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Estimation of Cadmium Contamination in Different Restoration Scenarios by RUSLE Model

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ABSTRACT

The Mae Tao watershed of Thailand faced cadmium (Cd) contamination problems from zinc mining for a long time until the mining area was closed to decrease the level of Cd concentration. This study reproduced the possible scenarios of Cd contamination due to soil loss. Four scenarios of forest restoration were implemented in this study, all of which were calculated with the Revised Universal Soil Loss Equation (RUSLE) integrated with satellite imagery and Geographic Information Systems (GIS). Landsat 8-OLI was acquired and land use/land cover (LULC) was classified in each scenario. Soil loss maps were created. An inverse distance weighting (IDW) technique was used to estimate the concentration of Cd based on the field data consisting of 101 points of measured Cd concentration. Results from RUSLE model and IDW technique were combined to calculate Cd contamination due to soil loss for all four scenarios. Results showed that the restoration of Scenario 3, forest restoration in old and new mining areas in cooperation with reservoir construction, helped decrease Cd contamination the most. The lowest level of Cd contamination from soil loss was found in this scenario by about 156 ha (total of Cd contamination by 165,924.32 ton/year).

1. INTRODUCTION

Mae Tao watershed, Mae Sot District, Tak Province has faced a cadmium contamination problem for a very long time. The largest zinc deposit of Thailand is located in this area (DPIM, 2009a). The zinc was excavated by surface mining which was a broad category of mining in which soil and rock overlaying the mineral deposit are removed (Suppakarn et al., 2016). During the years 1969-1975, the mine was first operated by a private company. However, there were no mine operations during the years 1976-1983 and this area was abandoned. Zinc mining then continued again from 1984-2017. In the first period of the zinc mine operation, in 1974, there was a dispute involving the problem of Cd contamination in Mae Tao Creek (Suppakarn et al., 2016). A high level of Cd contamination in paddy fields and rice seeds in Mae Tao watershed was first reported by the International Water Management Institute (IWMI) in 1998. In addition, studies on Cd contamination were performed by sampling rice seeds, paddy soil and bed load sediments continuously from the irrigation water of the Mae Tao River (DPIM, 2009b; Simmons and Pongsakul, 2002; Simmons et al., 2003; Simmons et al., 2005; Thamjedsada and Chaiwiwatworakul, 2012). It found that Cd from mining waste contaminating the groundwater can cause pollution of downstream paddy fields (Sriprachote et al., 2012). Also, the study of Unhalekhaka and Kositanont (2008) indicated that the level of Cd contamination has affected the health and livelihood of the farmers. Moreover, the Pollution Control Department (PCD) (2013) found that Cd paddy field soil with a depth of less than 30 centimeters had a high level of contamination (more than 30 mg Cd/kg soil) within a total area of 40 ha, and had a medium level of contamination (3-30 mg Cd/kg soil) within a total area of 570 ha. The PCD and other agencies furthermore suggested soil management guidelines from academic sources in which there would be surface dredging specifically in an area with high Cd contamination.

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As a problem mentioned above, four scenarios of forest restoration were suggested by relevant sectors (Royal Forest Department, Department of Primary Industries and Mines, and private company) for reducing Cd contamination due to soil loss in Mae Tao watershed. They were: 1) forest restoration in the old mining area; 2) forest restoration in both the old mining area and the new mining area; 3) forest restoration in both mining areas in cooperation with reservoir construction; and 4) forest restoration in both mining areas in cooperation with weir construction. Moreover, assessing the suitable scenario is an essential procedure to select the best measure to reduce Cd contamination and protect the Mae Tao watershed. Therefore, RUSLE model was applied to estimate soil loss (Atoma et al., 2020; Batista et al., 2017; Chuenchum et al., 2020; Farhan et al., 2013; Ganasri and Ramesh, 2016; Kassawmar et al., 2018; Kim, 2006; Lazzari et al., 2015; Lee and Lee, 2006; Millward and Mersey, 1999; Ostovari et al., 2017; Rammahi and Khassaf, 2018; Somprasong and Chaiwiwatworakul, 2015; Xu et al., 2012) and was integrated with IDW technique in GIS to estimate the spatial concentration of Cd (Mesnard, 2013; Somprasong and Chaiwiwatworakul, 2015). Soil loss with RUSLE model and Cd concentration with IDW were used as the parameters to estimate Cd contamination in soil loss in the last step (Somprasong and Chaiwiwatworakul, 2015). In the past, the studies on integration of RUSLE model to estimate soil pollution such as arsenic (As), copper (Cu), zinc (Zn), and lead (Pb) were limited. This study has therefore integrated RUSLE model with geoinformatics techniques to estimate Cd commination from soil loss.

