each cell to estimate the soil loss and sediment yield from a watershed. In the WinGrid system, the sediment delivery ratio is computed based on the ratio of receiving drainage length to the total drainage length. The WinGrid estimated sediment yield at five outlets are somewhat similar to the measured sediment data (Lin et al., 2002). However, this system is developed for research purpose, thus it is not readily available to the soil erosion decision makers.

Ⅲ. Development of SATEEC

To develop an easy-to-use sediment assessment tool for soil erosion decision makers, many Avenue scripts within the ArcView GIS were written to automate all procedures, such as extraction of slope length and slope steepness from DEM, delineation of watershed, computation of soil loss and sediment delivery ratio based on watershed size for every cell within the study area, and sediment yield for every cell within the study area. Thus, with several clicks of mouse button, it is possible to estimate the sediment yield for every cell within the watershed. Fig. 2 shows the overview of the SATEEC. Soil loss is estimated with RUSLE, and sediment yield map is generated based on RUSLE estimated soil loss and sediment delivery ratio map, generated from slope and flow accumulation. The input data for

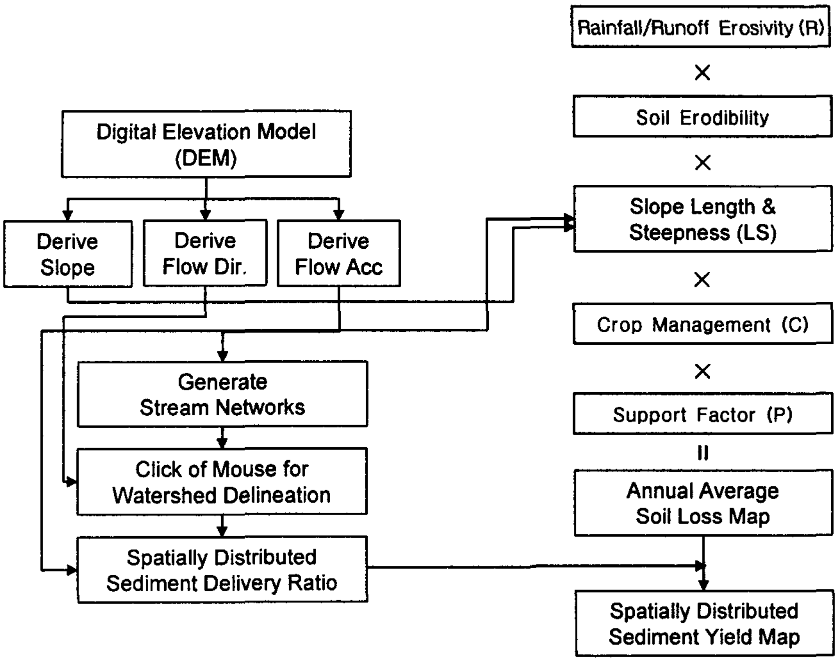

Fig. 2 Overview of the SATEEC

the SATEEC are R, K, DEM, C, and P maps, which is the basic input maps to the RUSLE. Thus, one of advantages of using SATEEC is that no additional input data, other than those for RUSLE, are needed to operate SATEEC. Also, all of the functions shown in Fig. 2 are fully integrated with the ArcView GIS system.

1. Integration of RUSLE with GIS

To compute soil loss from rill and interrill erosion, the RUSLE was first integrated with the ArcView GIS system. In the SATEEC system, the method developed by Moore and Burch (1986a and 1986b) was used to calculate LS factor from the DEM. All DEM pre-processing and map algebra were automated with many Avenue programings. According to the RUSLE Users Guide (Foster et al., 1996), the length of hill slopes in the experimental plots ranges from 10.7 m (35 feet) to 91.4 m (300 feet). Thus, it was recommended that the use of slope length less than 122 m (400 feet) are desired because overland flow becomes concentrated into the rills in less than 122 m (400 feet) under natural condition (Foster et al., 1996). Thus, the SATEEC computes LS factor using the method developed by Moore and Burch (Equation 7) (1986a and 1986b) and upper bound of slope length provided by users.

