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Abstract: In Korea, approximately 70% of the country is mountainous, with steep slopes and heavy rainfall in summer from June to September. Korea is classified as a high-risk country for soil erosion, and the rate of soil erosion is rapidly increasing. In particular, the operation of Doam dam was suspended in 2001 because of water quality issues due to severe soil erosion from the upstream areas. In spite of serious dam sediment problems in this basin, in-depth studies on the origin of sedimentation using physic-based models have not been conducted. This study aims to analyze the spatial distribution of net erosion during typhoon events using a spatially distributed physicsbased erosion model and to improve the model based on a field survey. The spatially uniform erodibility constants of the surface flow detachment equation in the original erosion model were replaced by land use erodibility constants based on benchmarking experimental values to reflect the effect of land use on net erosion. The results of the upgraded model considering spatial erodibility show a significant increase in soil erosion in crop fields and bare land, unlike the simulation results before model improvement. The total erosion and deposition for Typhoon Maemi in 2003 were 36,689.0 and 9893.3 m³, respectively, while the total erosion and deposition for Typhoon Rusa in 2002 were 142,476.6 and 44,806.8 m³, respectively, despite about twice as much rainfall and 1.2 times as high rainfall intensity. However, there is a limitation in quantifying the sources of erosion in the study watershed, since direct comparison of the simulated net erosion with observed spatial information from aerial images, etc., is impossible due to nonperiodic image photographing. Therefore, continuous monitoring of not only sediment yield but also periodic spatial detection on erosion and deposition is critical for reducing data uncertainty and improving simulation accuracy.

Keywords: erodibility; land use; net erosion; physics-based model

1. Introduction

All living things, from microorganisms to humans, rely on soil for survival. Human civilization began with fertile soil, an essential food source for humanity [1]. However, the rapid development of human society due to recent industrialization has resulted in soil degradation, such as soil pollution and soil erosion. If soil, which covers approximately 25% of the Earth's surface, continues to be eroded, food resources will be depleted, and natural disasters such as landslides may occur frequently. When eroded soil flows into a river, the river's discharge capacity is reduced [2]. In addition, the deterioration of water quality due to muddy water can destroy the aquatic ecosystem. Therefore, soil conservation is a critical issue that must be addressed [3,4].



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In Korea, approximately 70% of the country is mountainous, with steep slopes and heavy rainfall in summer from June to September. In addition, rainfall patterns have changed due to climate change caused by global warming, and heavy rainfall with high intensity has been increasing recently [5]. In particular, based on meteorological observations, 2020 recorded the most rainy days (approximately 30 days) during the rainy season, with a national average rainfall of 686.9 mm [6]. Furthermore, the number of rainy days with daily rainfall exceeding 80 mm was recorded as an average of two days across the country.

For these reasons, runoff occurs quickly and soil erosion is widespread during the rainy season [7]. Korea is classified as a high-risk country for soil erosion, and the rate of soil erosion is rapidly increasing [8,9].

Soil erosion is the phenomenon of soil loss by water or wind, and the majority of soil erosion in Korea is caused by water rather than wind. Moreover, soil erosion is intensified by various factors, including soil characteristics, land use, vegetation cover [10-12], and climatic factors [13,14].

To accurately calculate the amount of soil loss caused by soil erosion in a basin, a dense monitoring network needs to be established and long-term analysis must be conducted [15,16]. However, it is not a viable option due to the high cost of establishing a nationwide soil erosion monitoring network [17]. Thus, models that can simulate and predict soil erosion need to be developed based on physical factors affecting soil erosion.

In Korea, a preliminary investigation on soil erosion is conducted using the Universal Soil Loss Equation (USLE) [18,19] based on pre-estimated factors according to the "Notice on Topsoil Survey" of the Ministry of Environment of Korea (ME). In addition, when annual soil erosion exceeds 50 tons, a field survey is required for detailed analysis. However, the USLE model's results obtained using on-site samples are significantly inconsistent with actual data in erosion-prone areas subject to a preliminary survey [20,21]. This inconsistency is due to the USLE model structure, where sediment transport and deposition cannot be simulated physically. Since the USLE model cannot be directly verified using field observation data, uncertainty is inherent in the model results. Trimble et al. [22] pointed out that relying solely on USLE outputs to plan soil conservation and management has its limitations.

ANSWERS [23], WEPP [24], EUROSEM [25], the SSEM-Surface Soil Erosion Model [26], and other physically based soil erosion models have been developed as computer and geographic information system (GIS) technologies. Igwe et al. [27] provided a detailed description of the classification and characteristics of various erosion models, including physical erosion models.

Despite the development of such physical models, research on model applicability for the Korean basin has been limited. Lee et al. [26] used the SSEM to simulate the time series of both discharge and sediment yield in the upstream the Yongdam Dam Basin for three typhoon events. Kim et al. [28] integrated the Particle Filter (PF) algorithm into the SSEM to estimate parameters and evaluate the uncertainty of simulation results. Kim et al. [7] used the SSEM with probable maximum precipitation (PMP) as rainfall input data to calculate the probable maximum sedimentation (PMS) in the Yongdam Dam Basin. Kim [29] developed a new rainfall energy equation using rainfall intensity and applied it to the SSEM to analyze the effect of short-term rainfall intensity on soil erosion.

In all of the above studies, hydrological time series such as discharge and sediment yield produced from hillslopes over a catchment were used as the verification data of the model, and when the model performance index was above a certain level, the model applicability can be guaranteed. Although the SSEM family models provide spatial information on erosion and deposition of a specific domain, research on the physical feasibility of erosion occurrence by land cover and topographic features was found to be insufficient. In particular, land use is one of the typical surface characteristics that determine the type and amount of soil erosion, and annual average soil erosion depends on land use in Korea [30]. In other words, no physics-based distributed model analysis of when, where, and how

much soil loss occurs in the watershed for different land cover types during a heavy rainfall period has been performed in Korea.

