한국방재학회논문집
제7권 1호 2007년 3월
pp. 67 ~ 72

유역침식 및 퇴적 잠재능 예측모델 개발

Prediction of Watershed Erosion and Deposition Potentials

손 광 익*
Son, Kwang Ik

Abstract

A model for predicting potentials of land erosion and deposition over a natural basin was developed based on the mass balance principle. The program was developed based on sediment mass balance principle for each cell in a GIS. Sediment yield from a cell was estimated with RUSLE. The outflow sediment from a cell was calculated by multiplying the sediment yield of the cell by the sediment delivery ratio (SDR) of the cell. The outflow sediment from the upstream cell becomes the incoming sediment of the downstream cell. Therefore the erosion and deposition potential of each cell could be determined from the sediment mass balance i.e., the difference between the incoming and outflow of sediments of each cell. The developed model was validated by comparing the predicted sediment yields for three basins with measured data.

key words : sediment, sediment delivery ratio, deposition potential, erosion potential

요 지

본 연구에서는 토사에 대한 질량보존의 법칙을 이용하여 자연유역 내 토양의 침식 및 퇴적 잠재능을 산정할 수 있는 모델을 개발하였다. 이 프로그램은 각 셀 별 토사에 대한 질량보존의 법칙을 적용하여 GIS환경하에서 구동 가능하도록 구성되어있으며 셀 별 토사발생량은 RUSLE 공식을 이용하여 산정하였다. 토양의 침식 및 퇴적 잠재능은 토사의 유출량과 유입량의 차에 의해 각 셀이 침식되거나 퇴적된다는 질량보존의 법칙을 이용하여 산정하였다. 질량보존의 법칙을 적용하기 위한 셀 별 토사유출량은 토사발생량과 토사전달률을 곱하여 산정하였으며 이 토사 유출량이 흐름방향 알고리즘에 의해 결정되는 하류 셀의 토사유입량이 된다. 본 연구에서 개발된 모델을 이용하여 국내 소유역에 대해 적용하였으며 그 결과를 실측치와 비교함으로써 모델을 검증하였다.

핵심용어 : 유사, 토사전달률, 퇴적잠재능, 침식잠재능

1. Introduction

Soil erosion in mountainous areas not only causes the destruction of plants, but also nonpoint-source pollution within a basin. The environmental impacts of soil erosion, whether the result of anthropogenic activities or natural disasters (e.g. urbanization, wildfires) could be minimized by the introduction of best management practices. The appropriate location(s) for the introduction of such practices can be identified through the use of accurate soil erosion models.

---

* Member · Professor, School of Civil & Environmental Eng., Yeungnam Univ., (e-mail: kison@yu.ac.kr)

To achieve this goal, a two-dimensional distributed model for estimating sediment yield and deposition in mountainous basins was developed and tested. The validated model can then be used to predict the amount and destination of the eroded soil under various hydrological conditions. Further, predictions of the distribution of nonpoint-sources of sediment could be used to identify sites where appropriate countermeasures should be applied in an effort to reduce subsequent environmental impacts.

2. Basic Assumptions & Theory Development

The topographical variations in a basin exercise control over such factors as the soil yields, the sediment transport efficiency, and the sediment mass balance. Soil yields for each cell were estimated using the Revised Universal Soil Loss Equation (RUSLE). (Wischmeier & Smith, 1965) Improvements to the USLE, a relationship that has been widely used for planning purposes to predict the impact of land use on soil erosion, based on more recent data as well as a new evaluation of the original USLE data base have resulted in a modification known as the RUSLE.

$$Y = A \cdot SDR = RKLSCP \cdot SDR$$

Y is the average sediment yields from a basin per unit of area, and A is the average soil loss from a basin per unit of area. Sediment delivery ratio (SDR) is sediment transport efficiency for each cell.

