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Sediment Yield for Ungauged Watersheds in South Korea

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Abstract

Specific degradation (SD) is defined as the ratio of the sediment yield divided by the watershed area to compare sediment yield at the basin scale. The SD from 35 watersheds was calculated from field measurements of discharge and sediment concentrations. The watershed characteristics for each watershed were analyzed using GIS tools. All sediment gauging stations are located in alluvial river reaches and the estimated specific degradation typically ranges between 100 and 1,000 tons/km^2·yr. Six regression models based on the watershed characteristics are proposed to estimate the mean annual sediment yield. The most useful relationship is function of the drainage area and mean annual precipitation. The proposed models were tested and validated with 15 additional river stations. The root mean square errors (RMSE) of the predictions are approximately 100 tons/km^2·yr which is found to be satisfactory. The proposed models should be useful to estimate the sediment yield from ungauged watershed in South Korea.

Keywords: *sediment yield, multiple regression, ungauged watershed, GIS analysis, hypsometric curve, wetland*

1. Introduction

South Korea has distinctive climatic and characteristics for water resource management. First, the East Asian monsoon affects South Korean precipitation patterns during the summer season from June to September. Since two-thirds of the annual precipitation occurs during summer, water shortages are likely. Therefore, various dams and reservoirs have been constructed to use water efficiently. Second, 70% of South Korea is forested on steep mountains, and most plains are used for paddy fields (about 13% of total land). Because these unique conditions are favorable for holding sediment during floods, large scale sediment problems have not been experienced in South Korea. However, from the perspective of local and concentrated sediment issues, there have been many problems in South Korea including: riverbed aggradation/degradation, bridge scour, sediment deposition on the floodplain, and sediment problems near infrastructures. For this reason, it is necessary to develop a reliable and consistent method to predict sediment transport and yield based on watershed characteristics (Yoon and Woo, 2000).

Various types of models have been formulated to simulate erosion and sedimentation, and they are commonly classified into three categories, namely empirical (statistical) model, conceptual model, and physical model. The empirical model is commonly based on an analysis of field observations, and seeks to find responses between climatic and topographic characteristics and sediment observations (Wheater *et al*., 1993). Conceptual models provide a general description of catchment processes as a series of internal storages. Physical models are based on the solution of the physical equation for sediment and streamflow (Merritt *et al*., 2003). This paper is focusing on empirical and statistical approaches. The relationship between sediment yield and watershed characteristics has been studied using statistical models since 1950s and typical factors for statistical models for sediment yield are listed in Table 1 (Faran Ali and De Boer, 2008; Flaxman, 1972; Fournier, 1960; Haregeweyn *et al*., 2005; Jansen and Painter, 1974; Ichim, 1990; Kane and Julien, 2007; Langbein and Schumm, 1958; Sahaar *et al.*, 2003; Vanmaercke *et al.*, 2014; Vente *et al*., 2011). Even though statistical models are limited in describing temporal and spatial lumping patterns, they are able to identify the important parameters. Moreover, significant parameters could be used for other conceptual and physical models (Vente *et al*., 2011). Since the 1950s, numerous studies examined the relationship between sediment yield and watershed characteristics using statistical models. In Korea, several models also have been developed for sediment yield (Table 2). However, the most existing formulas seem to lack reliability and consistency (Yoon and Woo, 2000). This paper focuses on developing an empirical model for predicting mean annual total sediment load of ungauged watersheds based on watershed characteristics.

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Table 1. Typical Variables in Empirical Models for Sediment Yield and Specific Degradation

Classification		Factors
Morphometry	Linear Aspect	Stream order, Total drainage length, Length ratio
	Aerial Aspect	Watershed area, Drainage density, Catchment form, Drainage basin order.
	Relief Aspect	Relief ratio, Specific runoff, Maximum Elevation, Altitude, Hypsometric Index, Ruggedness index, Distance between valley outlet and highest point at the divide Difference between highest and lowest point
Climatology		Mean annual precipitation, precipitation erosivity index Maximum mean monthly precipitation, Mean annual precipitation, Mean annual temperature, Annual temperature range, Fournier index, Maximum mean monthly precipitation, Precipitation temperature ratio
Pedology		Lithology Index, Soil erodibility factor, Proneness to erosion parameter, Percentage with erodible lithology, Percentage of sieve analysis results
Land use	Vegetation	Vegetation group index, Percentage of forest cover, Percentage of forest transition, Percentage of bush/shrub cover
	Anthropogenic	Areas with terrace, Percentage of orchard, Percentage of poorly vegetated land, Percentage of agricultural land
	Others	Percentage of snow ice cover
Hydraulic factors related to discharge		Torrential Index, Mean annual discharge, Mean maximum river discharge, Mean annual runoff, Exceedance probability
Other		Index for gully and bank erosion

Table 2. Regression Model for Sedimentation in South Korea

Author	Models	R^2	N	Data
You and Min (1975)	$log V_r = 0.179 + 0.108 lgA - 6.72 logP + 2.2 logS$		30	Reservoir
*Ryu and Kim (1976)	$V_r = 1.43(C_d/A)^{0.531}$ $V_r = 672.61P^{0.024}$ $V_r = 267.21S^{0.587}$		9	Reservoir
*Saemaeul (1978)	$V_s = 255.4A^{0.1816}C^{0.5774}$			Reservoir
Yoon (1981)	$V_s = 1{,}334.08A^{0.8}E_t^{6.2668}$	0.92		Reservoir
*Ahn and Lee (1984)	$V_s = 1{,}744{,}301.05A^{0.02}E_t^{17.017}S^{0.429}S_f^{0.684}A_g^{-1.157}$ (1) $V_s = 66{,}023.72A^{0.546}E_t^{11.06}S^{0.068}S_f^{0.353}A_g^{0.877}$ (2) $V_s = 1{,}488.675A^{0.934}E_t^{4.985}A_g^{0.122}$ (3)			Reservoir
KICT (MOC, 1992)	$SD = 972D^{1.039}M^{-0.825}$(1); for $200 < A < 2{,}000$ $SD = 17.6D^{2.572}R^{0.847}M^{-0.938}$ (2); for $200 < A < 2{,}000$ $SD = 8{,}668A^{-0.896}$; for $A < 200$ $SD = 23{,}564A^{-1.341}A_f^{0.403}K^{0.582}$; for $A < 200$		8	MEP with River
Yoon and Choi (MOMTLA, 2011)	$V_r = 7.0632 \times 10^{11}D^{1.72}K^{5.45}C_{usle}^{-3.65}S^{-7.2}M^{-0.85}$ (1) $V_r = 43{,}954 \times A^{0.464}S^{-2.00}M^{-0.855}$ (2)	0.95 0.86	10	Reservoir