This study aims to analyze the spatial distribution of net erosion using a physics-based erosion model and to improve the original model based on a field survey considering land use erodibility.

2. Methodology

First, the SSEM, modified by [29] in terms of rainfall kinetic energy estimation (hereafter, R-SSEM) with the referenced parameters by [26], was used to spatially analyze the amount of soil erosion by land use for the target basin during the short-term torrential rainfall event caused by Typhoon Maemi in 2003. Second, a field survey was conducted to examine the reliability of soil erosion by land use provided by the model. The field survey did not measure the exact amount of soil erosion on slopes or sediment on rivers, but only confirmed the occurrence of soil erosion by land use and derived the improvement provided by the R-SSEM model algorithm. Third, the R-SSEM was improved by incorporating land use erodibility suggested by [31] into the model, and then, the applicability of the upgraded model was verified by comparing it with the R-SSEM. Finally, the modified R-SSEM was calibrated by the observed discharge and sediment discharge of the target basin and applied to simulate net erosion during the most intense typhoon events: Typhoons Rusa (2002) and Maemi (2003).

Figure 1 shows the comprehensive research procedure of this study.



Figure 1. Research flowchart of this study.

2.1. *R-SSEM*

The R-SSEM consists of two fundamental modules: rainfall-runoff and erosionsediment yield modeling. The rainfall-runoff process is explained below. When a rainfall event occurs, rainwater fills soil pores, and rainwater that cannot be infiltrated creates surface runoff. The conceptual water stage-discharge relationship curve [32] is used to simulate surface and subsurface flows. The erosion-sediment yield process is explained as follows. The detachment of soil particles occurs due to the raindrop impact, and the soil is detached when the erosion capacity of surface flow exceeds the resistance capacity of soil particles. Then, soil particles are moved by surface flow. The deposition occurs when the force of surface flow that moves soil particles is less than the weight of the soil particles. In this model, rainfall-runoff, erosion, and deposition are calculated sequentially along a predefined drainage network based on a flow direction for each grid.

The kinematic wave equation (Equation (1)) is used to simulate rainfall-runoff, whereas the soil detachment and transport equation, expressed in Equation (2), is used to simulate erosion-sediment yield.

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(x, t) \tag{1}$$

$$\frac{\partial (h_s C_s)}{\partial t} + \frac{\partial (q_s C_s)}{\partial x} - E_N(x, t) = 0$$
⁽²⁾

where *h* represents the water depth (m), *q* represents the discharge per unit width (m² s⁻¹), *x* represents the distance (m), *t* represents time, *r* represents rainfall intensity (mm hr⁻¹), q_s represents the surface flow rate (m³ s⁻¹), C_s represents the sediment concentration (kg m⁻³), h_s represents the depth of surface flow (m), and E_N represents net erosion (kg m⁻² hr⁻¹), which is the sum of soil particle detachment by surface flow (D_F) and soil particle detachment by raindrops (D_R).

The soil detachment by raindrops on the soil surface begins with early rainfall and decreases as the depth of surface flow increases. Soil erosion caused by raindrops does not occur when surface runoff occurs actively. Equation (3) expresses this relationship.

$$D_R = kKE_r e^{-bh_s} \tag{3}$$

where *k* represents the soil detachability (kg J⁻¹) [33]; *KE_r* represents rainfall kinetic energy per unit area (J m⁻² mm⁻¹); *b* is a constant determined by soil characteristics and a value of 2.0 can be widely used for a wide range of conditions [34]; and h_s represents the surface flow depth (m). Ref. [29] proposed a new rainfall kinetic energy equation based on rainfall particle distributions of various rainfall intensities, expressed in Equation (4).

$$KE_r = aI^c \tag{4}$$

where the coefficient and exponent of Equation (4) have the following values: a = 0.0133 and c = 1.8547; *I* represents rainfall intensity (mm hr⁻¹)

Soil particle detachment by the surface flow can be expressed using the relationship between transport capacity and sediment concentration (Equation (5)).

$$D_F = \alpha_f (T_c - C_s) \tag{5}$$

where α_f represents the soil erodibility coefficient, T_c represents the sediment transport capacity of surface flow, expressed by Equation (6), and C_s represents the sediment concentration from upstream hillslopes.

$$T_c = \tau_o - \tau_{cr} \tag{6}$$

If the shear stress ($\tau_o = \gamma_w h_s S$) of surface soil particles is larger than the critical shear stress (τ_{cr}), which is determined by [35], the surface soil particles are transported downstream. Moreover, if τ_o is less than or equal to τ_{cr} , T_c is zero. Here, γ_w is the unit weight of water, and *S* is the surface slope.

The sediment concentration can be calculated by Equation (7), which was proposed in [36]. The derivation of Equation (7) was well explained in detail in [29].

$$C_S = \frac{q_t \times W}{q_s} \times 10^3 \tag{7}$$

where q_t (kg m⁻¹ s⁻¹) represents the sediment yield, *W* (m) represents cell width, and q_s (m³ s⁻¹) represents the surface flow rate.

2.2. Modified R-SSEM

In the case of the R-SSEM, the spatially uniform value of α_f , optimized for the entire target watershed was applied to the soil erodibility coefficient in Equation (5). To determine the soil erodibility coefficient for each land use, it is necessary to analyze on-site soil samples considering soil properties. However, few experimental studies on the physical parameters of physical soil erosion models have been conducted in Korea. Therefore,

in this study, the model was improved using the soil erodibility coefficient proposed by [31] from the detachment test considering various soil properties. They found that the soil erodibility coefficient was significantly affected by both soil type and land use and developed a regression model to estimate the soil erodibility coefficient in a small Loess plateau watershed in China. Table 1 shows the reclassified mean values of soil erodibility coefficients and the relative ratio values to the maximum value corresponding to the farmland for land use in Korea.