Certain basic assumptions were made for this study. They include: (a) a basin consists of equal rectangular cells that are fairly standard in a grid-based Digital Elevation Model (DEM); all the rectangular cells in a basin were treated as small basins; (b) Erosion and deposition in each cell have an isotropic characteristic; (c) Steady-state conditions were assumed, to permit the determination of a mass balance and soil yields; and (d) All the erosion and deposition within the individual cells will occur contemporaneously. Based on the foregoing assumptions, the final model required completion of three steps: (a) estimation of soil erosion in each cell; (b) determination of the flow volume; and (c) determination of the direction of flow from each cell, and a mass balance for each cell.

Soil erosion was estimated with RUSLE. The application of RUSLE, with a single-flow algorithm, is commonly employed for the quantitative estimation of soil yields in many areas of Korea. However, it is well known that a single-flow algorithm is insufficient to simulate actual flow phenomena, especially in mountainous regions (Son, 2001).

Hence, in this study, the effects of nonuniform slopes on soil erosion were considered in estimating the slope length (L) and the degree of slope (S). To that end, a distributed model was used in conjunction with a multi-directional algorithm. Previous work indicated that this approach was likely to produce better estimates for L and S (Son, 2003). Further, the Maximum Downhill Slope (MDS) and the Neighborhood Slope (NBH) methods were used to estimate S.

Sediment transport from each cell was estimated using Ferro, et al.’ s and Swift’ s (2000) sediment delivery ratio methods.

In previous studies(Ferro and Minacapilli ; 1995, Ferro et al. ; 1998), the analysis, carried out for 13 Sicilian and two Calabrian basins, of the empirical cumulative distribution function (cdf) of the travel time showed that the DR_i coefficient has the following expression:

$$DR_i = \exp(-\beta t_{p,i}) = \exp\left(-\beta \frac{l_{p,i}}{\sqrt{s_{p,i}}}\right) \qquad (1)$$

where, DR_i is the sediment delivery ratio.

Swift(2000) developed a SDR equation for North Carolina and Georgia forested landscape.

$$DR_e = 0.9004 - 0.1341(\ln X) - 0.0465(\ln X)^2 + 0.00749(\ln X)^3 - 0.0399(\ln Y) + 0.0144(\ln Y)^2 + 0.00308(\ln Y)^3 \quad (2)$$

where, DR_e is the sediment passing efficiency (%), X is the distance to stream, and Y is the slope in percent.

Flow direction was determined using a GIS program. Lastly, an algorithm based on the mass balance principle of soil yield was employed to estimate the amount of erosion and deposition occurring in each cell.

The most appropriate method for estimating the SDR was determined by comparing various predictions with actual measurements made at the outlet of each sub-basin (cell).

3. Algorithm Development

The continuity equation for sediments for an individual cell "i" can be described as:

$$\Delta S_i = [(I_i^+ + I_i^-)/2 - (Q_i^+ + Q_i^-)/2]\Delta t \quad (3)$$

where,

ΔS_i : stored sediment in cell "i" during Δt

I_i^+, I_i^- : sediment inflows at the beginning and at the end of the routing period

Q_i^+, Q_i^-: sediment outflows at the beginning and at the end of the routing period.

The steady state assumption for cell "i" during Δt yields $I_i^+ = I_i^- = I_i$, $Q_i^+ = Q_i^- = Q_i$ Therefore, equation (3) was simplified as either:

$$\Delta S_i = I_i \Delta t - Q_i \Delta t \quad (4)$$

$$\Delta S_i = YI_i - YO_i \quad (5)$$

where,

YI_i : inflow sediment for cell "i"

YO_i : outflow sediment for cell "i" .

The difference between the sediment inflow (YI_i) and the sediment outflow (YO_i) represents sediment storage in a cell (ΔS_i). The (YO_i) at cell "i" is determined from the sediment yields at cell "i" (Y_i), and the sediment delivery ratio (DR_i).

$$Y_i \times DR_i = YO_i \quad (6)$$

The concept of the developed model was verified with a simplified imaginary basin consisting of nine cells. Fig. 1 shows the imaginary basin and the number in each cell represents (Y_i). Fig. 2 shows the DR_i. The simulated direction of sediment transportation for each cell is shown in Fig. 3.

