SOIL EROSION MODELING USING RUSLE AND GIS ON THE IMHA WATERSHED

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Abstract: The Imha watershed is vulnerable to severe erosion due to the topographical characteristics such as mountainous steep slopes. Sediment inflow from upland area has also deteriorated the water quality and caused negative effects on the aquatic ecosystem of the Imha reservoir. The Imha reservoir was affected by sediment-laden density currents during the typhoon "Maemi" in 2003. The RUSLE model was combined with GIS techniques to analyze the mean annual erosion losses and the soil losses caused by typhoon "Maemi". The model is used to evaluate the spatial distribution of soil loss rates under different land uses. The mean annual soil loss rate and soil losses caused by typhoon "Maemi" were predicted as 3,450 tons/km2/year and 2,920 ton/km2/"Maemi", respectively. The sediment delivery ratio was determined to be about 25% from the mean annual soil loss rate and the surveyed sediment deposits in the Imha reservoir in 1997. The trap efficiency of the Imha reservoir was calculated using the methods of Julien, Brown, Brune, and Churchill and ranges from 96% to 99%.

Keywords: soil loss rate, sediment delivery ratio, trap efficiency, life expectancy

1. INTRODUCTION

The Imha watershed is located in the northeastern part of the Nakdong River basin, which is between 36° 09' 42" ~ 36° 50' 08"N and 128° 43' 22" ~ 129° 18' 00"E. It includes Andong city, Pohang city, Chungsong-gun, and Yongyuang-gun of the Gyeongsangbuk-do province. Major tributaries of the Imha reservoir are the Ban-Byeon Stream, Dae-Gok stream, and Young-Jeon Stream. The area of the Imha watershed is 1,361 km^2, which covers 8% of the Nakdong River basin. The average elevation of the Imha watershed is 388 m and average watershed slope is 40%. Average annual temperature is between 11°C and 12°C, and the mean annual precipitation is 1,037 mm. The variation of annual precipitation is very high. About two thirds of the annual precipitation is concentrated in three months, between July and September. The average flow rate is 19.8 m^3 sec^{-1} or about 1,700×10^3 m^3 d^{-1}. The Imha multi-purpose dam was constructed on Ban-Byeon Stream from 1984 to1992. It is located 10km east of the city of Andong, Gyeongbuk province on the Ban-Byeon Stream, and about 350km upstream of the Nakdong River Estuary. It is a rockfill type dam with dimensions of 73 m in height and 515 m in length. Imha reservoir has the dead storage capacity of

40 million m^3 among the total storage of 595 million m^3. It also contributes to the water supply for agriculture, industry, and drinking as well as the reduction of flood damage and hydropower production. Figure 1. presents the location map of the Imha watershed

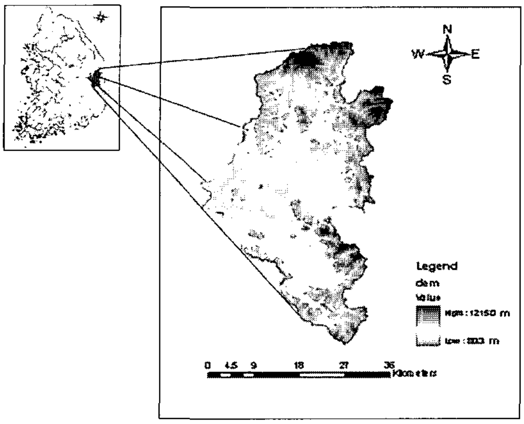


Figure 1. The location map of the Imha watershed

Since Imha reservoir was impounded, it has suffered from continuous sediment-laden density currents. When the typhoon "Rusa" came to the Imha watershed in 2002, the maximum turbidity of the Imha reservoir increased to more than 800 NTU (Neuphelometry Turbidity Unit). Furthermore, when the typhoon "Maemi" struck the Imha watershed on September 12, 2003, a turbidity level of more than 1200 NTU was measured from the total 184mm precipitation of the Imha watershed. The total volume through the spillway was approximately 100 million m^3. Even though turbidity in the Imha reservoir decreased with time, it still remained high for a period of three months.

The objectives of this study are to: (1) use the rainfall data, Digital Elevation Model (DEM), soil type map, and land cover map, and build the Soil Erosion Map (SEM) to calculate the soil loss rates on the Imha watershed. Two cases are analyzed: (1) the mean annual soil loss rate; and (2) the soil loss rate caused by typhoon "Maemi". The purpose of this study is also to analyze the spatial distribution of soil erosion in the Imha watershed, and to determine the Sediment Delivery Ratio (SDR) in the Imha watershed from sediment deposits surveyed in the Imha reservoir in 1997. Finally, this study will determine the Trap Efficiency (TE) at the Imha reservoir.