Soil Erodibility by [31]	Soil Erodibility Used in This Study
0.193	1
0.14	0.725389
0.011	0.056995
0.01	0.051813
0.0001	0.000518
0.0001	0.000518
0.0001	0.000518
0.0001	0.000518
	Soil Erodibility by [31] 0.193 0.14 0.011 0.001 0.0001 0.0001 0.0001 0.0001 0.0001

Table 1. Reclassified soil erodibility coefficients for land use in Korea.

2.3. Calibration Method

In general, the parameters of the physically distributed model can be measured, so the optimization process may be omitted, but measuring all physical parameters in the field is practically impossible [37].

The modified R-SSEM (hereafter, MR-SSEM) was calibrated using the Mixed Integer Distributed Ant Colony Optimization-solver (hereafter, MIDACO, [38]), a numerical highperformance solver for single- and multi-objective optimization to handle problems with thousands of variables and hundreds of objectives. The MIDACO is based on a probability density function that generates repeated samples for decision variables [39]. In Figure 2, $f_1(x)$ is the objective function used for model calibration, and the MIDACO focuses on finding the optimum trade-off solution (red pentagon in Figure 2) from objective function $f_1(x)$ [40]. A detailed description of MIDACO is introduced in [38]. The MR-SSEM was equipped with the MIDACO for model calibration.



Figure 2. Outline of single optimization in MIDACO.

3. Model Application

3.1. Study Site

The selected study site is the Doam Basin, located in Daegwallyeong, Pyeongchang, Gangwon (Figure 3), with an area of 144.9 km². The average annual precipitation is 1649 mm, which is 1.3 times higher than the annual mean precipitation in Korea. In particular, precipitation during summer from June to September is 1070 mm, accounting for 64.9% of the annual mean precipitation. Four tributaries in the basin (Samyang, Chahang, Hoenggye, and Yongpyeong) join the main stream, Songcheon, and flow into the Doam dam. The Doam dam was completed in 1991 for hydroelectric power generation. However, its operation was suspended in 2001 because of water quality issues due to severe soil erosion from the upstream areas [41].



Figure 3. The Doam Basin in Korea.

Land use in the Doam Basin is divided into forests (78.7%), farmland (9.7%), bare land (4.6%), grassland (3.5%), urban areas (1.8%), water bodies (1.2%), paddy fields (0.2%), and wetland (0.2%). Most of the farmland in this area consists of highlands with steep slopes (more than 15°), accounting for 22.8% of the total field area [42]. The ME of Korea has designated and managed this area as a non-point source management area, but the water quality problem caused by soil loss has not been resolved.

3.2. Data Sets

For the assessment of model applicability on the land use effect on the spatiotemporal patterns of erosion and deposition in the study basin, the original R-SSEM was preliminarily applied to Typhoon Maemi event, which hit Korea in 2003, and was one of the most powerful storms in the country's history. It was the second typhoon to cause severe property damage and flood victims to date. In Daegwallyeong station, the rainfall hit a record of 395 mm during the typhoon (12 and 13 September), and the maximum hourly

rainfall was 56.5 mm. In the Doam Basin, large amounts of sediments flowed into the dam, and water quality deteriorated significantly for approximately a month [43].

The drainage network of the R-SSEM is generated on the basis of the digital elevation model (DEM) outputs such as flow direction, flow accumulation, and slope. In this study, we used the ArcMap program to convert digital topographic maps from the National Geographic Information Institute into 90 m \times 90 m raster data to create topographic data. The MOE middle class 1:25,000 land-use map was used to determine the surface roughness parameter.

Hourly rainfall data from the Daegwallyeong station near the Doam Basin during the Typhoon Maemi period were used for soil erosion simulation. The meteorological data and spatial input data used in this study are depicted in Figure 4 and Table 2.



Figure 4. Spatial input data of the R-SSEM; (**a**) elevation, (**b**) flow direction, (**c**) flow accumulation, (**d**) land use.

Data Layer	Description	Data Source
Meteorological data	Hourly precipitation	Korea Meteorological Administration (http://data.kma.go.kr) (accessed on 17 October 2020)
Topography	(Cell size: 90 m)	National Geographic Information Institute of Korea (http://ngij.go.kr) (accessed on 10 October 2020)
Land use	1:25,000 (Resampled to 90 m)	Environmental Geographic Information Service of Korea (http://egis.me.go.kr) (accessed on 10 October 2020)

Table 2. Information about the data used in this study.

3.3. Field Survey

In this study, the field surveys were conducted over two days from 10 to 11 March 2020. To select erosion-vulnerable sites in the Doam Basin, a report on non-point source pollutant management, including soil loss analysis results from [44], was referenced. The report classified the Doam Basin into several zones according to soil loss levels (i.e., very high, high, moderate, and low), which was estimated using a modified USLE model. Based on the report, the field survey site was divided into four groups from A to D, as shown in Figure 5. Group A consists of sheep ranches and forest. Group B is the region that contains Daegwallyeong City and highlands. Group C covers the Yongpyeong Ski Resort, highlands, and forest along the river. Group D is mostly made up of forests and is located near the Doam dam.



Figure 5. Field survey sites of the Doam Basin; (**A**) sheep ranches and forest, (**B**) city and highlands, (**C**) ski resort, highlands, and forest along the river, (**D**) forest and the Doam dam.

Figure 6 shows representative photos of each field survey group. As a result of the field survey based on visual inspection, the runoff from forested mountains near the Doam dam in Group D was relatively clear. On the other hand, the runoff from cropland in Group A and B was mixed with a large amount of soil. In most cropland, the soil was eroded in the form of sheet or rill erosion, as shown in Figure 6, and flowed directly into the streams generating turbid water. In Group C, while cultivation was also carried out, soil erosion was less severe than in other groups.



Figure 6. Selected site photos of the field surveys; (a) A-01, (b) B-06, (c) C-03, (d) D-01.

4. Modeling Results

4.1. R-SSEM Result

Since the purpose of this study is to evaluate the adequacy of the R-SSEM simulation results for the distribution of erosion and deposition by land use, the parameter calibration based on hydrological times series: hydrograph and sedigraph are not performed, but the parameters suggested by [26] for the other basins are used without optimization. The parameters used in the R-SSEM application are described in Section 4.3.