A watershed area (km^2), A_f forest area (km^2), A_g duration of deposition of sediment (yr), C initial reservoir capacity (ha·m), C_d designed reservoir capacity (m^3), C_{usle} cover management factor, D drainage density (km/km^2), E_t trap efficiency, K soil erodibility factor, M bed material size (mm), P mean annual precipitation (mm), R rainfall erosivity (J/ha), S average watershed slope (%), SD specific degradation (tons/km^2·yr), S_f watershed shape factor, V_s annual deposited sediment (m^3/yr), V_r specific sediment deposition (m^3/km^2/yr)
*Reference from the report (MOC, 1992)

2. Data and Site Description

Einstein suggested that each sediment moving a cross-section of the stream must have been eroded somewhere on the watershed above cross-section and it must be transported by water flow (Einstein, 1950). When the soil particles are transported, the total sediment load in a channel could be classified into three ways (Julien, 2002): 1) bed load + suspended load, 2) measured load +

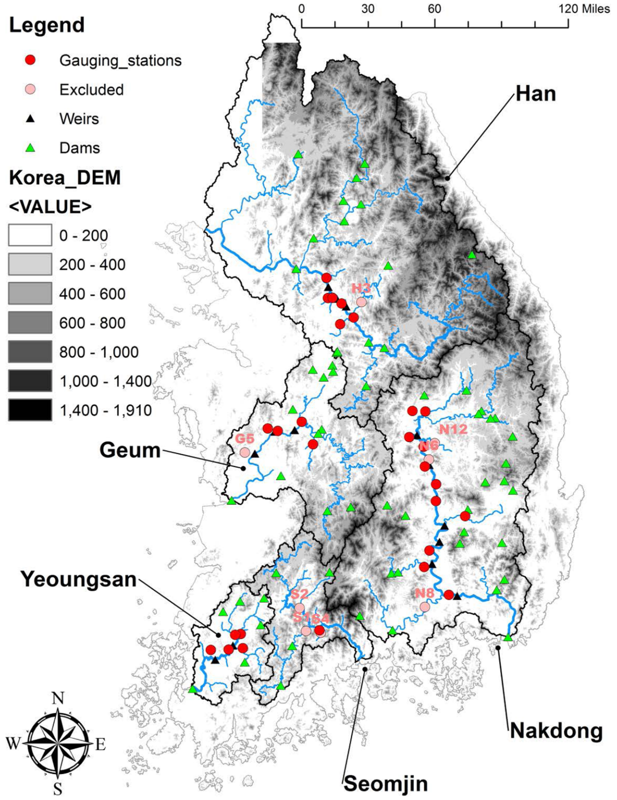

Fig. 1. The Major River Basins of South Korea and Location of Gauging Stations

unmeasured load, and 3) wash load + bed material. Einstein (1950) developed a method to calculate the total sediment discharge with the unit bed sediment discharge and unit suspended sediment discharge. There are 5 main rivers in Korea (i.e., Han, Nakdong, Geum, Yeongsan, and Seomjin), and they generally flow from east to west over South Korea except the Nakdong River. This is because the steep mountains are located in the east part, while the western part is a wide alluvial plain. In this study, we used 35 gauging stations shown in Fig. 1. In rivers, sediment measurements were collected with the depth-integrating sampler D-74, with a few samples from a P-61A, and surface sampler. Bed materials were collected using the US BM-54 material sampler, the 60L Van Veen Grab sampler and also by grid sampling in coarse bed rivers. The samples were analyzed with a sieve analysis and suspended materials were analyzed with the Bottom Withdrawal Tube method. A total of 1,808 data were used to estimate total sediment discharge from 2,084 sediment measurements.

The daily discharges and sediment measurements are provided by the Ministry of Land, Infrastructure and Transport (MOLIT). The daily discharges for 35 river stations from 2005 to 2014 were used to create flow duration curves. The example for Jeongam station (N8) is shown in Fig. 2. These curves are required to estimate the specific degradation using the Flow Duration and Sediment Rating Curve method (FD-SRC).

The exceedance probability (P) is calculated with the Weibull plotting position formula:

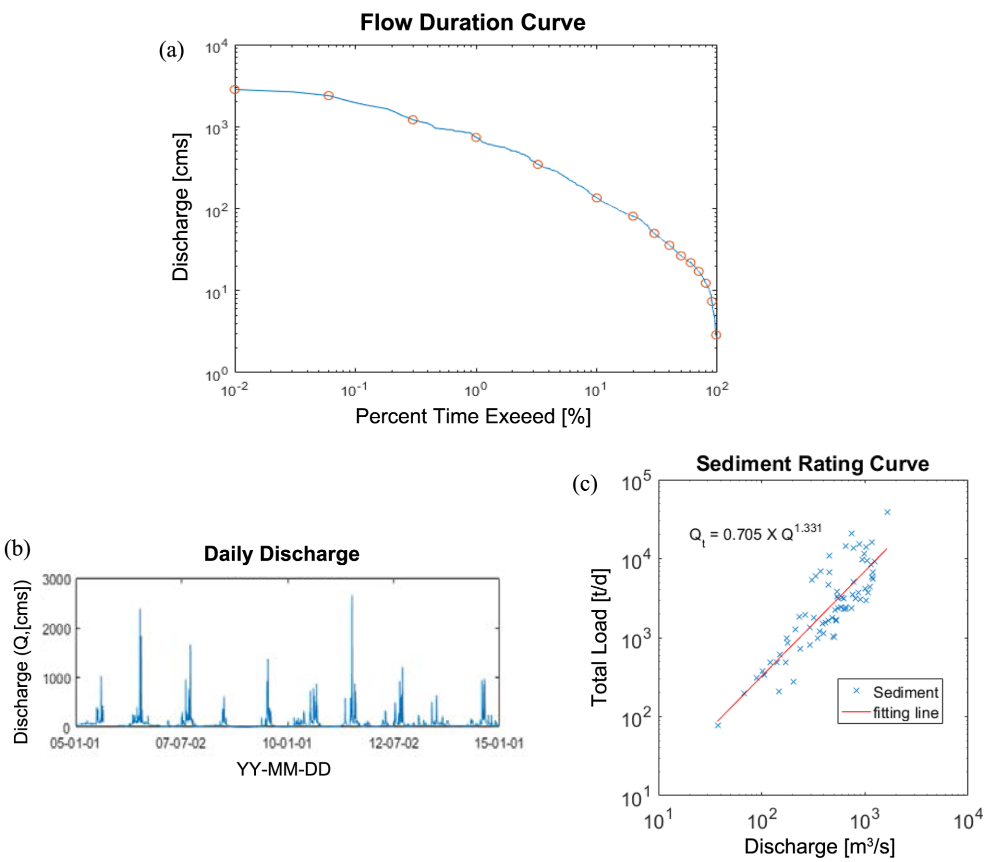

Fig. 2. Flow Duration Curve: (a) Flow Duration Curve, (b) Daily Discharge, and (c) Sediment Rating Curve for Juengam Station (N8)

