Geographic information system-coupling sediment delivery distributed modeling based on observed data

S. E. Lee and S. H. Kang

ABSTRACT

Spatially distributed sediment delivery (SEDD) models are of great interest in estimating the expected effect of changes on soil erosion and sediment yield. However, they can only be applied if the model can be calibrated using observed data. This paper presents a geographic information system (GIS)-based method to calculate the sediment discharge from basins to coastal areas. For this, an SEDD model, with a sediment rating curve method based on observed data, is proposed and validated. The model proposed here has been developed using the combined application of the revised universal soil loss equation (RUSLE) and a spatially distributed sediment delivery ratio, within Model Builder of ArcGIS's software. The model focuses on spatial variability and is useful for estimating the spatial patterns of soil loss and sediment discharge. The model consists of two modules, a soil erosion prediction component and a sediment delivery model. The integrated approach allows for relatively practical and cost-effective estimation of spatially distributed soil erosion and sediment delivery, for gauged or ungauged basins. This paper provides the first attempt at estimating sediment delivery ratio based on observed data in the monsoon region of Korea.

Key words | GIS, monsoon, sediment delivery rate (SDR), SEDD, SY

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INTRODUCTION

Sediment particles at downstream are transported through the river system as a result of runoff from rainfall. The sediment particles eroded from a basin are eventually deposited in a flood plain reservoir, or reach the sea. The variations of water discharge in the river affect the concentration or dispersal of sediments. Sediment yield (SY) data, except for large rivers, are very limited for South Korean river basin systems, owing primarily to a lack of logistics, and the high costs involved in sediment data collection. Consequently, a simple model is desirable to predict SY, for ultimately ungauged basins. Predictive models of SY have been developed by researchers through a combination of the relationship between soil erosion and SY (Gregory & Walling 1973), the sediment delivery rate (SDR)-area power function method (Lane *et al.* 1997) and spatially distributed modeling based on a geographic information system (GIS) (Renard *et al.* 1991; Kothyari & Jain 1997; Jain & Kothyari 2000).

Modeling is an important research technique for the planning and management of soil and water resources. Erosion and sedimentation involve the processes of detachment, transport and deposition of soil particles. Factors that influence fluvial sediment loads therefore include the various land uses and cultural practices that take place in these areas. Although erosion and SY processes have been studied in detail, modeling the linkage of soil erosion rates within a basin to the SY at the basin outlet is often problematical because of the lack of detailed input data at a river-basin scale (Milliman & Syvitski 1992; Van Rompaey *et al.* 2001; de Vente *et al.* 2013).

The objective of this study is to develop a sediment delivery model to estimate the suspended SY of basins in the monsoon region, and to apply the proposed model to estimate the SY being discharged into the sea. For this, a simple but useful distributed model based on GIS is proposed that allows the simulation of sediment delivery processes at a basin scale. The model was applied and validated on the basis of observed data for the study areas of South Korea.

Study areas

South Korea is located on the southern part of the Korean Peninsula as shown in Figure 1. South Korea's land mass