1	0	0
0	4	0
0	0	9

Fig. 1. Sediment yields (Y_i)

0.5	0	0
0	0.1	0
0	0	0.5

Fig. 2. Sediment delivery ratio (DR_i)

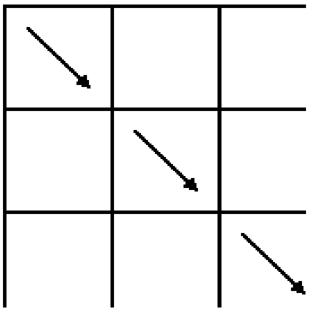

Fig. 3. Sediment transportation direction

Sediment outflow YO_i for each cell (Fig. 4) was estimated by multiplying Y_i with DR_i. Accumulated sediment for each cell along the flow path is shown in Fig. 5. Sediment inflow (YI_i) can be estimated using equation (7); Fig. 6.

0.5	0	0
0	0.4	0
0	0	4.5

Fig. 4. Sediment outflow (YO_i)

0	0	0
0	0.9	0
0	0	5.4

Fig. 5. Accumulated sediment outflow ($Acc.YO_i$)

−0.5	0	0
0	0.5	0
0	0	0.9

Fig. 6. Sediment inflow from equation (7)

$$Acc.YO_i - YO_i = YI_i \tag{7}$$

The "−0.5" shown in Fig. 6 was corrected to "0" (Fig.7) by considering the boundary condition. Sediment storage ($\varDelta Y_i$) is the difference between the sediment inflow (YI_i) and outflow (YO_i) as shown in Fig. 8.

$$YI_i - YO_i = \triangle Y_i \tag{8}$$

Negative (−) values in Fig. 8 indicate erosion in the cell whereas positive (+) values indicate deposition in the cell. The algorithm flow diagram is shown in Fig. 9.

0	0	0
0	0.5	0
0	0	0.9

Fig. 7. Real sediment inflow (YI_i).

−0.5	0	0
0	0.1	0
0	0	−3.6

Fig. 8. Sediment storage ($\varDelta Y_i$).

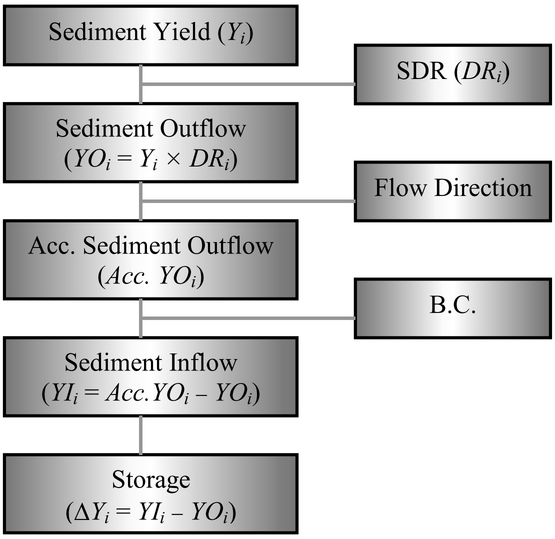

Fig. 9. Algorithm for sediment flow estimation

4. Application for Comparisons

The applicability of all the methods and the model described above, were evaluated by comparing predicted against measured values of soil yield determined at the outlet of a basin. The model was applied to Songjun agricultural reservoir in Korea. The reservoir locates at Yangbuk-Myun Songjun-Ri in Gyungbuk Province. Basin area, stream length and reservoir capacity is 503ha, 3.57km and 438,000 m^3 relatively. Used C and P for basin is shown in Table 1.

Table 1. C, P Values for Songjun Basin

	C	P
cropland	0.3	0.16
forest	0.002	0.8

Figs. 10~12 display the estimated results using the SDR suggested by Ferro & Minacapilli (1995), and Ferro et al. (1998). Ferro, et al.' s (1998) SDR equation was applied in Method 1, by assuming that eroded material will reach the nearest watercourse. The basic assumption of Method 2 is that the eroded material reaches to the basin outlet point.