Table 3. Total Sediment Load at Jeongam Station (N8) Based on MEP

Interval	Interval mid	Interval ΔP	Discharge Q	MEP	
				Q_t	$Q_t \times \Delta P$
			[m^3/s]	[tons/day]	[tons/day]
(1)	(2)	(3)	(4)	(5)	(6)
0 – 0.02	0.01	0.02	2,832	27,761	6
0.02 – 0.1	0.06	0.08	2,387	22,118	18
0.1 – 0.5	0.3	0.4	1,213	8,977	36
0.5 – 1.5	1	1	738	4,638	46
1.5 – 5	3.25	3.5	346	1,694	59
5 – 15	10	10	135	484	48
15 – 25	20	10	81	244	24
25 – 35	30	10	50	128	13
35 – 45	40	10	36	82	8
45 – 55	50	10	27	56	6
55 – 65	60	10	22	43	4
65 – 75	70	10	17	31	3
75 – 85	80	10	12	20	2
85 – 95	90	10	7	10	1
95 – 100	97.5	5	3	3	0.1
Total		100			274

$$P = m/(1+N) \tag{1}$$

where, m = the rank of discharge value from the largest daily discharge
N = the number of events (= daily discharge) for a period
P = the exceedance probability that a given discharge will be exceeded (%)

MOLIT developed Sediment Discharge Computation System (SDCS) based on modified Einstein procedure (MEP) in 2009 to estimate total sediment load (Lee *et al*., 2009). The provided total sediment load was estimated with the SDCS. Fig. 2(b) and 2(c) show the daily discharge measurements and sediment rating curve of Jeongam station (N8). With the estimated total sediment load, the specific degradation was estimated by the FD-SRC method. The total sediment load for each probability was estimated by integrating the results of FD and SRC. In Table 3, the average of daily total sediment discharge is given by the sum of column (6), and it could be converted as annual total sediment load. The final specific degradation (SD) which could compare the sediment yield at basin scale is obtained from annual total sediment load divided by the watershed area. The results of estimated specific degradation at each gauging station are summarized in Table 4. Seven stations (H3, N6, N12, G5, S1, S2, and S4) were excluded from the multiple regression analysis because of small sediment sample and unreasonable result (Fig. 1, Excluded). The approximate value of maximum total sediment load in South Korea is about 1,000 tons/km^2·yr because of favorable conditions for holding sedimentation (Yoon and Woo, 2000).

In Fig. 3, three existing models (KICT1, KICT 2, and Yoon and Choi in Table 1) developed by Ministry of Construction (MOC) and Yoon and Choi are used to validate 35 estimated specific degradations (MOC, 1992; MOLTMA, 1992). They include the bed material size (d_{50}) as a variable and it is classified as d_{50} in before and after flood event in data, therefore the results are provided with averaged value and have variation from minimum and maximum of bed material size. The Root Mean Square Error (RMSE) for each model is 275, 655, and 1409, respectively. Because Yoon and Choi's model was based on the specific degradation of reservoir data, the model has a tendency to over predict the sediment load of rivers. Other models were not tested because they require reservoir related factors.

3. Method

The erosion and transport of sediment from upland to the fluvial system is influenced by watershed characteristics such as physiography, topography, geology and pedology, and climatology and forestry (Julien, 2002). Therefore, various watershed characteristics are analyzed using GIS before developing a regression model for estimating the mean annual sediment yield. Precipitation is a main agent of erosion. It directly impacts soil detachment with raindrop and the transport of sediment downstream (Julien, 2002). Mean annual precipitation (mm) was calculated using daily precipitation data over the 60 stations from the Korea Meteorological Administration (KMA). To generate the grid precipitation data on the watershed, the Kriging method was applied to a 60-point mean annual precipitation value at a 30 m resolution. From the raster result of kriging, two values of mean annual precipitation were exported. One was the point value of mean annual precipitation at the gauging station, and the other was the average mean annual precipitation value over watershed area. For analyzing soil types, the detailed soil map, with the information about 390 soil series developed by the National Institute of Agriculture Sciences is used. The percentage of soil and rock is obtained from the soil database of the Soil and Water Assessment Tool for Korea (SWAT-K) developed by the Korea Institute of Construction Technology (KICT). The soil is classified into clay, silt, sand with a particle diameter of particles obtained from sieve analysis. Each soil series has a different percentage of clay, silt, and sand at different effective depths. With the assumption of homogeneous soils in each layer, the percentage of soil was calculated for four classified effective soil depths: 1) 0 – 10 cm; 2) 10 – 30 cm; 3) 30 – 50 cm; and 4) 0 –50 cm. The results did not have significant differences between each watershed (Fig. 4(a)). Furthermore, various watershed morphometric parameters were estimated with this GIS analysis. From the 5 m by 5 m resolution DEM, 3 parameters describing linear, areal, and hypsometric aspects of each watershed were analyzed. Linear parameters described the stream network and are directly estimated from the Korean Reach File (KRF) version 3 which was provided from the Ministry of Environment (ME). Three stream lengths (i.e., total, main, and tributary) were calculated and the Strahler's stream order (Strahler, 1952) for each gauging stations were analyzed. For areal parameters, general 2-D