2. Methods

The Universal Soil Loss Equation (USLE) model was based on the field measurements of soil erosion rates in agricultural areas by Wischmeier and Smith (1965). It has been enhanced during the past 30 years by a number of researchers. Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), Revised Universal Soil Loss Equation RUSLE (Renard et al., 1997), Areal Nonpoint Source Watershed Environmental Resources Simulation (ANSWERS) (Beasley, 1989) and Unit Stream Power - based Erosion Deposition (USPED) (Mitasova et al., 1996) are based on the USLE and represent an improvement of the former.

In 1996, the U.S. Department of Agriculture (USDA) developed a method for calculating the amount of soil erosion under conditions including pastures and forests. The Revised Universal Soil Loss Equation (RUSLE) model was announced to add many factors such as the revision of the weather factor, the development of the soil erosion factor depending on seasonal changes, the development of a new calculation procedure to calculate the cover vegetation factor, and the revision of the length and gradient of slope.

RUSLE is used to estimate the gross soil erosion in the Imha watershed combined with GIS techniques. It is a widely used and accepted empirical soil erosion model developed for sheet and rill erosion based on a large set of experimental data from agricultural plots. The gross soil loss from the RUSLE model is calculated based on following equation.

$$A = R \times K \times L \times S \times C \times P$$

Where: A is a computed spatial average soil loss and temporal average soil loss per unit of area (tons/acre/year); R is a rainfall-runoff erosivity factor; K is a soil erodibility factor; L is a slope length factor; S is a slope steepness factor; C is a cover management factor; P is a support practice factor.

RUSLE model has six parameters, which are rainfall-runoff erosivity factor (R), soil erodibility factor (K), slope length and steepness factors (LS), cover management factor (C), and support practice factor (P).

2.1Rainfall-runoff erosivity factor (R)

Wischmeier et al., (1953) derived the rainfall and runoff erosivity factor from research data from many sources. The rainfall – runoff erosivity factor is defined as the mean annual sum of individual storm erosion index values, EI_{30}, where E is the total storm kinetic energy and I_{30} is the maximum rainfall intensity in 30 minutes. To compute storm EI_{30}, continuous rainfall intensity data are needed. Wischmeier and Smith (1965) found that the best predictor of rainfall erosivity factor (R) is:

$$R = \frac{1}{n} \sum_{j=1}^{n} \left[\sum_{k=1}^{m} (E)(I_{30})_k \right] \quad (1)$$

Where: R is a rainfall-runoff erosivity factor—the rainfall erosion index plus a factor for any significant runoff from snowmelt ($100ft \cdot tonf \cdot acre^{-1} \cdot yr^{-1}$); E is the total storm kinetic energy in hundreds of ft-tons per acre; I_{30} is the maximum 30-minute rainfall intensity;

Based on the Wischmeier method, rainfall-runoff erosivity factors for two cases, which are the average annual rainfall erosivity factor, and the rainfall erosivity factor caused by typhoon "Maemi", are estimated in the Imha watershed. Table.1 and Figure 2 present the rainfall runoff erosivity factors and Isoerodent maps, which are drawn using the Ordinary Kriging interpolation method, for the 9 rainfall gauge stations in the Imha watershed, respectively.

Table 1. Rainfall-runoff erosivity factor

No.	Stations	Rainfall-Runoff Erosivity Factor		Beginning of Observations
		Annual average	Typhoon "Maemi"	
1	Cheong Song	146.2	21.4	Sep-87
2	Bu Dong	251.8	96.5	Jan-00
3	Bu Nam	184.8	54.2	Sep-87
4	Seok Bo	197.1	164.0	Sep-87
5	Jin Bo 2	203.0	34.9	Jan-00
6	Young Yang	154.0	31.6	Sep-87
7	Su Bi 2	186.6	151.3	Jan-00
8	Il Wol	179.6	90.0	Jun-92
9	An Dong	162.2	20.8	Jan-68