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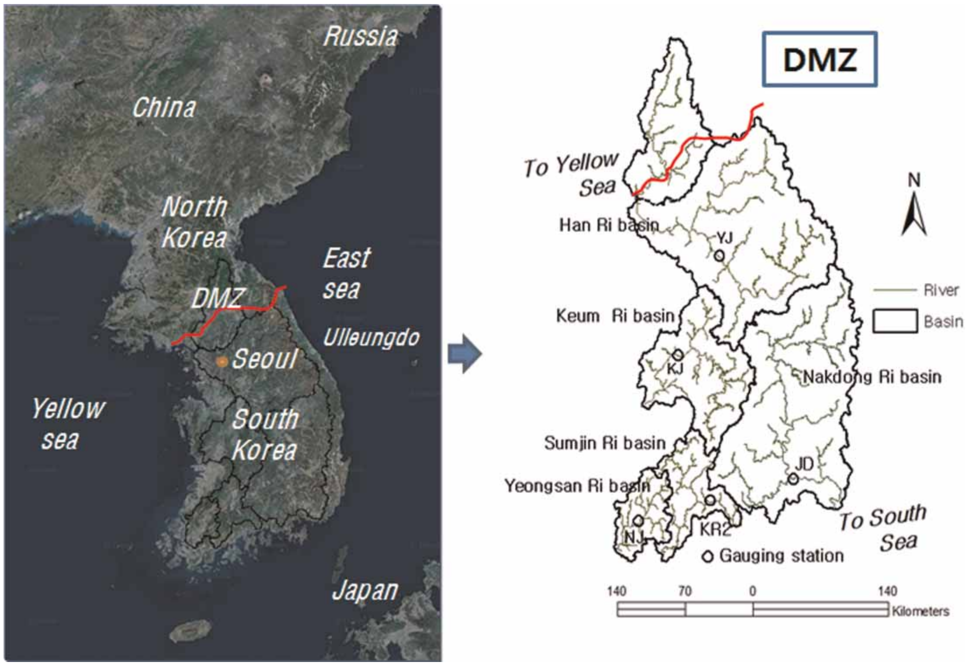

Figure 1 | Location map of the study area.

is ca. 100,032 km^2 with 2,413 kilometers of coastline, with the Yellow Sea to the west and the East China Sea to the south. It has five major rivers: the Han, Keum, Nakdong, Sumjin and Yeongsan rivers, whose basins comprise 86 percent of the land. Table 1 shows the five river basins used for this study with their gauged stations.

METHODOLOGY

Soil erosion model

The revised universal soil loss equation (RUSLE) is used as a soil erosion model to estimate the amount of soil erosion from basins in the five gauged stations of five river basins. Since the theoretical basis of RUSLE and its factors have been clearly reported elsewhere (Glymph 1954; Julien & Tanago 1991; Jain & Kothyari 2000; Kinnel 2008), we provide only a brief description of the model here.

The movement of sediment from the basin depends on geomorphologic and environmental surface factor such as topography and slope, drainage pattern, land cover, soil type and condition, and rainfall duration (USDA-ARS 1997).

In the RUSLE, the amount of soil loss is a product of five factors representing rainfall and basin characteristics, as follows:

$$A_{E,\,i} = R_i \cdot K_i \cdot LS_i \cdot C_i \cdot P_i \tag{1}$$

where A_E is the gross amount of soil erosion (tons ha^{-1} per year^{-1}) in ith cell; R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}); K is the soil erodibility factor (tons ha h

Table 1 | Five river basins with their gauged stations in South Korea

	Five major rivers			Sub-basins		
Total land area of South Korea (km^2)	**Main basin**	**Area**	**% of land area**	**Gauged station**	**Area**	**% of main basin**
100,210	Han River	35,770	36	YeaJu (YJ)	11,114	31.1
	Nakdong River	31,785	32	JinDong (JD)	20,311	63.9
	Geum River	9,915	10	KongJu (KJ)	7,213	72.7
	Sumjin River	4,914	5	KuRae (KR)	3,980	81.0
	Yeongsan River	3,468	3	Naju (NJ)	2,059	59.4

$\text{ha}^{-1}\,\text{MJ}^{-1}\,\text{mm}^{-1}$); LS is the slope steepness and length factor (dimensionless); C is the cover management factor (dimensionless); and P is the supporting practice factor (dimensionless). The precise description of RUSLE factors is contained in Appendix A (available online at http://www.iwaponline.com/wst/070/231.pdf).

River SY estimation model

SY is the amount of sediment passing a particular channel location, and is influenced by a number of geomorphic processes (Lane 1982). Calculating the annual sediment load of a river can be quite straightforward, if discharge and sediment concentration are measured at closely spaced intervals, particularly during floods. In most cases, however, a continuous record of sediment concentration is not available, and indirect methods must be utilized, often using a sediment rating curve (SRC). The SRC is a widely adopted method for estimating sediment concentration and load (Campbell & Bauder 1940; Mimikou 1982; Sadeghi & Saeidi 2010; Yekta *et al.* 2010). Since sediment concentration and load often vary over several orders of magnitude, the SRC is generally established by a power function that relates available sediment load (Q_S) to water discharge (Q_W):

$$Q_S = aQ_W^b \tag{2}$$

where a and b are the coefficients determined by regression analysis.