Table 4. Estimated Specific Degradation and Data Information of Gauging Stations

Watershed	Station	Number of discharge records	Number of years with sediment samples	Total Number of sediment samples	Watershed Area [km^2]	Estimated SD [tons/km^2·yr]
Han	H1	3,580	6	97	11,074	133
	H2	3,424	2	26	284	530
	*H3	3,536	3	48	1,346	1,102
	H4	1,640	2	29	173	308
	H5	3,535	3	49	519	453
	H6	1,282	2	30	8,823	24
	H7	3,245	2	37	307	90
Nakdong	N1	3,502	4	67	979	64
	N2	2,309	3	44	1,541	50
	N3	2,429	2	33	10,913	20
	N4	3,383	3	53	9,407	46
	N5	3,246	8	147	11,101	58
	*N6	2,800	1	16	9,533	5
	N7	3,516	5	84	20,381	99
	N8	3,528	3	74	2,999	34
	N9	2,122	3	63	1,512	150
	N10	1,826	2	29	175	75
	N11	3,533	3	48	614	38
	*N12	3,280	1	15	1,318	48
	N13	3,557	3	69	1,239	57
	N14	3,539	3	57	750	48
Geum	G1	3,550	4	50	606	126
	G2	3,157	6	105	6,275	128
	G3	2,741	2	30	1,850	152
	G4	1,319	2	21	257	60
	*G5	3,185	1	7	208	62
Yeongsan	Y1	2,921	2	40	190	98
	Y2	3,327	5	109	2,039	125
	Y3	3,333	2	36	668	164
	Y4	1,951	4	80	580	46
	Y5	3,634	4	68	552	41
Seomjin	*S1	3,561	1	15	1,269	32
	*S2	3,579	2	15	1,788	44
	S3	3,640	5	102	3,818	45
	*S4	1,096	1	15	128	28

*Stations not used for calibration

characteristics such as watershed area, drainage density (total stream length [km]/watershed area [km^2]) and shape factor (watershed length [km]/watershed area [km^2]) were determined. Additionally, the 3-D variables were introduced to describe elevation differences. In this paper, the hypsometric curve was used to describe relief and it is compared to the average watershed slope, this parameter identifies differences between mountain and plain regions. The hypsometric curve is the distribution of surface area with respect to elevation (Fig. 4(c)). It can be used for calculation of hydrologic information because the basin hypsometry is related to flood response, soil erosion, and sedimentation process (Strahler, 1952). Three hypsometric indexes: 1) relative height at mid relative area; 2) elevation at mid relative area; and 3) slope between 0.2 and 0.8 relative area were used as parameters. In this paper, the 5 m resolution of DEM is reclassified with every 100 m in each watershed, and the result is normalized to make the hypsometric curve as shown in Fig. 4(c). The generated hypsometric curve is expressed as below equation (Strahler, 1952):

$$\frac{h}{H}=\left[\left(\frac{d-x}{x}\right)\left(\frac{a}{d-a}\right)\right]^{z} \tag{2}$$

where, a is fitted to measurements, while $d = 1$, and $a < d$; z is exponent ($z > 0$).

The horizontal x-axis is the relative area ranging from 0 to d, and z is estimated after fitting curve to Eq. (2). This equation is similar with the equation of relative concentration with reference elevation as derived by Rouse (1937). Therefore, similar conversion of suspended sediment concentration profile was conducted for hypsometric curve and slope of generated results is exported as

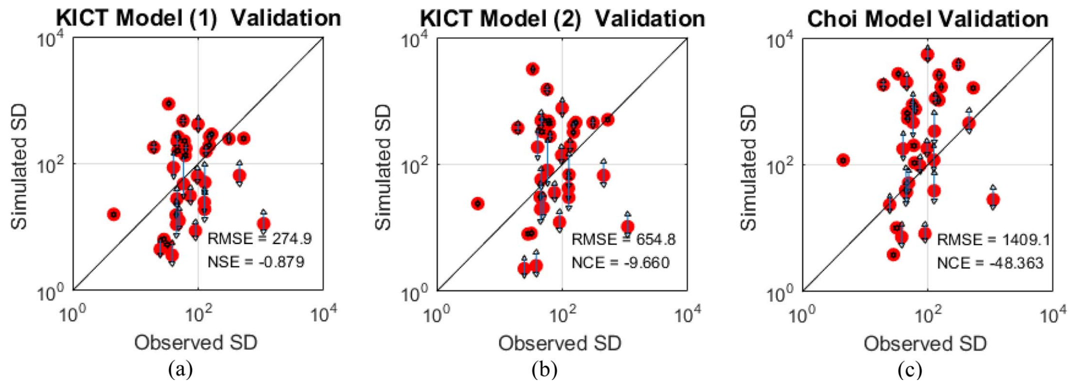

Fig. 3. Validation of Existing Specific Degradation (SD) Model: (a) KICT Model 1, (b) KICT Model 2, (b) Choi's Model (units: tons/km^2·yr)