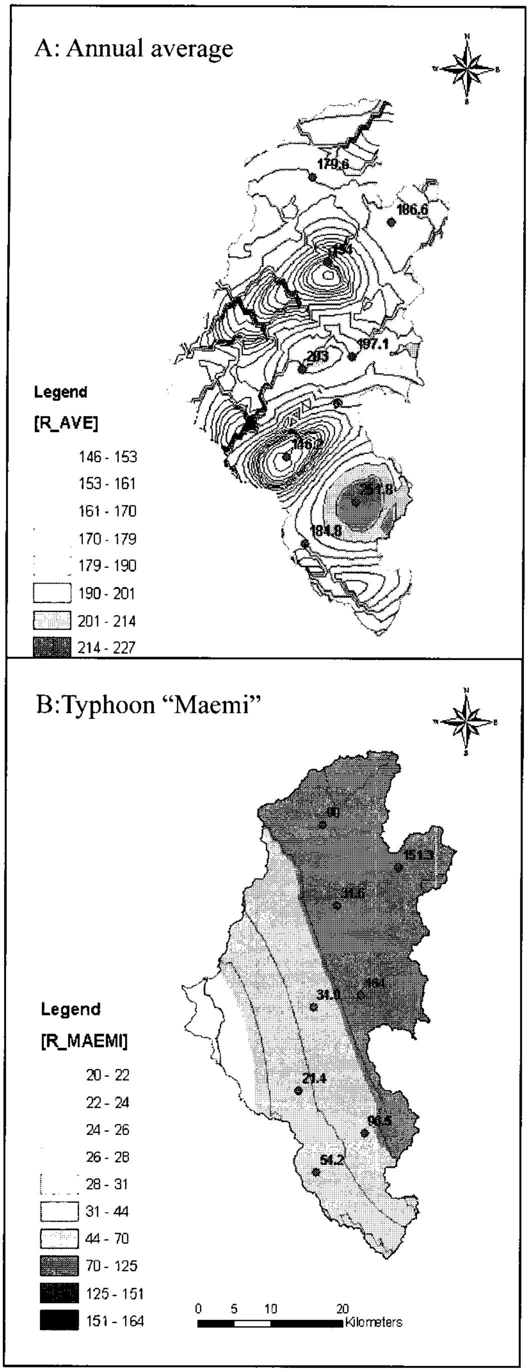


Figure 2. Isoerodent maps of the Imha watershed (A: annual average, B: Typhoon "Maemi")

As shown in Figure 3, computed R values of the Imha watershed are compared with sixty R values, taken from the Climate City Database of USDA Natural Resources Conservation Service (NRCS). The chosen R values from Ohio, Illinois, and North Carolina were similar in the mean annual precipitation and climatic patterns compared to the Imha watershed.

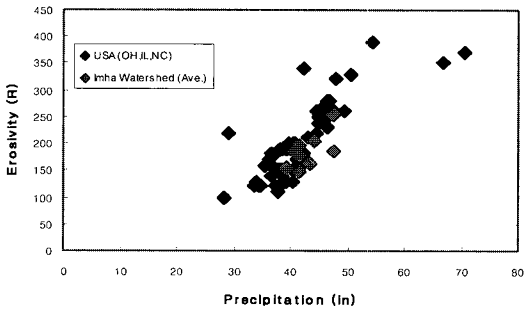


Figure 3. Comparison of Erosivity (R) between USA and Imha rainfall stations

2.2 Soil erodibility factor (K)

Soil erodibility (K) represents the susceptibility of soil or surface material to erosion, transportability of the sediment, and the amount and rate of runoff given a particular rainfall input, as measured under a standard condition. The standard condition is the unit plot, 72.6ft long with a 9 percent gradient, maintained in continuous fallow, tilled up and down the hillslope (Weesies, 1998). Soils of the Imha watershed are classified divided into 35 soil types. In this study, the soil erodibility (K) of the Imha watershed can be defined using the relationship between soil texture class and organic matter content proposed by Schwab et al. (1981). Figure 4 presents the soil erodibility factor (K), which ranges from 0.16 to 0.48, based on the soil texture class.