The main goal of this study was to estimate which area restoration measure scenario would help decrease the accumulation of the Cd the most. This study was conducted to help provide better proof for policy makers in advancing the measures of area restoration for agencies concerned with environmental impact. This estimation used the RUSLE model, satellite image, and GIS with the following purposes: 1) to estimate soil loss with RUSLE model and reproduce scenarios of the Mae Tao watershed restoration; and 2) to estimate Cd contamination in the sediment from the Mae Tao watershed restoration scenario.

2. METHODOLOGY

2.1 Study area

The Mae Tao watershed in its general vicinity covers the areas of the Sub-districts of Pra Tat Pa Daeng, Mae Tao, and Mae Gu in the Mae Sot District, Tak Province, Thailand. It covers an area of about 6,000 ha. It is in Eastern Thailand at 16°45′ latitude and 98°35′ longitude (Figure 1). Most of the area is high mountainous with a high gradient and is covered by forest. The watershed is divided into three part: the lower, upper left and upper right. The zinc mine is located in the upper right watershed which has an area of approximately 2,996 ha.

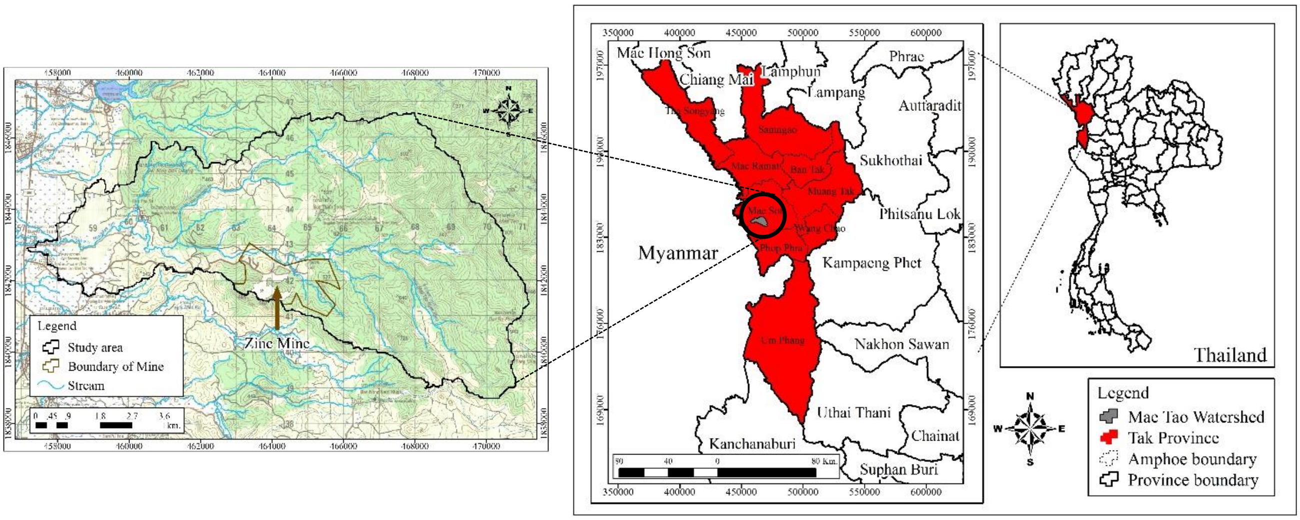


Figure 1. Study area: Mae Tao watershed, Thailand

2.2 Data to be used

1) Landsat 8-OLI with 30 m. spatial resolution captured on January 23rd, 2017 at 10:49 a.m. was used for analyzing the LULC of all four scenarios and for analyzing C-factor and P-factor in RUSLE model. Image selection was based on termination of zinc mine operations. The criterion on image selection for being used in differentiation were considered from the seasons of each compared scenario since the seasons affected farmers' planting in the area. LULC were decided based on Thailand's standard criterion (Land Development Department, 2000).

2) Annual average rainfall data of 10 years (2007-2016) in the study area was for analyzing R-factor in RUSLE model. Rainfall data derived from Mae Sot, Mae Ramad and Phawo meteorological stations, Tak Province.

3) Spatial data (.shp) of soil type from Land Development Department of Thailand was for analyzing K-factor in RUSLE model.

4) Contour line was for creating the data for the digital elevation model (DEM), input for analyzing LS-factor in RUSLE model. DEM resolution for this study was 30 m.

5) Field surveying data of LULC for examining the accuracy of LULC classification results from satellite imageries, and the 101 points of Cd concentration in the study area were for analyzing Cd contamination in sediment. The sampling points were chosen by random sampling along the Mae Tao River.

2.3 Scenarios