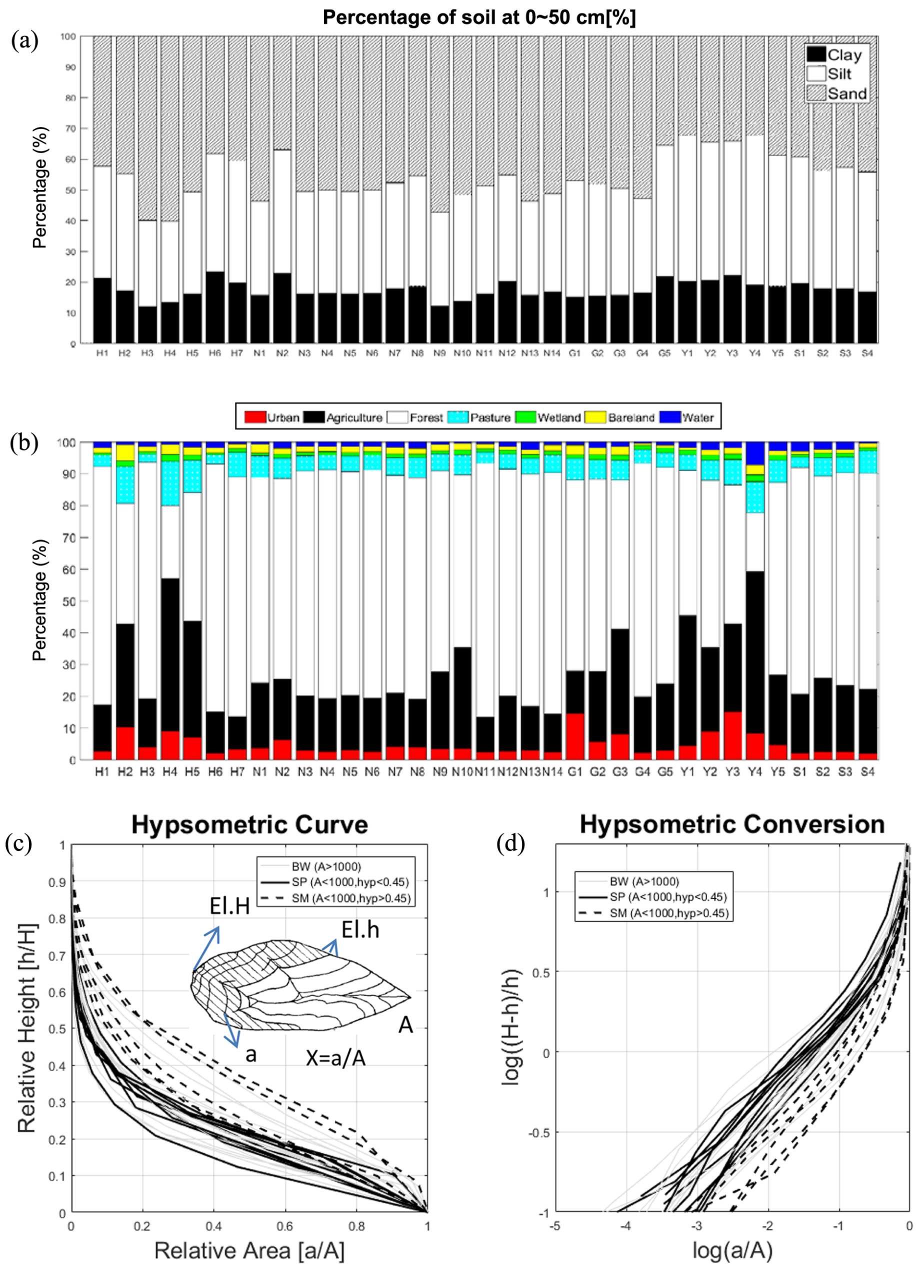

Fig. 4. Watershed Characteristics from GIS Analysis: (a) Percentage of Soil, (b) Percentage of Land Use, (c) Hypsometric Curve, (d) Converted Hypsometric Curve

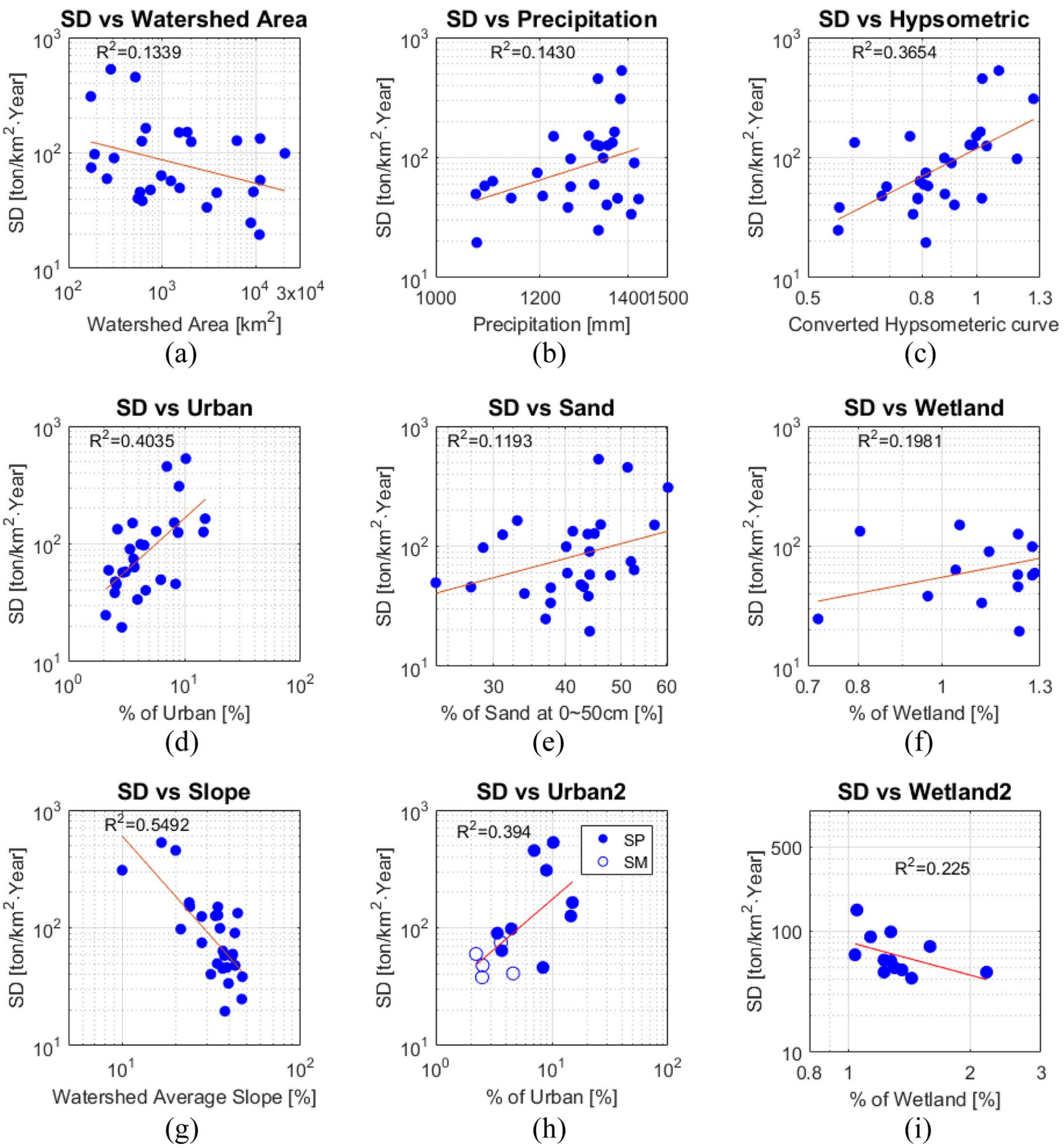

Fig. 5. Relationship between Specific Degradation and Nine Parameters: (a) Watershed Area, (b) Mean Annual Precipitation, (c) Slope of the Converted Hypsometric Curve, (d) Percentage of Urbanized Area, (e) Percentage of Sand in Soil, (f) Percentage of Wetlands, (g) Average Watershed Slope, (h) Percentage of Urbanized Area in Small Watershed, and (i) Percentage of Wetlands in Big Watershed (BW)

an additional relief aspect (Hyp, Fig. 4(d)). In both curves, three type of watersheds are considered: big (BW, A > 1,000 km^2), small mountain (SM, A < 1,000 km^2, Hyp > 0.45) and small alluvial plain (SP, A < 1,000 km^2, Hyp < 0.45). The value of Hyp defines classification between mountain and alluvial plain watersheds. Since land use influences soil erosion and sedimentation processes, the land cover data (10 m resolution) from the ME was used in this analysis. For analyzing land use, the land cover raster is first classified into 23 types and then simplified into 7 types: 1) Urban; 2) Agriculture; 3) Forest; 4) Wetland; 5) Pasture; 6) Bare land; and 7) Water. Most land is covered with forest and agricultural land (Fig. 4(b)). Additionally, channel width at the station, slope at the station, minimum, maximum and mean bed material (D min, D max, and D mean), elevation, and slope extracted from DEM (m/m) were analyzed.