$$LS = \left(\frac{A}{22.13}\right)^{0.6}\left(\frac{\sin\Theta}{0.0896}\right)^{1.3} \quad \cdots\cdots (7)$$

Where, A is specific watershed area (flow acc. * cell size^2/cell size)

Θ is slope angle in degree

The SATEEC estimates annual average soil loss by multiplying all input parameter maps, such as R, K, LS, C, and P maps. The SATEEC estimated soil loss can be used to identify spatial locations vulnerable to soil loss within the study area. The total soil loss for a given area is not the same as the sediment yield measured at a point of interest, such as a watershed outlet. To explain the possible deposition of eroded materials while they travel to the channel networks and eventually to watershed outlet, the spatially distributed sediment delivery ratio is computed in the SATEEC system.

2. Sediment Delivery Ratio and Sediment Yield

The SDR is related with many physical characteristics of the watershed, such as size and shape of watershed, rainfall patterns, direct runoff, peak runoff, land use, cover crop, slope, particle size, and channel density (Ouyang and Bartholic, 1997). Area based methods were used to estimate the SDR in the SATEEC system because watershed area at any point within a watershed can be easily computed from the flow accumulation map, which is one of by-product maps from DEM preprocessing to compute LS factor. Three area based methods (USDA, 1972; Boyce, 1975; Vanoni, 1975) are used in the SATEEC to compute the spatially distributed SDR map. The SDR curve developed by Vanoni (1975) is a generalized curve because it was derived from 300 watersheds in the world. Thus, it is recommended that the users select the default SDR curve by Vanoni if they are not familiar with different SDR curves. The SDR values for a very small watershed using the power functions by Vanoni (1975), Boyce (1975), and USDA ARS (1972) exceed 1.0 as shown in Fig. 1. The SATEEC computes the SDR value for every cell within the watershed. Thus, the SDR value for a single cell watershed, usually a cell at the watershed boundary, can exceed 1.0. The SATEEC users can set the upper limit of allowable SDR value when generating sediment delivery ratio map.

3. SATEEC GIS Interface

Fig. 3 shows the SATEEC ArcView GIS interface. All functionalities described previously are provided with the several options under the SATEEC menu. The "Preprocess DEM", "Derive LS Factor Map", and "Compute Average Annual Soil Erosion" options under "SATEEC Ver. 1.0" menu are for the estimation of soil loss using RUSLE. "Compute Sediment Yield at User Click Point" option is for the computation of sediment yield map for a subwatershed delineated at user-click point. Model users can specify the upper bound of slope length, such as 122 meters, with "Derive LS Factor Map" option.

Ⅳ. APPLICATION OF SATEEC

To demonstrate how the SATEEC can be used to estimate the soil loss and sediment yield for a watershed and to simulate the impacts of different erosion control management on sediment delivered to the stream networks, Banddong watershed, located at Chuncheon, Gangwon Province, was chosen in this study (Fig. 4). The area of this watershed is 14.74 km^2. The primary land uses in this watershed are forest, pasture,