The scenarios of Cd contamination from mining restoration in the Mae Tao watershed were defined based on the mining restoration measures which were put into four scenarios (Figure 2). They are as follows:

Scenario 1: Forest restoration in old mining area

This scenario used Landsat 8-OLI satellite imageries captured in January 2017 (a period of non-operating mining) as representative in LULC. There were two areas of forest restoration in this scenario. The first area was the forest plantation areas of the Royal Forest Department (forest restoration 3). The second area was the plantation forest area in an area of the zinc mining project (forest restoration 4). Originally an empty area of land with parts of ground cover, there were plans to restore the forest in the majority of the area, and to adjust the landscape to allow for a learning center and a place for ecotourism.

Scenario 2: Forest restoration in old mining area and new mining area

In this scenario, forest would be planted following Scenario 1 while adding two more areas of forest planting in the outer mining area. They are designated the forest planting area, orchard planting area, and integrated farming area (outside of the areas which invoke land use rights) (forest restoration 1 and 2), where the original area was cultivated on an area of conserved forest with mono-cropping destroying the land's surface. This area was a unit filled with zinc and Cd; therefore, there should be an adjustment to the agricultural activity methods from mono-cropping, to integrated farming for land surface preservation.

Scenario 3: Forest restoration in old mining area and new mining area in cooperation with reservoir construction

This scenario was a forest planting determination following Scenario 2 in cooperation with the reservoir construction area.

Scenario 4: Forest restoration in old mining area and new mining area in cooperation with weir construction

This scenario was a forest planting determination following Scenario 2 in cooperation with the weir construction area.

The LULC classification results were examined by field surveying. The classification accuracy for the LULC classes was 83%, examined with 85 randomly distributed points.

2.4 RUSLE Model

RUSLE model is a very powerful method for estimation of soil erosion in specific situations such as dam construction, mining, typhoon, assessing land management measures, LULC change, and mountain areas (Atoma et al., 2020; Chuenchum et al., 2020; Kassawmar et al., 2018; Kim, 2006; Lazzari et al., 2015; Rammahi and Khassaf, 2018; Somprasong and Chaiwiwatworakul, 2015). RUSLE model integrates remote sensing techniques together with GIS for estimation of the quantity of lost sediment in the four scenarios as shown in Equation (1).