As shown in Tables 3 and 4, the total erosion volume and the eroded depth per unit area of the basin were 6561.8 m³ and 4.4 cm, respectively, whereas the total deposition volume and the deposited depth per unit area were 19.03 m³ and 0.01 cm, respectively. In the case of erosion by land use, the total erosion amount was highest in the forest areas, whereas the erosion depth per unit area was highest in bare land. Conversely, deposition occurred only in forest areas. Figure 7 shows the soil erosion modeling results of the R-SSEM for the Typhoon Maemi event.

As shown in Figure 7, erosion occurred in most areas of the basin, and the maximum erosion was approximately 60 cm for shallow landslide, which was estimated to be an abnormal amount of erosion. The amount of erosion may contain uncertainty, since the model parameters were not properly estimated. However, although the soil erosion is relatively low in forest areas, the erosion rate of forest areas was overestimated in the R-SSEM. This result is presumed to be because the shear stress on hillslopes is highly sensitive to slopes, regardless of land use types: most of the steep slopes are found in forest areas of the study site. Therefore, the transport capacity of Equation (6) is calculated to a

large extent. In addition, although the forest area near the dam was classified as a rock base of the soil depth map in Figure 8, the R-SSEM led to active erosion results.

Land Use	Percentage of Land Use	Total Erosion (m ³)	Rank of Total Erosion	Erosion Depth per Unit Area (cm)	Rank of Unit Erosion
Total	100	6516.8	-	0.04	-
Water body	1.20	54.78	6	0.03	8
Urban	1.78	121.16	5	0.05	2
Bare land	4.61	317.89	3	0.05	1
Wetland	0.19	12.90	7	0.05	3
Grassland	3.55	225.99	4	0.04	6
Forest	78.72	5136.10	1	0.04	5
Paddy	0.23	11.17	8	0.03	7
Farmland	9.72	635.86	2	0.04	4

Table 3. Results of erosion by land use (R-SSEM).

Table 4. Results of deposition by land use (R-SSEM).

Land Use	Percentage of Land Use	Total Deposition (m ³)	Rank of Total Deposition	Deposition Depth per Unit Area (cm)	Rank of Unit Deposition
Total	100	19.03	-	0.01	-
Water body	1.20	-	-	-	-
Urban	1.78	-	-	-	-
Bare land	4.61	-	-	-	-
Wetland	0.19	-	-	-	-
Grassland	3.55	-	-	-	-
Forest	78.72	19.03	1	0.01	1
Paddy	0.23	-	-	-	-
Farmland	9.72	-	-	-	-



Figure 7. Spatial distribution of net erosion by the R-SSEM.





For the above unconvincing simulation results that do not reflect the impact of erosion by land use, it was necessary to investigate the actual erosion status by land use through a field survey on the target basin. In addition, the results of the field survey indicate that the simulation results of the R-SSEM are significantly different from the actual sites. Therefore, it is essential to improve the R-SSEM by considering the erodibility factors for each land use in order to accurately simulate the spatiotemporal patterns of soil erosion by land use.

4.2. MR-SSEM Result

The MR-SSEM was used for spatial analysis of soil erosion, with Typhoon Maemi as the R-SSEM, and the net erosion map was obtained as shown in Figure 9.



Figure 9. Spatial distribution of net erosion by the MR-SSEM.

Unlike the R-SSEM (Figure 7), erosion was dominantly identified on cropland and bare land, similar to the field survey results. The total amount of erosion and the depth of erosion per unit area are 6051.5 m³ and 0.004 cm, respectively, whereas the total amount of deposition and depth of deposition per unit area are 1628.1 m³ and 0.001 cm, respectively. In particular, the total amount of erosion was highest in cropland, and the unit erosion depth was highest in bare land. Tables 5 and 6 show the results of erosion and deposition in the improved model.

Land Use	Percentage of Land Use	Total Erosion (m ³)	Rank of Total Erosion	Erosion Depth per Unit Area (cm)	Rank of Unit Erosion
Total	100	6051.5	-	0.004	-
Water body	1.20	0	-	0	-
Urban	1.78	98.8	4	0.004	4
Bare land	4.61	1813.6	2	0.027	1
Wetland	0.19	0	-	0	-
Grassland	3.55	497.3	3	0.009	3
Forest	78.72	0	-	0	-
Paddy	0.23	0	-	0	-
Farmland	9.72	3740.6	1	0.026	2

Table 5. Results of erosion for land use (MR-SSEM).

Table 6.	Results	of de	position	for la	nd use	(MR-SSEM)).

Land Use	Percentage of Land Use	Total Deposition (m ³)	Rank of Total Deposition	Deposition Depth per Unit Area (cm)	Rank of Unit Deposition
Total	100	1628.1	-	0.001	-
Water body	1.20	51	3	0.003	4
Urban	1.78	311	2	0.012	1
Bare land	4.61	0	-	0	-
Wetland	0.19	13	5	0.005	2
Grassland	3.55	3.2	6	0.000	6
Forest	78.72	1192.3	1	0.001	5
Paddy	0.23	13.8	4	0.004	3
Farmland	9.72	0	-	0	-

The above results were analyzed by modifying only the land use erodibility among the parameters used in the R-SSEM. Therefore, since the quantitative values for the amount and depth of soil erosion contain uncertainty, it is necessary to calibrate the parameters of the improved model using the observed discharge and sediment yield of the river in the target area and analyze the simulation results.

4.3. Calibration of MR-SSEM

In the previous section, we discussed how realistic the spatial distribution of erosion and deposition is when the land use erodibility is used in soil erosion modeling. However, the model results are unreliable because the parameters optimized for the different study sites in the previous study [29] were used in the improved model as they were.

The optimal parameters of the MR-SSEM, estimated by the MIDACO with a single objective function, the Nash-Sutcliffe efficiency (NSE), based on the observed time-series of discharge and sediment yield are described in the fifth column of Table 7.