Sediment load is dependent on the river discharge. For most parts of South Korea, over 70% of the annual total water discharge occurs in the monsoon rainy season (Lee & Kang 2013).

For estimating the SY using SRC, we analyze the relation between water discharge and suspended sediment concentration during individual hydrologic events for clarifying sediment dynamics of the study river.

In order to estimate annual SY, an SRC was derived as a linear regression using Equation (2), on the basis of field measured data. The regression approach can provide good results for the prediction of the annual sediment load in streams with large drainage basins. For deriving the SRC, we used a data classification method to show the relationship between incoming sediment discharge and water discharge.

The SDR is the ratio of SY at the outlet, over the total volume of produced sediment in the drainage basin. It is well known that the SDR is related to basin size, i.e., it decreases with the size of the basin. Generally, there are two methods to estimate SDR: (1) an observed SRC model linking RUSLE; and (2) a combination of the sediment delivery distributed (SEDD) and RUSLE model as shown in Figure 2. The SDR values can be assessed with empirical regression equations using lumped drainage basin parameters, or with GIS-based spatially distributed sediment models using field experimental data.

SDR model coupling RUSLE and SRC

RUSLE is a basin model so it cannot be directly used to estimate the amount of sediment reaching downstream areas, because some portion of the eroded soil may be deposited while traveling to the watershed outlet or the downstream point of interest (Neibling & Foster 1977). To account for these processes, the SDR for a given watershed should be used to estimate the total sediment transported to the

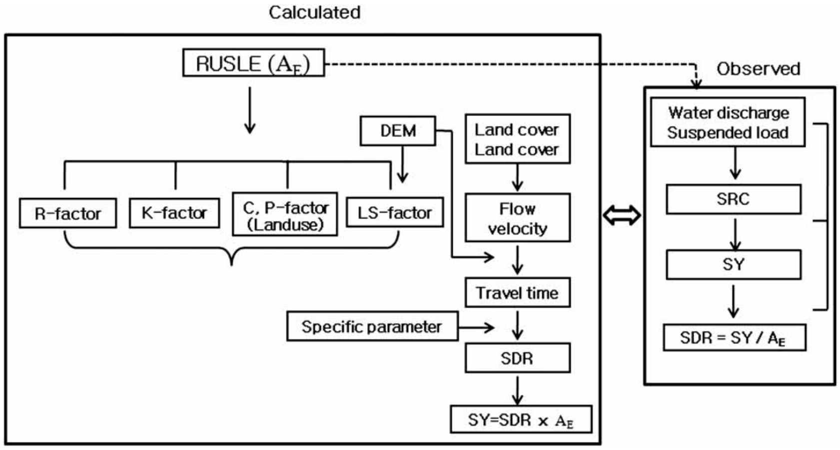

Figure 2 | Combination for calculating SY and SDR using Model Builder (MB) in the ArcGIS environment.

watershed outlet. The SDR can be expressed as follows:

$$\mathrm{SDR} = \mathrm{SY}/A_{\mathrm{E}} \tag{3}$$

where A_{E} is the gross erosion for the entire watershed.

SEDD model

Empirical equations for SDR are usually based on variables such as catchment area, slope and land cover (Walling 1983; Ferro & Porto 2000). For example, Kothyari & Jain (1997) estimated the SDR values from the watershed area, relief ratio and average runoff curve number value. They applied a lumped approach, but improved this by division of the modeled catchment into smaller watersheds. According to some authors (Jain & Kothyari 2000; Mutua & Klik 2006), the SDR_i coefficient, which is a measure of the probability that the eroded particles are transferred from the morphological unit under consideration to the nearest stream reach, can be generalized as follows:

$$\begin{aligned}\mathrm{SDR}_i = \exp(-\beta t_{\mathrm{P},i}) &= \exp\left[\sum_{i=1}^{N_{\mathrm{P}}} \frac{l_i}{v_i}\right] \\ &= \exp\left[-\beta\left(\sum_{i=1}^{N_{\mathrm{P}}} \frac{l_{i,}}{a_i S_i^{0.5}}\right)\right]\end{aligned} \tag{4}$$

where β is basin specific parameter depending on morphological data, $t_{\mathrm{P},i}$ is travel time (hr) of overland flow from the ith overland cell to the nearest channel cell down the drainage path.