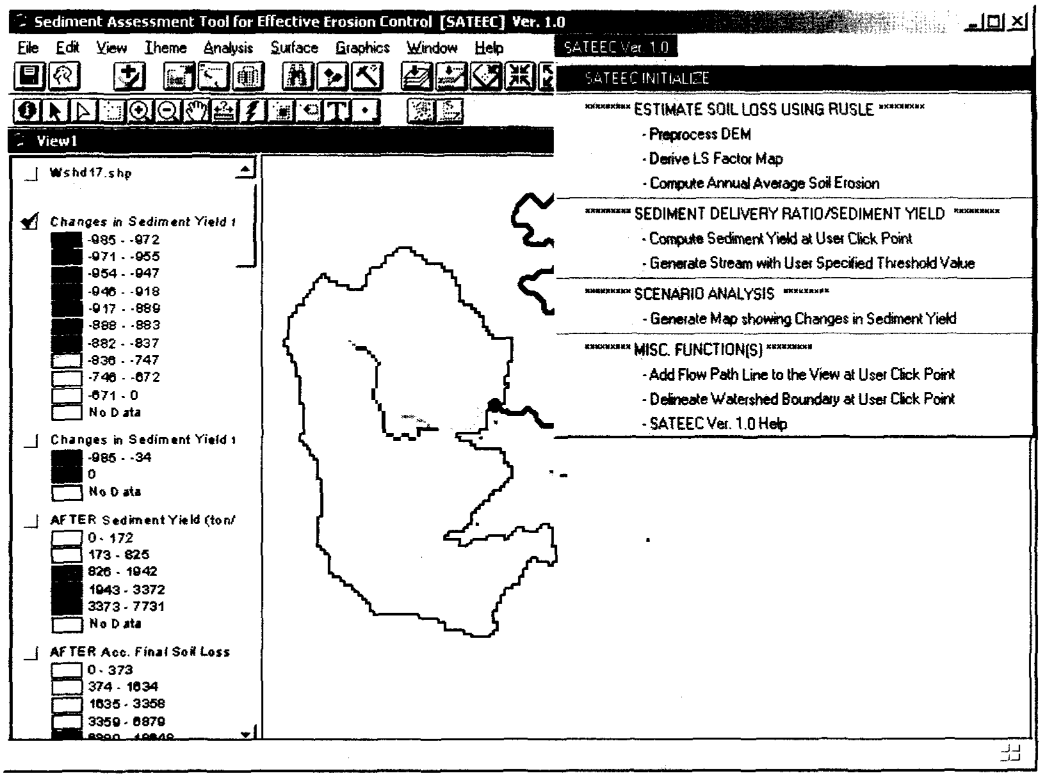

Fig. 3 SATEEC ArcView GIS interface

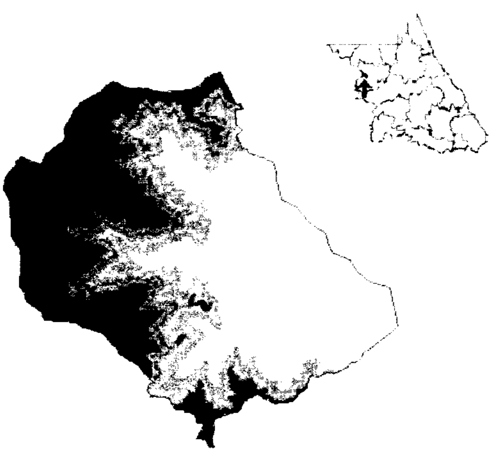

Fig. 4 Location of Bangdong Watershed, Chuncheon, Gangwon Province

agricultural, and residential. More details on Bangdong watershed can be found at the study by Koo (2002).

To estimate the soil loss using the SATEEC, R, K, LS, C, and P maps were prepared. The value of 464 for Chuncheon is used as a representing R factor in this area. K factor each soil type was computed based on the ratio of sand, silt, and clay content. LS factor was estimated using LS module in the SATEEC. The C and P factors for Banddong watershed were prepared based on land uses (Koo, 2002). Detailed information about these input parameters are discussed in Koo (2002). Fig. 5 shows how the SATEEC computes the spatially distributed sediment yield for a subwatershed in Bangdong watershed. The SATEEC first delineates the subwatershed at user click point, and then computes the accu-