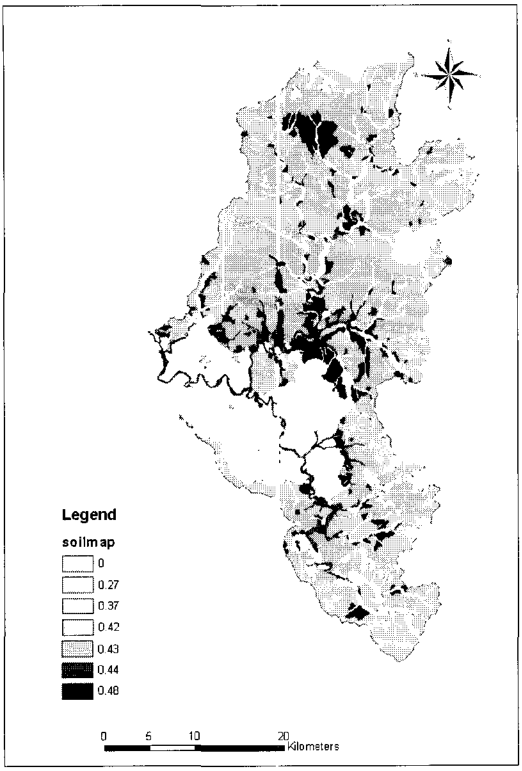


Figure 4. Soil erodibility (K) map of the Imha watershed

2.3 Slope length and steepness factor (LS)

The effect of topography on soil erosion is described by the LS factor in RUSLE, which combines the effects of a slope length factor (L), and a slope steepness factor (S). The L and S factors are extracted from the Digital Elevation Model (DEM) and calculated by the equations suggested by Renard et al. (1997), McCool et al., 1987, and McCool et al., 1997 in RUSLE.

$$L = \left(X_h / 72.6 \right)^m \tag{2}$$

Where: L is the slope length; X_h is the horizontal slope length in ft; m is a variable slope length exponent.

$$S = 10.8 \times \sin\Theta + 0.03 \qquad \sigma \le 9\%$$
$$S = 16.8 \times \sin\Theta - 0.50 \qquad \sigma > 9\% \tag{3}$$

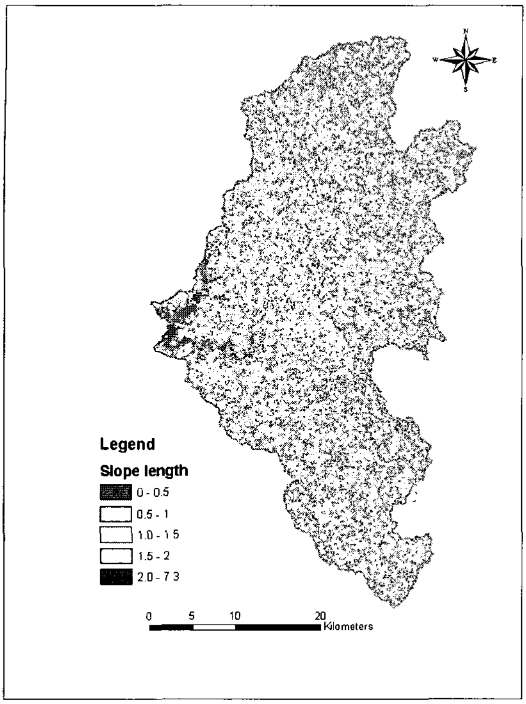
Where: S is the slope steepness; Θ is the slope angle; σ is the slope gradient in percentage.

The slope length and slope steepness (S) can be defined from the Digital Elevation Model (DEM) (Hickey et al., 1994; Molná r and Julien, 1998) and are calculated using an Arcinfo AML coded by Van Remortel et al. (2001) (visit http://www.yogibob.com/slope/slope.html for more information). Figure 5, and Figure 6 represent the slope length (L), slope steepness (S), and LS factor, respectively.

2.4 Cover management factor (C)

The cover management factor (C) represents the effects of vegetation, management, and erosion control practices on soil loss. The value of cover management factor ranges from 1.0 in barren before plant grows to 0.0 in waterbody area.

Based on the "Nakdong River Basin Survey Project, (MOCT and KOWACO, 2005)", the land cover of the Imha watershed is classified with six land cover classifications: Water, Urban, Wetland, Forest, Crop field, and Paddy field. The National Institute of Agricultural Science and Technology (NIAST, 2003) has studied the cover management factor with crop coverage based on Lysimeter experiments from 1977 to 2001. The cover management factor for the forested areas of the Imha watershed has been calibrated by Kim (2006) to reflect the recent changes in land use attributed to deforestation, road construction, and agricultural development. Accordingly, the appropriate C value shown in Figure 7 represents the cover management factor in the Imha watershed.