If the flow path from cell ***i*** to the nearest channel traverses *Np* cells, then the travel time from that cell is calculated by adding the travel time for each of the *Np* cells located along the flow path (Jain & Kothyari 2000; Fernandez *et al.* 2003).

$l_{\mathrm{P},i}$ is the length of segment i in the flow path (m), and is equal to the length of the side or diagonal of a cell, depending on the flow direction in the cell. v_i is the flow velocity for the cell (m/s). The flow velocity is considered to be a function of the land surface slope and the land cover characteristics (Fernandez *et al.* 2003; Mutua & Klik 2006), i.e., $v_i = a_i \times S_i^b$. If A_{E} is the amount of soil erosion produced within the ith cell of the catchment estimated using Equation (5), then the SY for the catchment, SY, is obtained, as below:

$$\mathrm{SY} = \sum_{i=1}^{n} \mathrm{SDR} \cdot A_{\mathrm{E}} \tag{5}$$

where n is the total number of cells over the catchment, and the term SDR is the fraction of $\mathrm{S_E}$ that ultimately reaches the nearest channel. Since the SDR of a cell is hypothesized as a function of travel time to the nearest channel, this implies that the gross erosion in that cell multiplied by the SDR value of the cell becomes the SY contribution of that cell to the nearest stream channel. The SDR values for the cells marked as channel cells are assumed to be unity. SY modeling is a more complicated and time-consuming process, since the RUSLE method cannot drive the SY directly. In order to estimate the SY, we combine the RUSLE and SDR model, using the Model Builder (MB) in the ArcGIS environment.

RESULTS AND DISCUSSION

Soil erosion

The gross amount of soil erosion from each identified cell of the five gauged stations was computed by integration of the RUSLE erosion factors, namely R, K, LS, C and P. Maps for values of the RUSLE parameters can be integrated in ArcView GIS, using a raster calculator to form a composite map denoting gross soil erosion, based on 30 m digital elevation model (DEM).

Rainfall erosivity is determined by climatic data. For calculating R factors in the study area, we used an annual average value using the isohyetal method (Ufoegbune *et al.* 2011).

Changes occurring in the values of the factor *C* due to crop growth over such a small duration were negligible. The composite term *KLSCP* of RUSLE represents the soil erosion potential of different cells. A high value of this term indicates a higher potential of soil erosion in the cell. The annual average soil erosions of the five gauged stations ranged from 449 to 792 tons/km^2/year. A computed map of the annual soil erosion is presented in Figure 3.

Estimate of SDR

In relation to cell-based methods for estimating SDR and SY as expressed in Equations (4) and (5), the SDR in the ith cell represents the soil loss from cell i that actually reaches a continuous stream system. The *SDR* was estimated following the definition given by Ferro & Minacapilli (1995), which is a function of travel time. The sensitivity of the coefficient β appearing in Equation (4) for *SDR* was studied empirically (Ferro 1997). Jain &