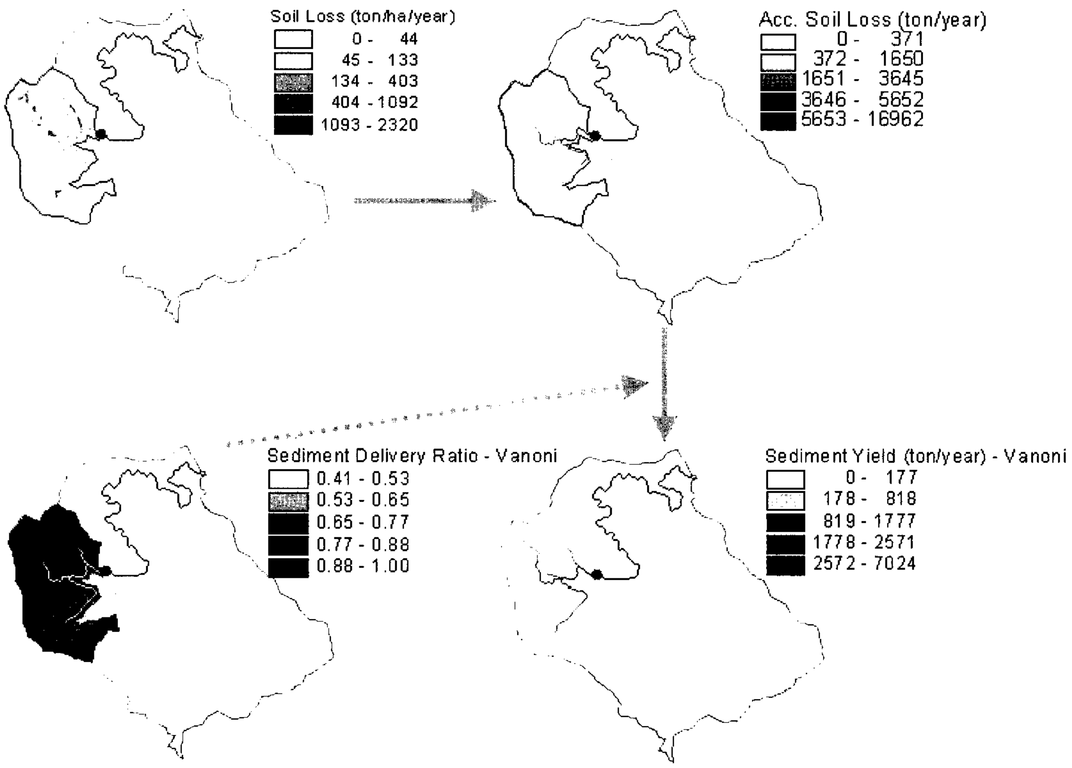

Fig. 5 Soil loss, sediment delivery ratio, accumulated soil loss, and sediment yield

mulated soil loss for a subwatershed. The area based SDR map for a subwatershed is multiplied by the accumulated soil loss map to compute the spatially distributed sediment yield map (4th map in Fig. 5).

Three area based SDR power functions are provided in the SATEEC as described before. The minimum cell values of three SDR maps are 0.41, 0.29, and 0.50, respectively. This indicates the sediment yield for the entire subwatershed using USDA SDR method is almost double the amount obtained using the Boyce SDR method with the same RUSLE input parameter data. The sediment yield for the entire watershed using USDA SDR method is 8,544 ton/year and 4,949 ton/year with the method by Boyce. As shown in this study, it is highly recommended that the SATEEC users use watershed specific SDR method when comparing the estimated sediment yield with the measured data. The cell value in sediment yield map represents the total amount of sediment delivered to the watershed having each cell as an outlet. Thus, the SATEEC estimated sediment yield map can be used to find the most vulnerable reach to sediment loadings. Based on the sediment yield map, erosion control decision makers can prioritize the most vulnerable areas for effective erosion control management plans.