A simple linear regression between specific degradation and each variable was conducted. The R-squared values ranged from 0.1 to 0.55, as shown in Figs. 5(a) – 5(g). The average watershed slope (R^2 = 0.55) and the hypsometric parameter (R^2 = 0.37) shows significant correlation with specific degradation. Unexpectedly, these two parameters show a negative slope with the specific degradation (Figs. 5(e) and 5(g)). These results are comparable to those of Kane and Julien (2003) where specific degradation decreased on steep watersheds, most likely due to increased vegetation while flat floodplain areas were prone to erosion from agriculture and urbanization. Furthermore, the percentages of urban and wetland (R^2 = 0.4 and R^2 = 0.2) provide a notable

Table 5. Watershed Characteristics Used for Regression Analysis

Station	Watershed Area [km^2]	Mean Annual Precipitation [mm]	Watershed Average Slope [%]	Percentage of Urban [%]	Percentage of Wetland [%]	Percentage of Sand at 0 – 50 cm [%]	Slope of Converted Hypsometric Curve
H1	11,074.0	1,361.1	44.4	42.2	0.8	2.6	0.6
H2	283.5	1,383.4	16.6	44.9	1.7	10.3	1.1
*H3	1,346.0	1,349.4	43.0	59.9	2.3	4.0	1.3
H4	173.4	1,380.2	10.0	60.2	1.5	9.0	1.0
H5	518.6	1,327.4	20.0	50.6	0.7	7.0	0.6
H6	8,822.7	1,328.6	46.8	38.2	1.1	2.1	0.9
H7	306.7	1,414.3	42.8	40.6	1.0	3.4	0.8
N1	978.8	1,104.4	36.7	55.9	1.3	3.7	0.9
N2	1,541.1	1,072.5	34.1	22.5	1.2	6.2	0.8
N3	10,912.8	1,074.3	37.7	44.9	1.2	2.9	0.8
N4	9,406.8	1,140.9	38.6	43.6	1.2	2.6	0.8
N5	11,100.6	1,089.2	37.5	44.9	1.3	3.1	0.9
*N6	9,532.9	1,105.7	40.3	43.7	1.1	2.6	0.8
N7	20,381.0	1,339.4	35.3	40.6	1.0	4.2	0.8
N8	2,998.6	1,406.7	39.4	37.9	1.6	3.9	0.8
N9	1,512.0	1,228.3	34.4	57.7	1.0	3.6	0.6
N10	175.3	1,193.9	28.0	52.9	1.3	3.6	0.7
N11	614.4	1,259.7	47.1	45.2	1.4	2.5	0.7
*N12	1,318.0	1,123.1	36.3	31.9	1.2	2.7	1.0
N13	1,239.1	1,265.5	41.3	49.8	1.6	2.9	1.0
N14	749.9	1,205.1	43.0	45.1	1.6	2.5	1.0
G1	606.4	1,350.6	33.3	43.1	1.3	14.6	0.8
G2	6,275.1	1,322.8	34.4	45.3	1.6	5.7	1.2
G3	1,850.0	1,306.3	24.0	46.6	1.5	8.2	1.0
G4	257.5	1,318.8	41.6	39.7	1.8	2.2	1.0
*G5	207.5	1,332.8	34.3	26.5	2.2	2.9	1.0
Y1	190.1	1,265.5	21.3	28.1	1.4	4.5	0.9
Y2	2,039.0	1,330.6	27.9	29.8	1.4	8.8	0.8
Y3	668.1	1,366.5	23.8	31.4	0.8	15.0	0.6
Y4	580.3	1,373.6	36.7	25.3	1.7	8.4	1.1
Y5	551.9	1,348.0	31.4	33.7	2.3	4.6	1.3
*S1	1,268.5	1,404.4	37.8	32.7	1.5	2.1	1.0
S2	1,787.6	1,369.5	34.9	37.2	0.7	2.6	0.6
*S3	3,817.7	1,425.0	36.5	36.7	1.1	2.6	0.9
*S4	127.7	1,429.0	43.7	38.8	1.0	1.9	0.8

correlation with specific degradation (Figs. 5(c) and 5(i)). The regression analysis was performed using R-program (v.3.3.2). The general form of multiple linear regression models with normal error terms could be presented as Eq. (3).

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \tag{3}$$

where,

Y_i = response variable

$X_{i1}, \ldots, X_{i,p-1}$ = explanatory variables

$\beta_{i1}, \ldots, \beta_{i,p-1}$ = regression coefficients

ε_i = error term

p = number of explanatory variables.

In this study, the response variable is specific degradation, and the explanatory variables are the watershed characteristics and precipitation. The regression model for specific degradation has commonly used the log-log transformation to linearize regression relation and stabilize error variation. It could be expressed as:

$$\ln Y_i = \beta_0 + \beta_1 \ln X_{i1} + \beta_2 \ln X_{i2} + \cdots + \beta_{p-1} \ln X_{i,p-1} + \varepsilon_i \tag{4}$$

which is equivalent to:

$$SD_i = e^{\beta_0} \times X_{i1}^{\beta_1} \times X_{i2}^{\beta 1} \times \cdots \times X_{p-1}^{\beta_{p-1}} \tag{5}$$

4. Results

Total 38 watershed parameters were used as explanatory variables for 28 specific degradation data in river were used as response variables. Six regression models were developed to estimate the mean annual specific degradation (SD) in tons/

km²·yr for ungauged watersheds based on watershed characteristics and precipitation data. This structure helps to avoid multi-collinearity problem in multiple regression.

$$M1)\ \mathrm{SD} = 357.16\mathrm{A}^{-0.204} \qquad \mathrm{RMSE} = 118 \qquad (6)$$

$$M2)\ \mathrm{SD} = 3.35 \times 10^{-7}\, A^{-0.16} P^{2.864} \qquad \mathrm{RMSE} = 113 \qquad (7)$$

$$\mathrm{M3})\ \mathrm{SD} = 0.0003 \times A^{-0.08} P^{1.65} U^{0.75} \qquad \mathrm{RMSE} = 101 \qquad (8)$$

$$M4)\ \mathrm{SD} = 1.75 \times 10^{-7} A^{-0.05} P^{1.89} U^{0.89} Sa^{1.931} \qquad \mathrm{RMSE} = 84 \qquad (9)$$

$$M5)\ SD = 1.77 \times 10^{-5} A^{-0.009} P^{1.91} U^{0.53} Sa^{1.09} Sl^{-0.93}$$
$$\mathrm{RMSE} = 87.6 \qquad (10)$$

$$M6)\ SD = 2.45 \times 10^{-7} A^{-0.04} P^{1.94} U^{0.61} W^{-0.64} Sa^{1.51} Hyp^{1.84}$$
$$\mathrm{RMSE} = 81 \qquad (11)$$