Figs. 13~15 show the sediment yields using Swift's (2000) SDR equation. The results or this method was named Method 3.

Comparisons of soil yield for Songjun reservoir (Fig. 16) indicate that MDS Method in conjunction with the Method 2 or Method 3, produced the best result based on dredging records for the reservoir. Table 2 shows the estimated sediment yields and the dredged sediment amount.

Table 2. Estimated and Dredged Sediment

	Sediment Amount (m^3)	
	MDS	NBH
Method 1	54,124	45,904
Method 2	79,024	136,550
Method 3	65,099	106,705
Dredged	60,000	

In general, Ferro's equation gives higher SDR than Swift's equation.

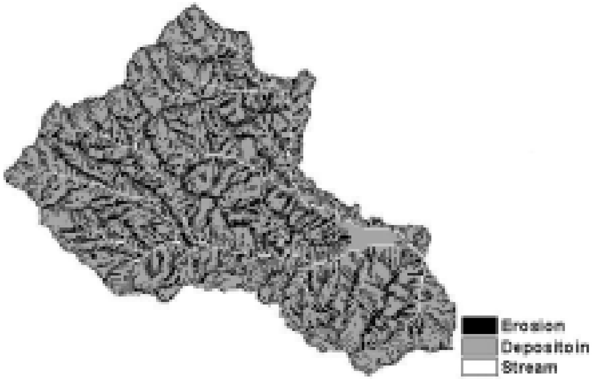

Fig. 10. Eroded and deposited area(Method 2)

Fig. 11. Predicted erosion potential(Method 2)

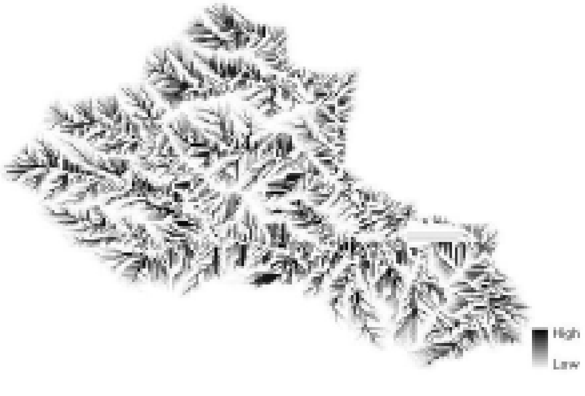

Fig. 12. Predicted deposition potential(Method 2)

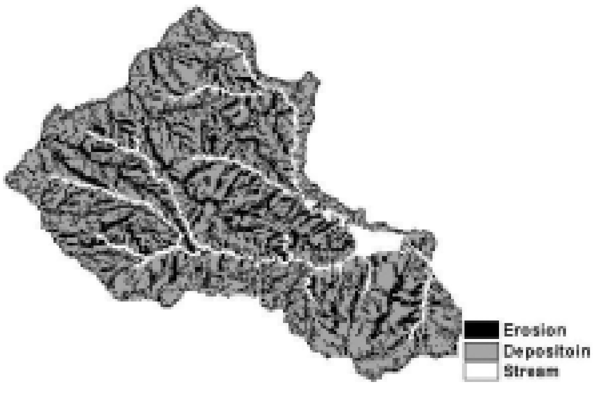

Fig. 13. Eroded and deposited area(Method 3)

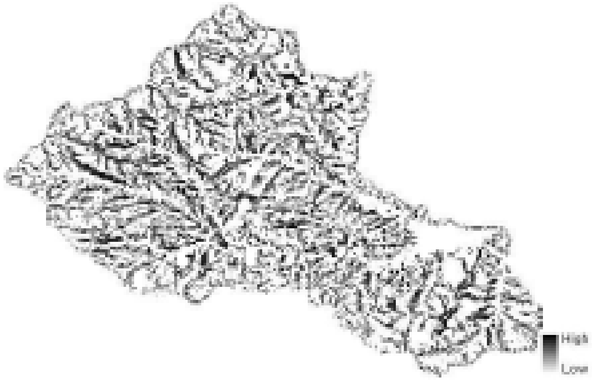

Fig. 14. Predicted erosion potential(Method 3)