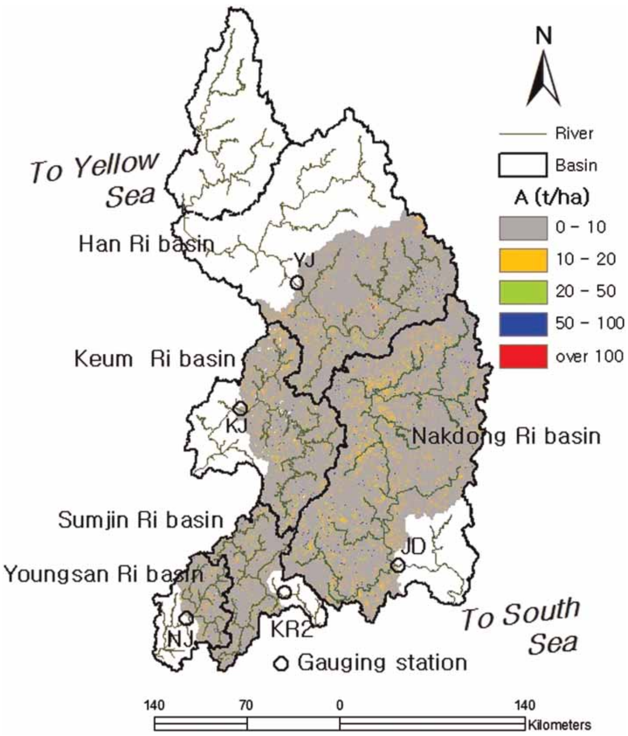

Figure 3 | Annual calculated soil loss in the five gauged stations.

Kothyari (2000) reported that the SY is not very sensitive to the β value. Conversely, Fu *et al.* (2006) asserted that SDR was very sensitive to the β value. Despite these different findings, the β value is treated as a constant parameter. In our case, we found that SY and SDR were sensitive to the β value, with the range from 0.6 to 1.2 as shown in Table 2. At that time, the range of calculated SDR was from 0.033 to 0.152.

Figure 4 shows calculated maps of the SDR values for the study basins. It can be seen from Figure 4 that, as expected, large SDR values are associated with steep headwater areas, while channel areas in the catchment and smaller SDR values are mainly found to be associated with the overland regions that surround the confluences of the main stream with the smaller-order streams. It is, however, important to note that the river basins vary greatly in size and topographic conditions, and that SDR calculation methods vary between studies, so any comparison must be made with caution.

Furthermore, the accuracy of the SDR shown in this study strongly depends on the model selection for soil erosion, the quality of geospatial data, measurement accuracy, and basin characteristics.

Estimating SY

The annual SY predicted can be obtained from the SDR multiplied by the RUSLE using Equation (5). Figure 5 shows the spatial mapping of SY across the entire basins selected for the study area. The value of β for those river basins ranged from 0.6 to 1.2, with an SY from 179,379 to 1,830,000 t/yr. The specific SY observed was from 30 to 141, with the river basins ranging from 2,059 to 20,311 km^2. The observed specific SY was somewhat lower than that established by Milliman & Syvitski (1992) for South Asia and Oceania rivers.

With regard to the low SY, Moss (1979) pointed out that land cover is the major controlling factor suggests that SYs in forested areas are very low. In our study area, over 70 percent of the five gauged stations are covered with forest, and also with rice farms using water. In addition, a long period of the year has a winter season, with little or no rainfall (December to March).

In addition, over 90% of total SY is concentrated in wet monsoon periods, which will reduce the specific SY to rivers.

For estimating the sensitivity of SY value, a basin specific parameter β was used on the basis of observed data. The major purpose of this method is to create a range of upper and lower bounds for each river basin, by applying Equation (5). It is found that the β value is sensitive to the SY but its range is not large.

Table 2 | Validation of ß value with SDR and SY

		SY		SDR		
Gauged station	**Area (km^2)**	**Measured**	**Calculated**	**Measured**	**Calculated**	**ß**
JD	20,311	1,830,000	1,746,793	0.052	0.045	0.6
YJ	11,104	454,375	430,000	0.050	0.058	0.9
KJ	7,149	211,517	233,000	0.036	0.033	0.7
KR	3,810	179,379	182,616	0.068	0.052	1.2
NJ	2,059	290,491	277,615	0.331	0.152	0.8