The meaningful parameters of the watershed characteristics are the watershed area in square kilometers (A), the mean annual precipitation in millimeters (P), the percentage of urbanized area (U), the percentage of sand in the soil (Sa), the average watershed slope (Sl), the percentage area covered by wetlands (W), and the slope of the converted hypsometric curve (Hyp). The models show that the Root Mean Square Error (RMSE) decreases from 120 to 81 tons/km²·yr as the number of variables increase. First two models were developed with the common parameters (A and P). Since the RMSE of model 5 decreases with the average watershed slope, model 6 was developed with two additional parameters (the percentage of wetlands and the slope of the converted hypsometric curve).

$$X_h = \begin{bmatrix} 1 \\ logA \end{bmatrix}, X_h = \begin{bmatrix} 1 \\ logA \\ logP \end{bmatrix}, X_h = \begin{bmatrix} 1 \\ logA \\ logP \\ logU \end{bmatrix}, \cdots, or\ X_h = \begin{bmatrix} 1 \\ logA \\ logP \\ \vdots \\ logHyp \end{bmatrix} \qquad (12)$$

where X_h is the observation for estimating the mean response.

$$SD_h \pm t\left(1 - \frac{\alpha}{2};\ n-p\right) s\{SD_h\} \qquad (13)$$

where α is level of significant ($\alpha = 0.05$),
$s\{SD_h\}$ is the estimated standard deviation.

Because most wetlands are located near alluvial rivers and

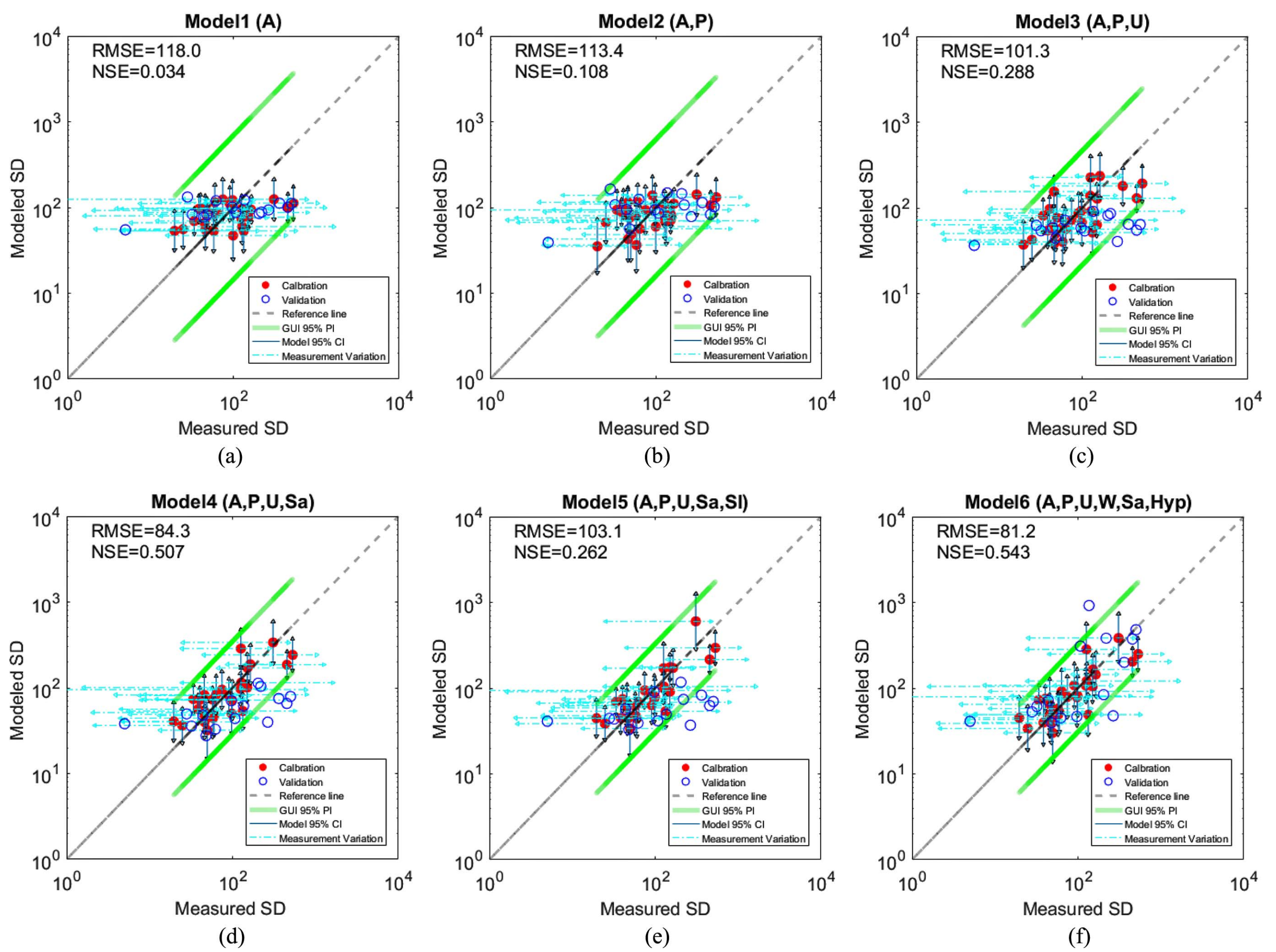

Fig. 6. Confidence and Prediction Intervals of the Six Regression Models (units: tons/km²·yr): (a) 1 var Model, (b) 2 Vars Model, (c) 3 Vars Model, (d) 4 Vars Model, (d) 5 Vars Model, (e) 6 Vars Model

sediment deposition occurs in wetland during floods, the percentage of wetland has a reasonable relationship with specific degradation (Fig. 5(i)). The logarithmic hypsometric related parameter could well classify between mountainous and plain region.