The SATEEC can be used to assess the impacts of different cropping and management practices on the sediment yield in the down-

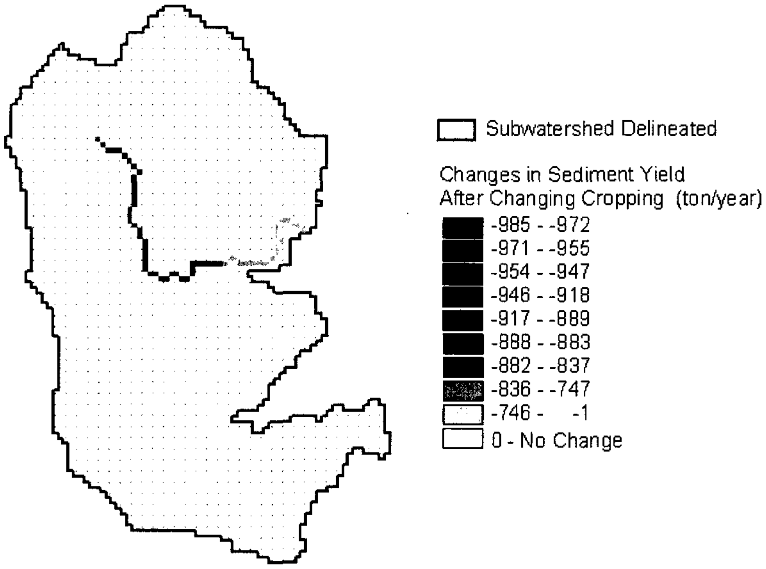

Fig. 6 Changes in sediment yield with new cropping scenario

stream areas. The hypothetical cropping scenario was made to demonstrate how the SATEEC can be easily used to find the best erosion control practice. The land use conversion from "Extensive Pasture" to "Upland" results in increased USLE C cropping factor from 0.08 to 0.31 (Koo, 2002).

The SATEEC is used to estimate the sediment yield with the new cropping scenario. The sediment yield difference map with new cropping scenario was created with one of options in the SATEEC. Fig. 6 shows how new cropping scenario affects the sediment yield in the downstream areas. The cell value of 0 in the tributaries indicates that new cropping scenario does not affect the sediment delivered to the these tributaries. The negative cell value in the reach, displayed in red in Fig. 6, indicates that the sediment yield increase with new cropping scenario. As shown here, the SATEEC can be used to find the sediment source areas for a reach of interest.

V. SUMMARY AND CONCLUSIONS

In this study, the SATEEC was developed to estimate spatially distributed soil loss and sediment yield for an effective erosion control practice. All functionalities in the SATEEC are fully integrated with the ArcView GIS system. No additional input data, other than those for RUSLE, are needed to operate the SATEEC. Thus, the easy-to-operate SATEEC can be used by soil erosion decision makers to establish an effective erosion control plans without any special training. The SATEEC was applied to Bangdong watershed to estimate soil loss and sediment yield for every cell within the study area. The sediment yield values for the sub-watershed are 8,544 ton/year and 4.949 ton/year, respectively, with USDA and Boyce methods. The sediment yield value using USDA method is almost double compared with the value obtained from Boyce method. Hence, use of watershed specific SDR method is highly recommended for better estimation of sediment yield in the watershed. To demonstrate how SATEEC can be used to find effective erosion control practices, hypothetical cropping scenario was made. The SATEEC generated sediment yield difference map can be used to simulate how different cropping scenario affects the sediment delivered to downstream reaches. As shown in this study, the SATEEC is an efficient tool to find the erosion control practice to meet the allowable sediment delivered to the stream networks and to find the sediment source.

Although the SATEEC was found as an efficient tool in this study, the SATEEC estimated soil loss and sediment yield do not include the gully and channel erosion. Thus, the SATEEC should not be used for a large scale watershed if the significant amount of erosion is caused by gully and channel within watershed. The SDR estimation methods in the SATEEC only consider the watershed size although the sediment delivery ratio varies with many physical characteristics of the watershed. Thus, a better technique to estimate the sediment delivery ratio needs to be incorporated into the SATEEC though it may require addition input data set. The SATEEC computes the average annual potential soil erosion and sediment yield in the watershed. Sometimes, it is necessary to estimate the sediment yield from a single storm event, such as thunderstorm driven storm event, for an effective sediment control management. Thus, the SATEEC needs to be extended to generate sediment yield map from a single storm event.

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