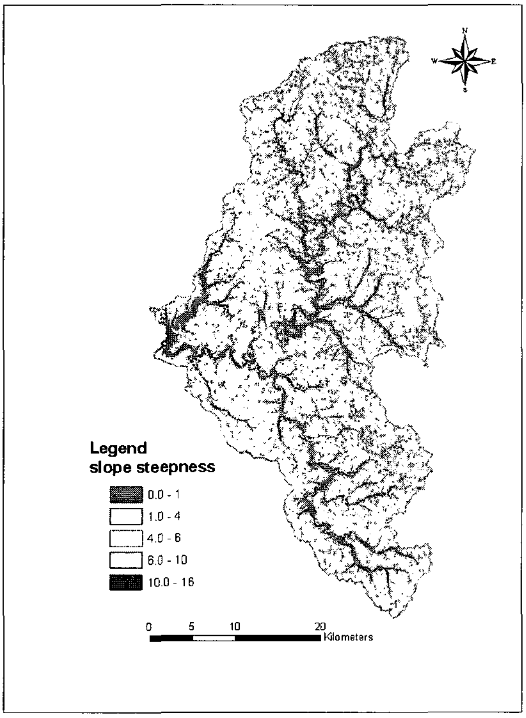


Figure 5. Slope Length (Above) and Slope Steepness (Below) map

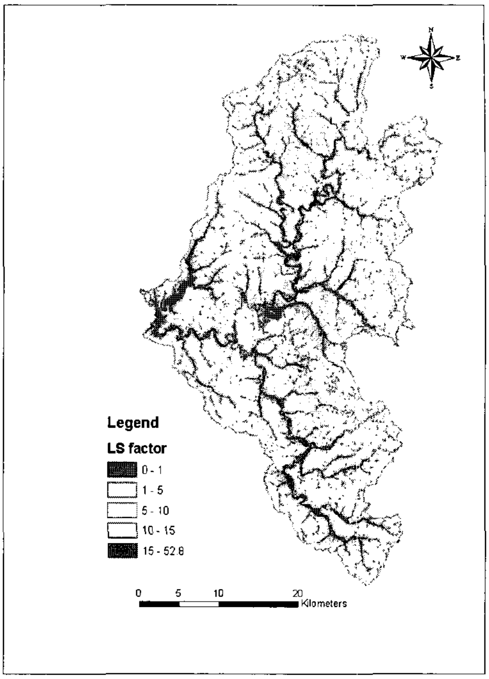


Figure 6. Slope Length and Steepness (LS) map of the Imha watershed

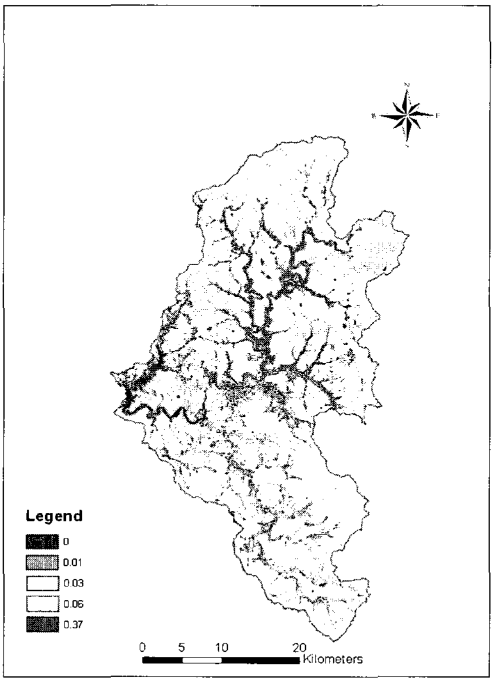


Figure 7. Cover management factor in the Imha watershed

2.5 Support practice factor (P)

The support practice factor accounts for control practices that reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil. The supporting mechanical practices include the effects of contouring, stripcropping, or terracing.

Most of the Imha watershed is forested and only 15 percent is used for agriculture with paddy and crop fields. Figure 8 represents the support practice factor in the Imha watershed according to the cultivation method and slope (Shin, 1999).

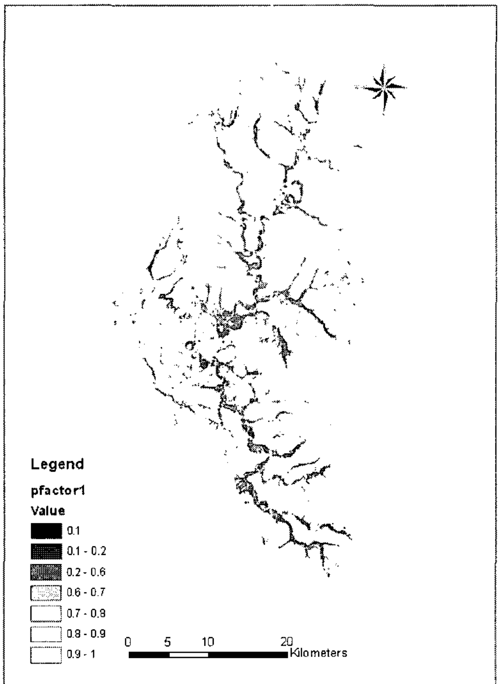


Figure 8. Support practice factor in the Imha watershed

2.6 The mean annual soil loss rate

In order to predict the annual average soil loss rate in the Imha watershed, the six parameters of the RUSLE model are multiplied. Figure 9 and Figure 10 represent the mean annual soil loss rate map and the spatial variability of gross soil erosion in the Imha watershed, respectively. The annual average soil loss rate is predicted to be 14 tons/acre/year (3,450 tons/km^2/year) and the value of 50% is about 2,100 tons/km^2/year.