Furthermore, the confidence and prediction intervals were suggested as Eqs. (12) and (13). The 95% of confidence interval for estimation of mean specific degradation SD_h can be calculated as Eq. (13). In Fig. 6, the vertical solid arrow delineates the 95% confidences interval. In this study, Graphical User Interface was developed to apply the proposed regression models (http://feelingwc.wixsite.com/ungaugedsd). When the user enters appropriate variables, the mean specific degradation and sediment yield will be estimated. In the multiple linear regressions, the explanatory variables are independent, so the prediction intervals could not be simply expressed. To cope with this complexity, the approximated prediction interval at 95% is provided. The approximated prediction interval is calculated as:

$$\bar{Y} = 1.96\sigma, \quad \sigma = s\left\{\log\left(\frac{SD_m}{SD_c}\right)\right\} \tag{14}$$

where,

SD_c = specific degradation from regression model

SD_m = specific degradation from MEP

σ = the standard deviation of the log of measured to calculated specific degradation ratios from calibration dataset

The new prediction intervals of specific degradation for six models are provided in Table 6. In the result, the standard deviation of log ratio between measured and calculated specific degradation decrease when the variables for equations increase. The result of the new prediction interval is suggested as solid line in Fig. 6. The GUI also provides applicability index, which is based on range of calibration dataset. The GUI shows the number of inputs that are within the range of calibration dataset

Table 6. Prediction Interval for GUI

Model	σ	± 1.96σ
1 variable model	0.33	± 0.65
2 variables model	0.31	± 0.61
3 variables model	0.26	± 0.51
4 variables model	0.22	± 0.43
5 variables model	0.21	± 0.41
6 variables model	0.2	± 0.39

Table 7. Applicability Index for GUI

Number of variable within measured range	Predictability	Variable symbol	Range
5	Good	A	173 – 20,380 km^2
4	Moderate	P	1,072 – 1,425 mm
3	Fair	U	2 – 15%
2	Poor	Sa	22 – 60%
1	Very Poor	Sl	10 – 47%

(1 is within the range and 0 is outside the range), and total number of variables of which values are within range of calibration dataset (Table 6). The percentage of urban of 29 stations ranged from 2% to 15%. When the percentage of urban is lower than 2%, the index value is "-1" to consider some possible watersheds which have low percentage of urban. This index could provide information for applicability when the user puts the extreme value of variables for small watershed, city, and drought/flood regions.

5. Validation and Discussion

To validate the developed models, the mean annual total sediment yield at 15 additional stations was used (Table 8). The validation results of the proposed models are shown as empty circles in Fig. 6 and organized in Table 9. Most of the validation

Table 8. Validation Dataset and Measured Specific Degradation

Name	A	P	W	U	Sa	Sl	Hyp	SD	Reference
	[km^2]	[mm]	[%]	[%]	[%]	[%]		[tons/km^2·yr]	
N12	1,318	1,123	1.3	2.7	32	36	0.95	48	
N6	9,533	1,106	1.3	2.6	44	40	0.80	5	
G5	208	1,333	1.6	2.9	26	34	1.03	62	
S1	1,269	1,404	1.0	2.1	33	38	0.90	32	
S2	1,788	1,370	1.5	2.6	37	35	1.02	44	
S4	128	1,429	1.0	2.0	39	44	0.69	28	
Hwajeon Bridge	188	1,407	0.2	3.5	33	44	1.68	136	MOLTMA (1992)
Janghyeon Bridge	923	1,376	0.8	4.0	47	45	1.37	219	
Seokpo Bridge	299	1,269	0.6	2.9	51	37	1.52	501	
Songriwon Bridge	491	1,215	0.5	2.7	50	36	1.36	453	
Daeso Bridge	971	1,279	0.3	2.5	38	44	1.24	107	
Socheon	697	1,214	0.5	1.9	45	45	0.56	266	Additional Data
Sancheong	1,130	1,548	0.9	2.9	52	33	0.57	204	
Cheoncheon	291	1,318	0.3	2.6	49	30	0.78	361	
Cheongseong	490	1,271	1.9	2.7	50	26	0.73	97	

Table 9. Simulated Specific Degradation from Developed Models

Name	M1	M2	M3	M4	M5	M6
N12	82	56	44	28	33	40
N6	55	39	37	38	41	41
G5	120	125	72	33	39	45
S1	83	108	54	36	44	61
S2	77	95	59	48	57	72
S4	133	165	63	50	45	53
Hwajeon Bridge	123	148	91	62	50	821
Janghyeon Bridge	89	107	86	104	74	383
Seokpo Bridge	112	102	64	79	70	480
Songriwon Bridge	101	83	55	66	63	373
Daeso Bridge	88	86	54	44	42	309
Socheon	94	78	41	40	37	48
Sancheong	85	145	82	113	117	84
Cheoncheon	112	114	65	75	83	200
Cheongseong	101	95	59	71	91	47

results are within the range of prediction interval. The models show more plausible RMSE values (Fig. 6) than previous models. The Nash-Sutcliffe Efficiency coefficient (NSE) was calculated for each model and the corresponding results also show similar results. Additionally, model 5 which includes the average watershed slope could not well explain the validation dataset. Model 5 underestimates the specific degradation for stream watershed. To be specific, steep small mountain watershed tends to carry higher sediment load.

Since the proposed models are based on 10 years daily discharge and sediment measurement, the variability in specific degradation for each watershed is also shown in Fig. 6. The minimum and maximum specific degradation for 28 calibration data are presented as horizontal dashed arrow in Fig. 6. They varied from 4 to 8,000 tons/km^2·yr. The extreme specific degradation results generated from low sediment measurements. It suggested that the monitoring of sediment concentration and discharge should be continued. With a longer record, the variability of specific degradation may be reduced.

After all, it seems that the first two models perform best overall. Adding more parameters does not significantly reduce the RMSE of the prediction. Therefore, the developed models are best used to describe specific degradation of rivers. They may have limited applicability to watersheds for smaller drainage areas (< 170 km^2), less urbanized watersheds (< 2%), or steeper and milder slope (average watershed slope < 9% or average watershed slope > 47%). In the future, we recommend an increased number of gauging stations, longer sampling period, and longer sediment records.

6. Conclusions

The annual sediment yield of 35 river stations in South Korea ranged from 10 to 1,000 tons/km^2·yr. The results from the five major river basins in South Korea show quite similar patterns. A multiple regression analysis for specific degradation and watershed characteristics was conducted. Six regression models are proposed based on precipitation and watershed characteristics such as watershed area, mean annual precipitation, percentage of urbanized area, percentage of wetland, percentage of sand, and hypsometric index. The predictability of the developed models showed better accuracy compared to existing statistical models. The validation results are within the 95% prediction intervals and the root mean square error of the prediction is less than 100 tons/km^2·yr. These models can be very helpful to estimate the sediment yield at basin scale of ungauged watersheds in South Korea. It could find a watershed which has sediment related problems. The relationship function of drainage area and precipitation seems best suited for practical use at this time. Further improvement of this prediction methodology most likely under the number of field measurements will increase significantly in the future.

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