Parameter	Description	The Range of Value	R-SSEM [26]	MR-SSEM
k_s	Hydraulic conductivity (m s ^{-1})	0.001-0.1	0.007	0.006
D	Effective soil depth (mm)	1-1000	1000	950
d_c	Water depth corresponding to maximum water content in the capillary pore (mm)	20-300	31.88	95
d_s	Water depth corresponding to water content (mm)	1–700	60.03	570
β	Non-linear exponent for the unsaturated soil layer	2–10	7.0	3.0
D_{50}	Median grain size (mm)	1–10	9.5	1.0
k	Soil detachability (kg J^{-1})	0.0001-1	0.002	0.068
α_f	Soil erodibility coefficient	0.1-1.0	0.86	-
KÉr	Kinetic energy of net rainfall (J m ^{-2})	1–30	2.29	-

Table 7. The optimal parameters used in R-SSEM and MR-SSEM.

The optimal parameters of the MR-SSEM, estimated by the MIDACO based on the observed time-series of discharge and sediment yield, are described in the fourth column of Table 7.

In particular, the regression equation of discharge-suspended sediment relation, estimated using on-site measurements [45], was used to produce sediment yield time-series, as shown in Figure 10.



Figure 10. Discharge-suspended sediment correlation plot.

Figure 11 shows the hydrological simulation results using the optimal parameter values by the MIDACO. The NSE and peak ratio (PE) were used to evaluate model performance (Equations (8) and (9)).

NSE =
$$1 - \frac{\sum_{t=1}^{N} (O_t - S_t)^2}{\sum_{t=1}^{N} (O_t - \overline{O})^2}$$
 (8)

$$PE = \frac{S_{peak}}{O_{Peak}} \tag{9}$$

where *N* represents the number of data, O_t represents the observed value at time t, \overline{O} represents the mean of the observed value, S_t represents the simulated value of the model at time t, and O_{peak} and S_{peak} represent the observed and simulated peak values, respectively.



Figure 11. Comparison of the simulated hydrological time series by the calibrated model to observations; (**a**) hydrograph, (**b**) sedigraph.

For both rainfall-runoff and erosion-sediment yield simulations, the simulated hydrological time series described the trends of observed data well, whereas the simulated results were slightly overestimated compared to the observation, and the peak time was slightly delayed despite the model calibration.

The imperfect simulation results might be caused by various uncertainty sources, such as data, model structure, and parameters; however, in general, this imperfection is greatly influenced by data uncertainty. The sediment load regression equation of Figure 10, generated by only approximately by 20 samples, was applied to the overall range of observations from low to high water levels. This means that the equation may not contain accurate information about extremely high or low water levels during the event period because data were obtained from trend lines extrapolated from insufficient numbers of samples. Therefore, even with a marginal change in discharge, the estimated regression equation with uncertainty is likely to result in a relatively large difference in sediment load.

4.4. Calibrated MR-SSEM Result

The spatial distribution of net erosion was analyzed using the calibrated MR-SSEM for the Typhoon Maemi event. In addition, the same model was applied to another typhoon, Typhoon Rusa, which caused the most extensive damage in Korea, and the spatial distribution of erosion and deposition was analyzed as well.

Figure 12 shows the spatial distribution of net erosion for Typhoon Maemi using the calibrated model. The results of the calibrated model show a significant increase in both erosion and deposition, unlike the simulation results before calibration. The total erosion and the depth of erosion per unit area were 36,689.0 m³ and 0.025 cm, respectively. The total deposition and depth of deposition per unit area were 9893.3 m³ and 0.007 cm, respectively. These results show an increase in both the amount and the depth of approximately 6–7 times when compared to when the model was not calibrated.

This rapid increase in net erosion is due to the difference in the soil particle diameter optimized in the model. The soil particle size should be determined by measurement from field surveys, field survey measurements, but setting the soil particle size for each grid cell in a distributed model is difficult or impossible. Therefore, in this model, the areal average particle diameter across the watershed was used as a parameter of the model, and the optimized value was obtained through the automatic optimization process using the MIDACO.





The optimized soil particle diameter before the calibration of the model was 9.5 mm, suggested by [26], whereas the calibrated optimal value was calculated as 1 mm (Table 6). This means that small soil particles are susceptible to erosion by rainfall and surface flow and can be easily moved, resulting in more erosion and deposition.

Tables 8 and 9 show that the total erosion was highest on crop fields and that the erosion depth was highest on bare land for Typhoon Maemi. This rank is similar to the results obtained before the calibration. However, unlike before the calibration, erosion occurred in all land uses. For the deposition, the total deposition was highest in the forests and the deposition depth was highest in the urban area with mild slopes. This result shows the same rank as the simulation result before the calibration.

Land Use	Percentage of Land Use	Total Erosion (m ³)	Rank of Total Erosion	Erosion Depth per Unit Area (cm)	Rank of Unit Erosion
Total	100	36,689.0	-	0.025	-
Water body	1.20	122.3	6	0.007	6
Urban	1.78	639.9	5	0.024	4
Bare land	4.61	10,961.7	2	0.161	1
Wetland	0.19	8.9	8	0.003	8
Grassland	3.55	1662.1	4	0.032	3
Forest	78.72	3937.4	3	0.003	7
Paddy	0.23	26.7	7	0.008	5
Farmland	9.72	19,798.8	1	0.138	2

Table 8. Results of erosion for land use (the calibrated MR-SSEM, Typhoon Maemi).