Table 2 shows the annual average soil loss rate based on the land cover type. The total annual average soil loss rate of the Imha watershed is about 2.7million tons /year. Of this soil loss rate, forested area covers primarily 93% of total annual average soil loss rate and crop field area is the second order.

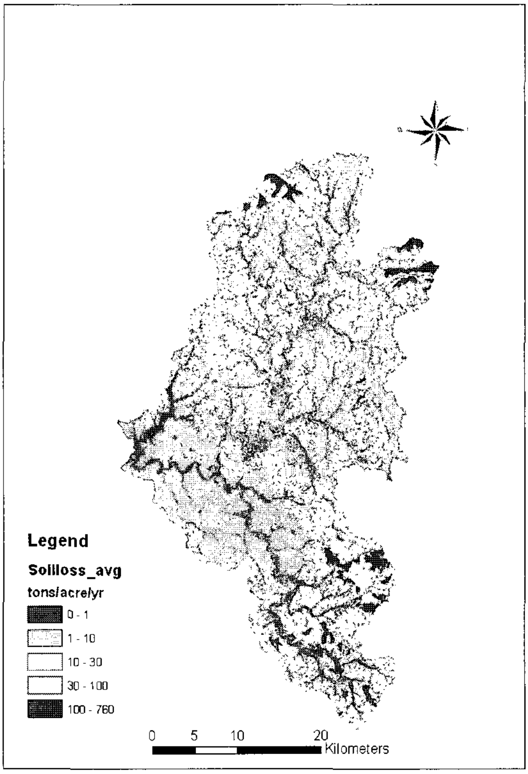


Figure 9. Annual average soil loss rate map of the Imha watershed

2.7 Sediment Delivery Ratio

The Sediment Delivery Ratio (SDR) denotes the ratio of the sediment yield Y at a given stream

Table 2. The annual average soil loss rate based on the land cover type

Land cover type	Area (km2)	Portion of area (%)	Soil loss rate (tons/km^2/year)	Soil loss rate (tons/year)	Portion of soil loss rate (%)
Water	15.0	1.1	0.0	0.0	0.00
Urban	9.9	0.7	0.003	0.03	0.00
Wetland	4.2	0.3	0.0	0.0	0.00
Forest	1122.4	82.5	2248.6	2523940.9	93.49
Paddy field	61.9	4.5	19.8	1222.8	0.05
Crop Land	147.6	10.8	1181.2	174382.3	6.46
Total	1361.0	100.0	3449.6	2699546.0	100.0

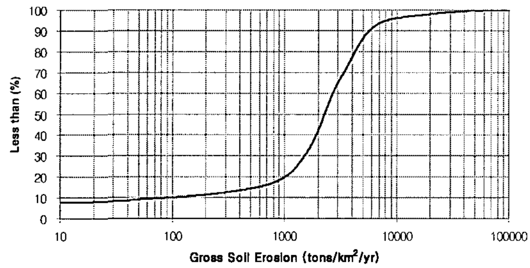


Figure 10. Spatial variability of gross soil erosion

cross section to the gross erosion A_T from the watershed upstream from the measuring point (Julien, 1998). Sediment delivery ratio can be calculated as follows:

$$S_{DR} = \frac{Y}{A_T} \tag{4}$$

Where: Y is a sediment yield; A_T is gross erosion per unit area

The sediment delivery ratio can be calculated using following equations based on watershed characteristic information of the Imha watershed.

Vanoni (1975)

$$SDR = 0.42A^{-0.125} \tag{5}$$

Boyce (1975)

$$SDR = 0.31A^{-0.3} \tag{6}$$

Renfro (1975)

$$\log(SDR) = 2.94259 + 0.82362\log(R/L) \tag{7}$$

Williams (1977)

$$SDR = 1.366 \times 10^{-11} \times Area^{-0.0998} \times ZL^{0.3629} \times CN^{5.444} \tag{8}$$

Roehl (1962)

$$\log SDR = 4.5 - 0.23\log(10 \times Area) - 0.51\log(\frac{L}{R}) - 2.79\log B \tag{9}$$

Where: A is the catchment area (mile^2); R is the relief of a watershed, defined as the difference in elevation between the maximum elevation of the watershed divide and the watershed outlet; L is a maximum length of a watershed, measured approximately parallel to mainstream drainage; Area is the catchment area (km^2); ZL is a relief-length ratio in m/km; CN is a long-term average SCS curve number; B is the weighted mean bifurcation ratio.