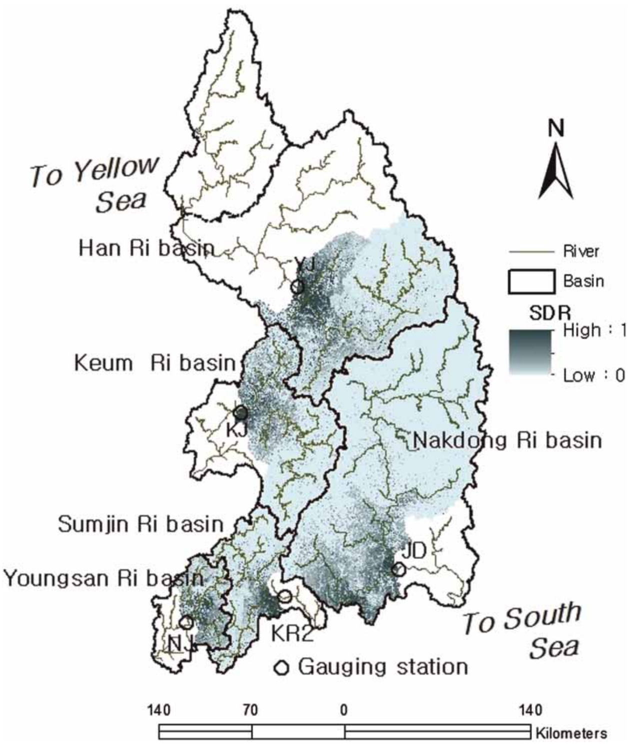

Figure 4 | Predicted spatial distribution of SDR for the five gauged stations.

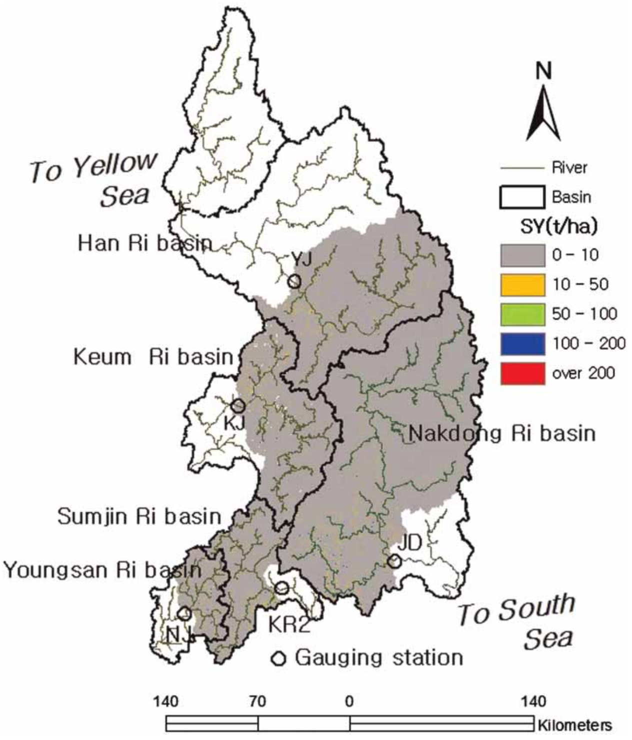

Figure 5 | The calculated results of SY in the five gauged stations.

Table 2 shows the observed and calculated SY with the calibrated basin specific parameter β in the study areas. The results of calibration were fairly good, even if there were insufficient data. Nevertheless, these efforts will help to estimate the SY for ungauged basins.

CONCLUSIONS

This paper proposes a methodological approach to calculate the sediment discharge from rivers to coastal areas that couples RUSLE with the SEDD model, within MB of the ArcGIS environment. It was found that the topographic coefficient β was estimated in the range from 0.6 to 1.2, with the range of SDR from 0.033 to 0.152. It was also found that the topographic coefficient β is sensitive for estimating annual SY, having a range with reasonable results.

The observed specific SY was of low value, but not extreme, considering the high variability when compared with the major world river basins. This is due to the limited rainy season and the land use patterns in the study areas. The low SDR in the rivers appears to offer a unique opportunity to examine the mechanisms of sediment delivery. The calibrated SY value by modeling was quite similar to the value of the SRC method that was based on observed data. Limited data sets for sediment transfer have been reported, even if some basin areas have abundant sediment load data (De Aruújo & Knight 2005; Goodrich & Woolhiser 1991). This means that the modeling approach is a valid means of estimating SY for ungauged river basins in the future.

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