Figure 13 shows the spatial distribution of net erosion for Typhoon Rusa using the calibrated MR-SSEM. The total rainfall during Typhoon Rusa (30 August to 1 September) at the Daegwallyeong station was 760 mm, and the maximum hourly rainfall was 67.5 mm, higher than Typhoon Maemi. Similar to Typhoon Maemi, erosion occurred dominantly in the crop fields and bare land. The total erosion and depth per unit area were 142,476.6 m³ and 0.096 cm, respectively. The total deposition and depth per unit area were 44,806.8 m³ and 0.03 cm, respectively. The amount of erosion was approximately 3.9 times and the amount of deposition was 4.5 times those of Typhoon Maemi, despite there being about twice as much rainfall and 1.2 times as high rainfall intensity. As shown in Tables 10 and 11,

the net-erosion results show similar results to those of Typhoon Maemi, with both erosion and erosion depth being high in crop fields and bare land. Total deposition and deposition depth were highest in the forests and urban areas, respectively.

Table 9. Results of deposition for land use (the calibrated MR-SSEM, Typhoon Maemi).

Land Use	Percentage of Land Use	Total Deposition (m ³)	Rank of Total Deposition	Deposition Depth per Unit Area (cm)	Rank of Unit Deposition
Total	100	9893.3	-	0.007	-
Water body	1.20	294.8	3	0.017	4
Urban	1.78	2168.4	2	0.082	1
Bare land	4.61	5.7	8	0.000	8
Wetland	0.19	50.2	6	0.018	3
Grassland	3.55	55.1	5	0.001	6
Forest	78.72	7098.0	1	0.006	5
Paddy	0.23	64.8	4	0.019	2
Farmland	9.72	31.6	7	0.000	7





Table 10. Results of erosion for land use (the	e calibrated model, Typhoon Rusa	a).
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Land Use	Percentage of Land Use	Total Erosion (m ³)	Rank of Total Erosion	Erosion Depth per Unit Area (cm)	Rank of Unit Erosion
Total	100	142,476.6	-	0.096	-
Water body	1.20	362.1	6	0.02	5
Urban	1.78	2613.9	5	0.099	4
Bare land	4.61	38,991.8	2	0.571	1
Wetland	0.19	37.3	7	0.013	7
Grassland	3.55	7200.9	4	0.137	3
Forest	78.72	20,441.2	3	0.018	6
Paddy	0.23	37.3	8	0.011	8
Farmland	9.72	74,962.3	1	0.521	2

Land Use	Percentage of Land Use	Total Deposition (m ³)	Rank of Total Deposition	Deposition Depth per Unit Area (cm)	Rank of Unit Deposition
Total	100	44,806.77	-	0.03	-
Water body	1.20	1069.2	3	0.06	4
Urban	1.78	7746.8	2	0.293	1
Bare land	4.61	817.3	4	0.012	6
Wetland	0.19	274.6	6	0.097	2
Grassland	3.55	86.7	7	0.002	7
Forest	78.72	33,625.5	1	0.029	5
Paddy	0.23	282.7	5	0.083	3
Farmland	9.72	0	8	0	8

Table 11. Results of deposition for land use (the calibrated model, Typhoon Rusa).

Many studies have been conducted to simulate the amount of soil loss from watersheds using various erosion models. Then, such models are generally calibrated and verified based on the watershed-aggregated observations such as discharge, sediment concentration, pollutant, etc. On the other hand, there have not been many attempts to analyze the spatial origin of soil loss provided by the physics-based model. This study is able to provide useful information for erosion model applications at the watershed scale by considering the potential for erosion according to land use.

5. Discussion

Many studies have been conducted to simulate the amount of soil loss from watersheds using various erosion models. Then, such models are generally calibrated and verified based on the watershed-aggregated observations such as discharge, sediment concentration, pollutant, etc. On the other hand, there have not been many attempts to analyze the spatial origin of soil loss provided by the physics-based model. This study is able to provide useful information for erosion model applications at watershed scale by considering the potential of erosion by land use.

Although an improved physics-based erosion model distinguishes areas of erosion and deposition and estimates the amount of sedimentation considering land use erodibility, the model used in this study still suffers from prediction uncertainty due to the sources involved in modeling. Continuous monitoring of not only the sediment yield but also periodic spatial detection of erosion is critical for reducing data uncertainty and improving simulation accuracy. In particular, in-depth experiments using local data will be required to estimate erodibility values of the model in the study site

Moreover, the model needs to identify the physical relationship between parameters and erosion factors and robustly parameterize for minimizing calibration trials. For example, among the parameters in Table 7, this study optimized the median grain size by considering it as a parameter since it is impossible to quantify the spatially distributed median grain size over the catchment. Therefore, researchers need to develop new techniques to estimate the actual particle diameter based on the soil composition ratio of the digital soil map in the near future.

Finally, it is critical to establish a monitoring system to continuously measure the amount of erosion, ensuring the reliability of model results based on such observations for future soil conservation and management planning in this region.

6. Conclusions

This study aimed to analyze the spatial distribution of net erosion during a typhoon event using a physics-based erosion model and to improve the model based on data from field surveys of the study site. The surface flow erosion term in the model was specifically improved to reflect the effect of land use on net erosion. To achieve these objectives, first, the R-SSEM was applied to the Doam basin for Typhoon Maemi, which occurred in 2003, without considering spatially different land use erodibility, and then, the reliability of simulated net erosion was tested and compared to the visual field survey results. Second, the R-SSEM was improved by modifying the spatially uniform erodibility coefficients to spatially distributed values based on the experimental study by [31]. Finally, the improved model, with calibrated parameters by the automatic optimization tool, was applied to simulate net erosion for the largest rainfall events due to Typhoons Maemi and Rusa, which occurred in 2003 and 2002, respectively. The major findings of this study are as follows.

The R-SSEM could provide spatial information regarding erosion and deposition within the study site. However, about 78.8% of the erosion occurred in the forest area, not in cropland or bare land, whereas deposition occurred only in the mountainous regions with forest land use. This means that the original R-SSEM cannot accurately simulate the change in erosion amount by land use, and the modeling results are sensitive to other variables.