KOWACO carried out the sediment deposits survey at the Imha reservoir in 1997. Based on the "Sediment Deposits Survey Report of the Imha reservoir (KOWACO, 1997)", the observed sediment deposition is about 890 tons/km^2/year at the Imha reservoir. The annual average soil erosion predicted by the RUSLE model is 3,450 tons/km^2/year. Figure 11 presents the results of SDR in the Imha watershed.

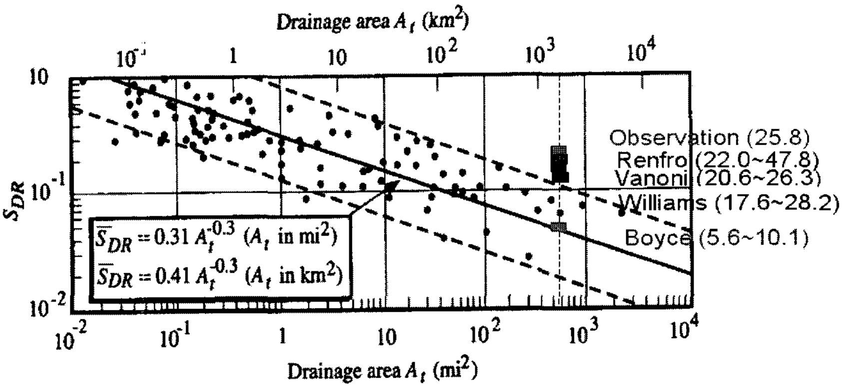


Figure 11. The results of SDR in the Imha watershed

2.8 Trap efficiency & life expectancy

The trap efficiency (TE) of a reservoir can be defined as the percentage of the total inflowing sediment that is retained in the reservoir.

$$TE = \frac{[Y_S(in) - Y_S(out)]}{Y_S(in)} \tag{10}$$

Where: TE is the trap efficiency; Ys (in) is a sediment yield in weight units (inflow); Ys (out) is a sediment yield in weight units (outflow);

After typhoon "Maemi", several measurements were made by KOWACO at the Imha reservoir. The d_{50} is 3.2 micron (0.0032mm) based on the particle size distribution of suspended solid. Based on these surveyed data, trap efficiency at the Imha reservoir is analyzed by some methods such as Julien, Brown, Brune, and Churchill. Table 3 presents the results of TE at the Imha reservoir.

Table 3. The results of TE at the Imha reservoir

d_{50}	Kinematic viscosity	Dimensionless particle diam	Fall Velocity	Unit Discharge	Distance of Reservoir	TE
(mm)	(m^2/s)	d*	(m/s)	(m^2/s)	(m)	(%)
0.0032	1.00E-06	0.081	9.22E-06	0.040	20,000	99.0

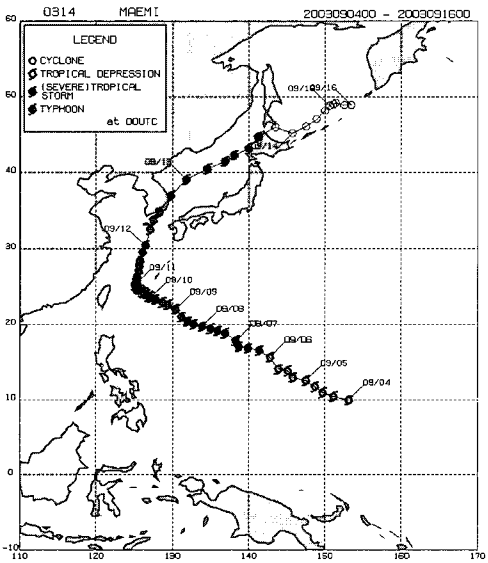
Reservoir Capacity	Inflow rate	Watershed area	Reservoir length	TE (%)		
acre-ft	acre-ft/year	miles^2	ft	Brown	Brune	Churchill
466,153	506,212	525	65,616	98.9	96.8	Out of range
			Assume:	K=0.1	median curve	

When the Imha multi-purpose dam was constructed, the sediment deposits per unit area of the reservoir were designed to be 300 $m^3/km^2/year$. Given the dead storage capacity of the Imha reservoir at $40x10^6$ m^3, the life expectancy for the dead storage of the Imha reservoir is determined to be 100 years. The sedimentation rates of the Imha reservoir were surveyed to be 680 $m^3/km^2/year$ in 1997. These are over twice compared the design values. As a result, even though inaccuracies in the sediment deposits survey are considered, the life expectancy for dead storage might be significantly decreased compared to the design life expectancy for dead storage. Therefore, a new survey of the sediment deposits of the Imha reservoir is recommended for a better evaluation the life expectancy of reservoir. In addition, the life expectancy for the entire storage of the Imha reservoir is evaluated to be about 670 years.