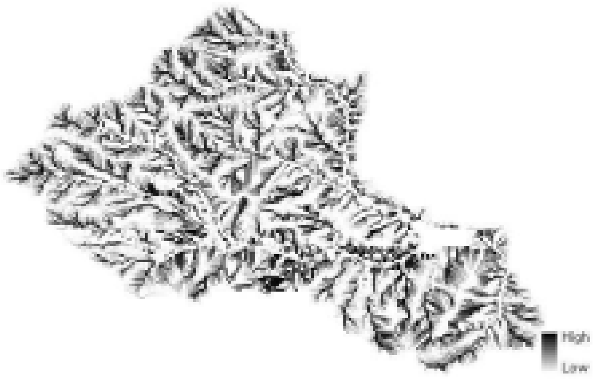

Fig. 15. Predicted deposition potential(Method 3)

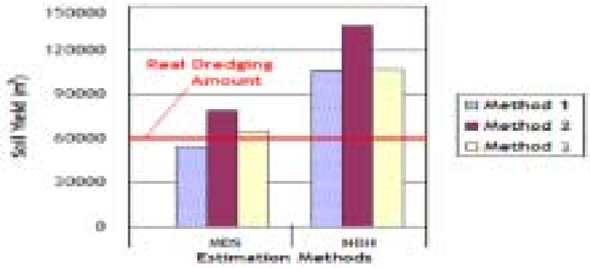

Fig. 16. Soil yield comparisons for Songjun basin

5. Conclusions

A distributed model for quantifying erosion and deposition over a mountainous basin was successfully developed based on the sediment mass balance principle. The model was validated by comparing the predicted sediment yields for a upstream basin of an agricultural reservoir with measured data. Ferro's SDR method used in conjunction with the MDS method appears to generate the best results for mountainous basins in Korea.

Acknowledgements

This research was supported by the Yeungnam University research grants in 2004.

References

Elliot, W. J., Hall, D. E. & Scheele, D. L. (2000). *WEPP Interface for Disturbed Forest and Range Runoff, Erosion and Sediment Delivery*, USDA Forest Service Rocky Mountain Research Station and San Dimas Technology and Development Center

Ferro, V. & Minacapilli, M. (1995) Sediment delivery processes at basin scale. *Hydrol. Sci.* 40(6), pp. 703-717

Ferro, V., Porto, P. & Tusa, G. (1998) Testing a distributed approach for modelling sediment delivery. *Hydrol. Sci.* 43(3), pp. 425-442.

Hickey, R, Smith, A. & Jankowski, P. (1994) Slope length calculations from a DEM within ARC/INFO GRID: *Computers, Environment and Urban Systems* 18(5), pp. 365-380.

Quinn. P., Beven, K., Chevaller, P. & Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modelling using Digital Terrain Models. *Hydrol. Processes* 5, 59-79.

Son, K. I. (2003). Evaluation of LS Parameters in USLE using GIS. *J. Korean Soc. Civil Engnrs* 23,(4B), pp. 281-287.

Son, K. I. (2001). Applicability examination of the RUSLE sediment yield prediction equations in Korea. *J. Korea Water Resour. Assoc.* 34(3), pp. 199-207.

Swift, L.W. Jr. (2000). *Equation to dissipate sediment from a grid cell downslope.* USDA Forest Service, USA

Wischmeier W. H. & Smith, D. D. (1965). Predicting rainfall erosion losses from cropland East of the Rocky Mountains. US. Dep. Agric. *Agricultural Research service. Agricultural Handbook.* no. 282

◎ 논문접수일 : 2007년 01월 11일
◎ 심사의뢰일 : 2007년 01월 29일
◎ 심사완료일 : 2007년 03월 27일