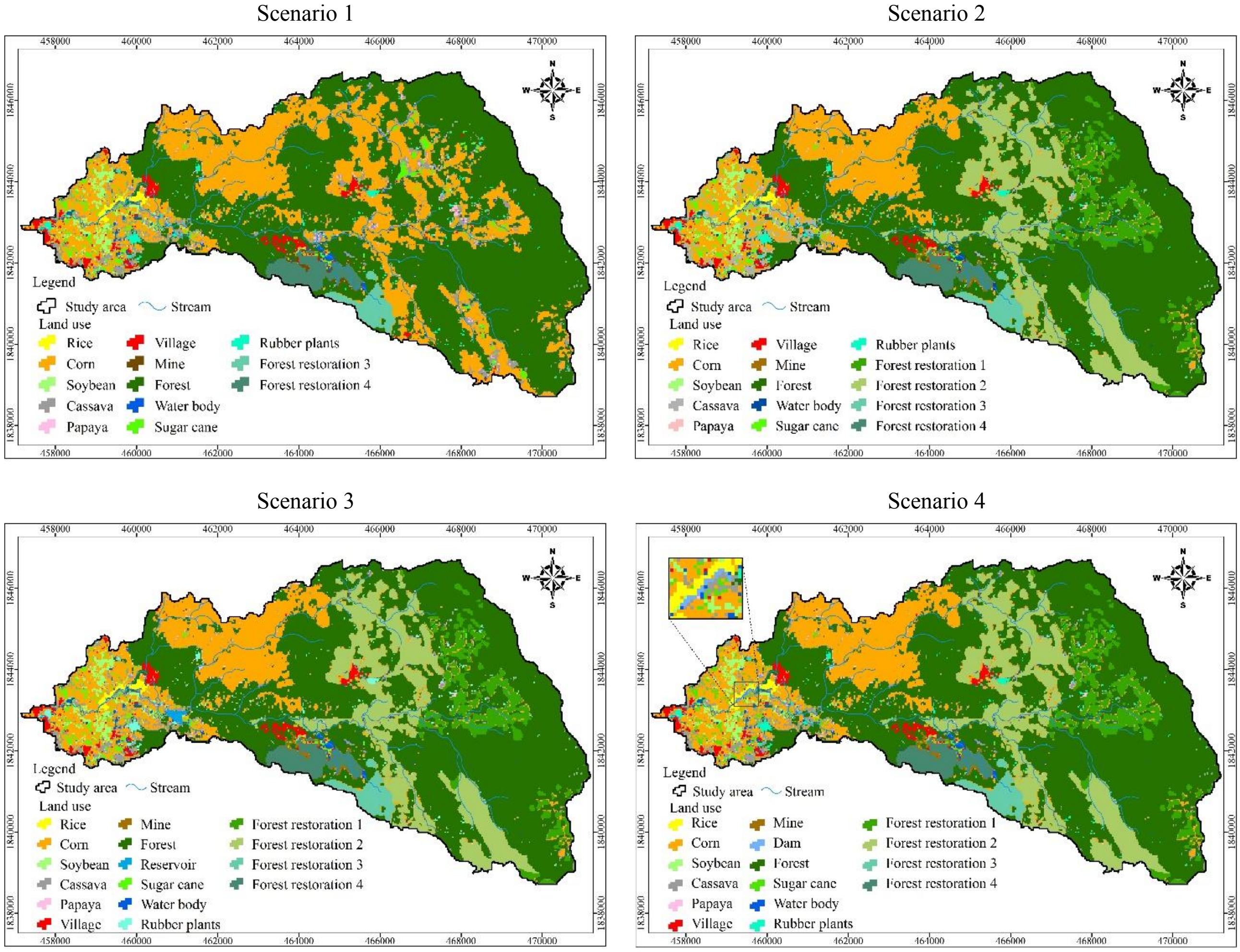


Figure 2. Land use/land cover classification of each scenario

$$A = R\,K\,C\,P\,L\,S \qquad (1)$$

Where; A=the average of soil loss (ton/ha/year), R=the rainfall and runoff erosivity factor (mm/ha/year), K=the soil erodibility factor (no unit), C=the crop management factor) (no unit), P=a term representing the conservation practice factor (no unit), and LS=the slope length and steepness factor (no unit).