In this study, we conducted a field survey to verify the erosion types in the study site for each land use and compared the R-SSEM simulation results with the actual site information. According to the field survey, most of the erosion in the study area occurred in the form of sheet and rill erosion in the crop fields surrounding the city and the bare land near the tributaries. In the case of the turbidity of the river flowing into the dam, the main stream flowing directly from the mountainous hillslopes was clear, whereas the small river flowing through the crop fields was very muddy. Therefore, it is essential to upgrade the R-SSEM to properly reflect the effect of land use on the spatial pattern of erosion and deposition.

The spatially uniform erodibility constants of the surface flow detachment equation in the R-SSEM were replaced by land use erodibility constants based on benchmarking experimental values. As a result, the effect of spatially distributed land use erodibility on net erosion was extensively considered in the upgraded model for both extreme typhoon events. About 83.8% and 80% of the total erosion in Typhoon Maemi (2003) and Rusa (2002), respectively, occurred in crop fields and bare land.

However, there is a limitation of this model in quantifying the sources of erosion in the watershed, since direct comparison of the simulated net erosion with observed spatial information from aerial images, etc., is impossible due to nonperiodic image photographing. Therefore, continuous monitoring of not only the sediment yield but also periodic spatial detection of erosion and deposition is critical for reducing data uncertainty and improving simulation accuracy.

The model developed in this study can quantitatively analyze the amount of soil erosion caused by short-term rainfall events and can be very useful for soil conservation or management.

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References

- 1. Lal, R.; Stewart, B.A. Soil Degradation: A Global Threat; Springer: New York, NY, USA, 1990; Volume 11. [CrossRef]
- Mineo, C.; Ridolfi, E.; Moccia, B.; Russo, F.; Napolitano, F. Assessment of Rainfall Kinetic-Energy–Intensity Relationships. *Water* 2019, 11, 1994. [CrossRef]
- Lal, R.; Bouma, J.; Brevik, E.; Dawson, L.; Field, D.J.; Glaser, B.; Hatano, R.; Hartemink, A.E.; Kosaki, T.; Lascelles, B.; et al. Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective. *Geoderma Reg.* 2021, 25, e00398. [CrossRef]
- Keesstra, S.; Mol, G.; De Leeuw, J.; Okx, J.; Molenaar, C.; De Cleen, M.; Visser, S. Soil-Related Sustainable Development Goals: Four Concepts to Make Land Degradation Neutrality and Restoration Work. *Land* 2018, *7*, 133. [CrossRef]