2.9 Soil loss rate caused by Typhoon "Maemi"

Typhoon "Maemi" struck the South Korea Peninsula on the evening of September 12, 2003, dumping 432mm of rain and triggering massive floods and landslides. It is reported that at least 110 people lost their lives, some 25,000 people were evacuated from their homes, and 1.4 million households were left without power. "Maemi" was the worst typhoon to hit South Korea in more than a decade. Figure 12 shows the passage (TRC, 2003) and GOES-9 1km image (KMA, 2003) of typhoon "Maemi".

Due to the typhoon "Maemi", the average soil loss rate of the Imha watershed is estimated about at 5.4 tons/acre/Maemi (1330 $ton/km^2/$ Maemi) and is around 39 percent of the annual average soil loss rate of 14.0 tons/acre/year. Figure 13 shows the spatial distribtution of the soil erosion at the Imha watershed caused by typhoon "Maemi".



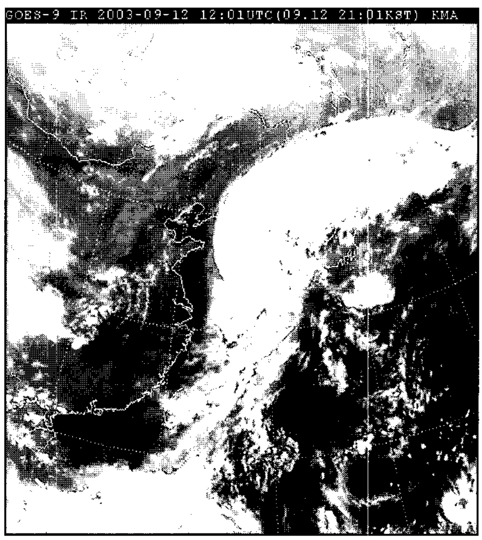


Figure 12. Passage of typhoon "Maemi" (left; TRC, 2003) and GOES-9 image (Right; KMA, 2003)

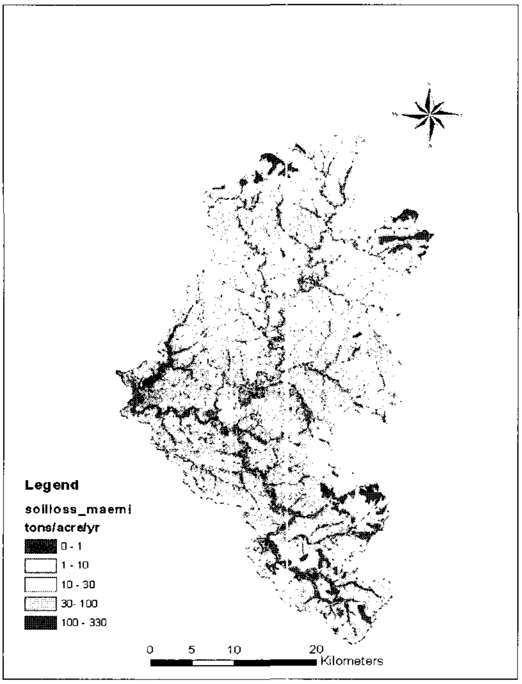


Figure 13. Soil loss rates map by typhoon "Maemi" of the Imha

3. Conclusions

The RUSLE model was combined with GIS to analyze the mean annual soil loss rates and soil losses caused by typhoon "Maemi". The spatial distribution of soil loss rates under different land cover is also determined. Specific conclusions are summarized as following:

1) The annual average soil loss rate was analyzed to be 14 tons/acre/year (3,450 tons/ km^2/year) and gross annual average soil erosion was about 2.7million tons/year in the Imha watershed. The average soil loss rate caused by the typhoon "Maemi" was analyzed to be about 5.4 tons/ acre/"Maemi"(1,330ton/km^2/"Maemi").
2) The spatial variability of gross soil erosion of the Imha watershed is analyzed using the relationship between probability and gross soil erosion. The value of 50% is about 2,100 tons/km^2/year.
3) The SDR of the Imha watershed was estimated to be 25.8%. This SDR is fairy high compared to the Boyce, Vanoni, Williams, and Roehl models. Several reasons for high SDR were found such as high, steep slopes, no floodplain, and many crop field areas near the reservoir and streams.
4) The trap efficiency of the Imha reservoir was calculated using the methods of Julien, Brown, Brune, and Churchill and ranges from 96% to 99%.

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