R-factor: The R-factor is an index of the runoff power of rain. It includes the factors of rainfall and runoff. These factors are different based on the area in which they occur (Oliveria et al., 2012). This equation relies on annual rainfall for calculation as shown in Equation (2) (Land Development Department, 2000).

$$R = 0.4669X - 12.1415 \qquad (2)$$

Where; R=rainfall erosivity (mm/ha/year) and X=average annual rainfall (mm/year)

Annual rainfall data for the period from 2007-2016 (10 years) were collected from three stations: Mae Sot, Mae Ramad, and Phawo. This data was used to create spatial interpolation data and calculated with Equation (2) (Figure 3).

K-factor: This factor indicates soil erodibility of any type of soil. The Land Development Department (1983, stated in Land Development Department, 2000), assigned soil types by different sets of soil based on the property of the soil. The K-factor was calculated following the soil types and their geological units. The K-factor of Thailand is between 0.04 and 0.56. However, in the times period for which this study was conducted, the K-factor had little to no change (Figure 3).

LS-factor: This factor relates to geographical characteristics and is calculated from an analysis of the slope length index. The L-factor influences erosivity and is a 'no unit' number. The index of slope-steepness, or S-factor, is a gradient index and has no size or unit. Both factors can be greater than or less than 1. The LS-analyzing method can be completed by following Equation (3) (Ozcan et al., 2007).

$$LS = \left(\frac{xn}{22.13}\right)^{0.4} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3} \qquad (3)$$

Where; LS=slope length and steepness of inclination, x=flow accumulation, n=cell size, and θ=steepness (degree).

The result of the LS-factor is presented in Figure 3. Because this factor had no change in a short period of time, the LS-factor of all four scenarios remained the same.