- Jentsch, A.; Beierkuhnlein, C. Research frontiers in climate change: Effects of extreme meteorological events on ecosystems. Comptes Rendus Geosci. 2008, 340, 621–628. [CrossRef]
- 6. Mun, J.; Gang, S.; Lee, J. *National Precipitation Analysis of Floods in 2020*; Water for Future; Korea Water Resources Association: Seoul, Korea, 2020; pp. 135–143.
- 7. Kim, S.; Lee, D.; Jung, S.; Lee, G. Assessment of Soil Erosion and Sedimentation in Cheoncheon Basin Considering Hourly Rainfall. *J. Korean GEO-Environ. Soc.* 2020, *21*, 5–17. [CrossRef]
- 8. OECD. Environmental Performance of Agriculture in OECD Countries Since 1990; OECD: Paris, France, 2008. [CrossRef]
- Shin, K. Case Study of EIA for Soil Resource Conservation; Korea Environment Institute: Sejong, Korea, 2013; pp. 1–87. Available online: http://kiss.kstudy.com/thesis/thesis-view.asp?g=kissmeta&m=exp&enc=13BA5457B08C96678BE597DDA9EFFEEE (accessed on 10 October 2020).
- 10. Cerdà, A.; Terol, E.; Daliakopoulos, I.N. Weed cover controls soil and water losses in rainfed olive groves in Sierra de Enguera, eastern Iberian Peninsula. *J. Environ. Manag.* **2021**, *290*, 112516. [CrossRef]
- 11. Novara, A.; Cerda, A.; Barone, E.; Gristina, L. Cover crop management and water conservation in vineyard and olive orchards. *Soil Tillage Res.* **2021**, *208*, 104896. [CrossRef]
- 12. Rodrigo-Comino, J.; Terol, E.; Mora, G.; Giménez-Morera, A.; Cerdà, A. Vicia sativa Roth. Can Reduce Soil and Water Losses in Recently Planted Vineyards (*Vitis vinifera* L.). *Earth Syst. Environ.* **2020**, *4*, 827–842. [CrossRef]
- 13. Raza, A.; Ahrends, H.; Habib-Ur-Rahman, M.; Gaiser, T. Modeling Approaches to Assess Soil Erosion by Water at the Field Scale with Special Emphasis on Heterogeneity of Soils and Crops. *Land* **2021**, *10*, 422. [CrossRef]
- 14. Yang, D.; Kim, J.; Kim, J.; Kim, M. The Effects of Surface Condition on Soil Erosion. J. Korean Geomorphol. Assoc. 2005, 12, 63–72.
- 15. Morris, G.L.; Fan, J. Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use; McGraw-Hill: New York, NY, USA, 1998.
- Cerdà, A.; Novara, A.; Dlapa, P.; López-Vicente, M.; Úbeda, X.; Popović, Z.; Mekonnen, M.; Terol, E.; Janizadeh, S.; Mbarki, S.; et al. Rainfall and water yield in Macizo del Caroig, Eastern Iberian Peninsula. Event runoff at plot scale during a rare flash flood at the Barranco de Benacancil. *Cuad. Investig. Geográfica* 2021, 47, 25. [CrossRef]
- 17. Yu, W.; Park, J.; Yang, J.-E.; Lim, K.; Kim, S.; Park, Y.; Hwang, S.; Lee, G. Development and Application of a Physics-based Soil Erosion Model. *J. Soil Groundw. Environ.* **2017**, *22*, 66–73. [CrossRef]
- Wischmeier, W.H.; Smith, D.D. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation; Agricultural Research Service, US Department of Agriculture: Washington, DC, USA, 1965.
- 19. Wischmeier, W.H.; Smith, D.D. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*; No, 537; Department of Agriculture, Science and Education Administration: Washington, DC, USA, 1978.
- Son, K. Applicability Examination of the RUSLE Sediment Yield Prediction Equations in Korea. J. Korea Water Resour. Assoc. 2001, 34, 199–207.
- 21. Son, K. Applicability Examination of the MUSLE Sediment Yield Prediction Equations in Korea. J. Korea Water Resour. Assoc. 2001, 34, 209–216.
- 22. Trimble, S.W.; Crosson, P.U.S. Soil Erosion Rates-Myth and Reality. Science 2000, 289, 248-250. [CrossRef]
- 23. Beasley, D.B.; Huggins, L.F.; Monke, E.J. Modeling sediment yields from agricultural watersheds. *J. Soil Water Conserv.* **1982**, 37, 113–117.
- Nearing, M.; Ascough, L.; Chaves, H. WEPP model sensitivity analysis. In *Water Erosion Prediction Project Landscape Profile Model Documentation*; NSERL Report; National Soil Erosion Research Laboratory: West Lafayette, IN, USA, 1989.
- Smith, R.; Goodrich, D.; Quinton, J.N. Dynamic, distributed simulation of watershed erosion: The KINEROS2 and EUROSEM models. J. Soil Water Conserv. 1995, 50, 517–520.
- Lee, G.; Yu, W.; Jung, K.; APIP. Catchment-scale soil erosion and sediment yield simulation using a spatially distributed erosion model. *Environ. Earth Sci.* 2013, 70, 33–47. [CrossRef]
- 27. Igwe, P.U.; Onuigbo, A.A.; Chinedu, O.C.; Ezeaku, I.I.; Muoneke, M.M. Soil Erosion: A Review of Models and Applications. *Int. J. Adv. Eng. Res. Sci.* 2017, *4*, 138–150. [CrossRef]
- 28. Kim, Y.; Lee, G.; Lee, D.; Noh, S. Parameter Estimation and Uncertainty Assessment of a Soil Erosion Model Using Data Assimilation Method. *J. Korean Soc. Hazard Mitig.* 2015, *15*, 373–382. [CrossRef]
- 29. Kim, S. Estimation of Topsoil Erosion Considering Physical Characteristics of Rainfall Intensity and Overland Flow; Chungnam National University: Daejeon, Korea, 2019.
- 30. Jang, C.; Shin, Y.; Kum, D.; Kim, R.; Yang, J.E.; Kim, S.C.; Hwang, S.I.; Lim, K.J.; Yoon, J.-K.; Park, Y.S.; et al. Assessment of soil loss in South Korea based on land-cover type. *Stoch. Environ. Res. Risk Assess.* 2015, *29*, 2127–2141. [CrossRef]
- 31. Li, Z.-W.; Zhang, G.-H.; Geng, R.; Wang, H. Rill erodibility as influenced by soil and land use in a small watershed of the Loess Plateau, China. *Biosyst. Eng.* 2015, 129, 248–257. [CrossRef]
- 32. Tachikawa, Y.; NAGATANI, G.; TAKARA, K. Development of Stage-Discharge Relationship Equation Incorporationg Saturated-Unsaturated Flow Mechanism. *Proc. Hydraul. Eng.* 2004, *48*, 7–12. [CrossRef]
- Morgan, R.P.C.; Quinton, J.N.; Smith, R.E.; Govers, G.; Poesen, J.W.A.; Auerswald, K.; Chisci, G.; Torri, D.; Styczen, M.E. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surf. Process. Landf.* 1998, 23, 527–544. [CrossRef]
- 34. Torri, D.; Sfalanga, M.; Del Sette, M. Splash detachment: Runoff depth and soil cohesion. Catena 1987, 14, 149–155. [CrossRef]

- 35. Vanoni, V.A. Sedimentation Engineering; American Society of Civil Engineers: New York, NY, USA, 2006. [CrossRef]
- 36. Engelund, F.; Hansen, E. A Monograph on Sediment Transport in Alluvial Streams; Technical University of Denmark: Copenhagen K, Denmark, 1967.
- 37. Sorooshian, S.; Gupta, V. Model calibration. Comput. Models Watershed Hydrol. 1995, 1, 23–68.
- Schlueter, M.; Erb, S.O.; Gerdts, M.; Kemble, S.; Rückmann, J.-J. MIDACO on MINLP space applications. *Adv. Space Res.* 2013, 51, 1116–1131. [CrossRef]
- 39. Hagedorn, B. Hydrograph separation through multi objective optimization: Revealing the importance of a temporally and spatially constrained baseflow solute source. *J. Hydrol.* **2020**, *590*, 125349. [CrossRef]
- 40. Hagedorn, B.; Meadows, C. Trend Analyses of Baseflow and BFI for Undisturbed Watersheds in Michigan—Constraints from Multi-Objective Optimization. *Water* **2021**, *13*, 564. [CrossRef]
- Lee, S.; Choi, Y.; Park, M.; Kim, K.; Kim, J.; Park, J.; Ryu, I.; Hwang, S.; Yu, S.; Lee, J.; et al. *A Study on Management and Reduction Plan of Non-Point Source in Doam Lake Watershed* (2); National Institute of Environmental Research: Incheon, Korea, 2016. [CrossRef]
 MOE. *The Doam Lake Basin Non-Point Pollution Source Management Measures*; Ministry of Environment: Sejong, Korea, 2007.
- 43. Heo, S.; Kim, K.; Sa, G.; Ahn, J.; Lim, K. Evaluation of SWAT applicability to simulate soil erosion at highland agricultural lands. *J. Korean Soc. Rural Plan.* **2005**, *11*, 67–74.
- 44. MOE. The Doam Lake Basin Non-Point Pollution Source Management Measures; Ministry of Environment: Sejong, Korea, 2019.
- 45. WREO. Lake Doam Nonpoint Pollution Source Management Area Monitoring and Evaluation Program; Wonju Regional Environmental Office: Wonju, Korea, 2016.