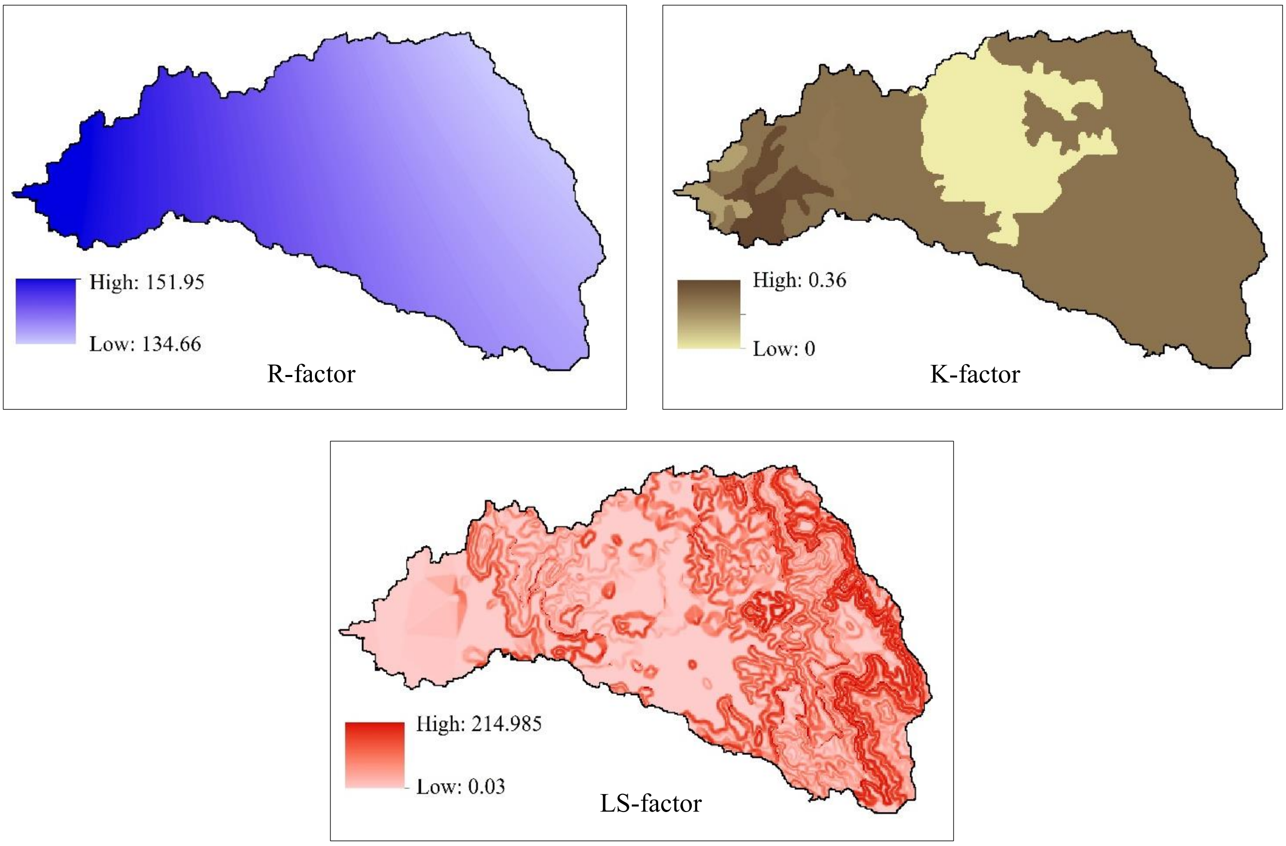


Figure 3. R-factor, K-factor, and LS-factor

C-factor: The cropping management factor of this study was an application of the Normalized Difference Vegetation Index (NDVI). NDVI is from calculations between reflectance in the near infrared band (NIR) and reflectance in the red band (RED). When NDVI is known, it can be converted into C-factor using Equation (4). Nevertheless, the C-factor is different based on each scenario (Figure 4).

$$C = \exp\left(-\alpha \frac{NDVI}{\beta - NDVI}\right) \quad (4)$$

Where, α is a constant of -2, β is a constant of 1 (European Commission, 2000), and exp is a constant of 2.71828.

P-factor: The practice management factor is a factor of erosion-control measure which is used in the management of soil erosion in different areas where preservation is practiced. This study used P-factor based on a LULC of the Land Development Department (2000). The values of cropping management factor were used to define P-factor which was have been different in each scenario as there were different land use types (Figure 4).

The criterion used in classifying the levels of sediment movement or average soil loss in this study was used from the criterion of the Land Development Department (2000) for organizing the level range (Table 1).

Table 1. Category of soil loss severity in Thailand

Severity level	Soil loss rate (ton/ha/year)	Status
Very low severity	0-12.5	Balance
Less severity	12.5-31.25	Monitor
Moderate severity	31.25-93.75	Monitor
High severity	93.75-125	Risk
Very High severity	>125	Crisis

Source: Adapted from Land Development Department (2000)

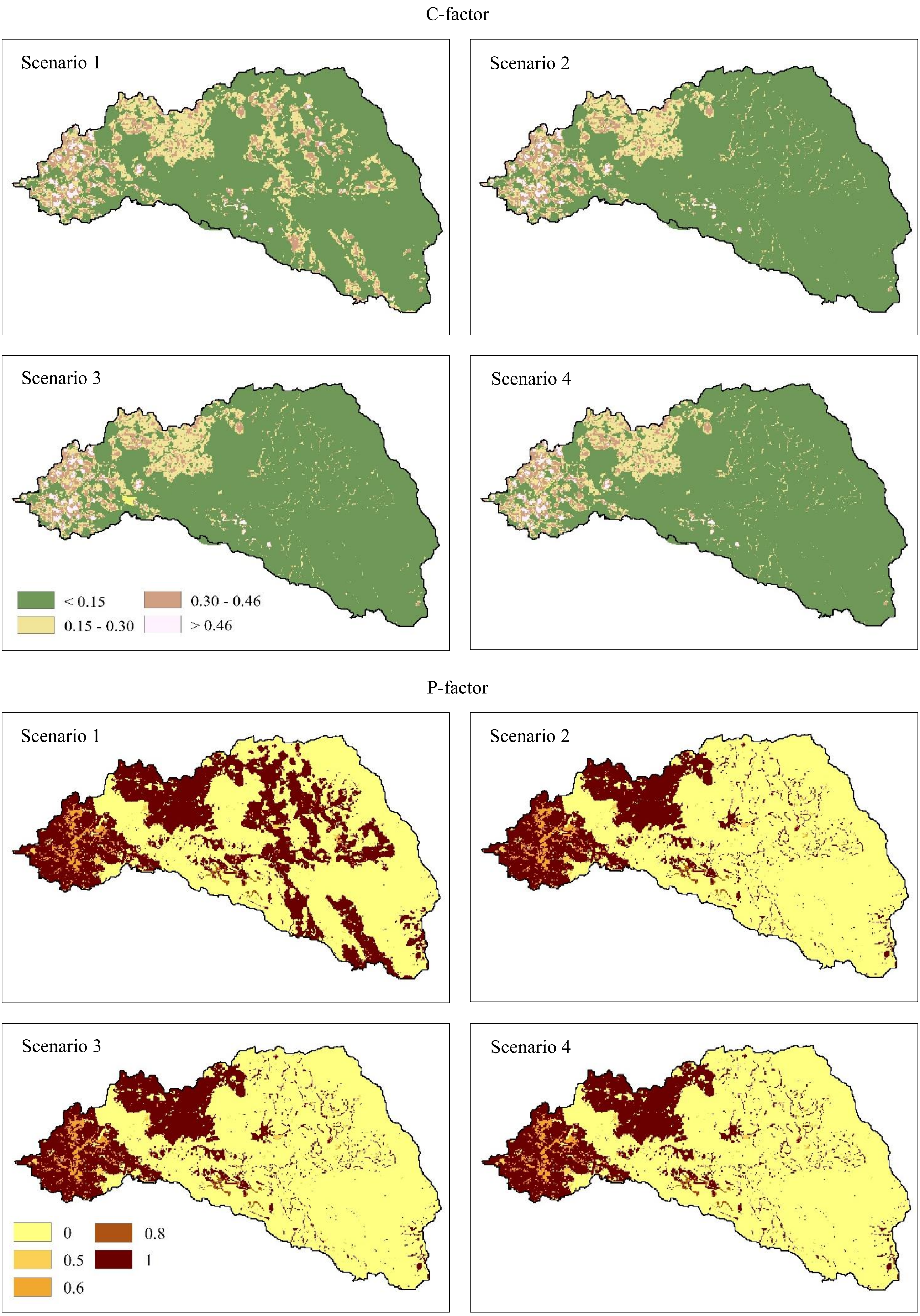


Figure 4. C-factor and P-factor

2.5 Inverse distance weight (IDW)

IDW is used to estimate the spatial concentration of Cd. The advantages of this method were for estimation of unknown values and it has a superior performance than other interpolation methods (Azpurua and Ramos, 2020). This study used data from actual Cd collection points in the Mae Tao watershed with 101 points in total collected on February 5th, 2017. Each sample was a collection of top soil (0-15 cm) from which the Cd concentration was determined. This existing data as shown in Equation (5) is considered as a means of prediction of the concentration of Cd in areas that have not yet been measured.

$$\mathrm{CdIDW} = \sum_{n}^{i=1} \mathrm{wifi} \tag{5}$$

Where; CdIDW=cadmium concentration (mg cadmium/kg soil), i=Cd concentration from field surveying (mg Cd/kg soil), w_i=weight value, and n=the amount of mg Cd collected from the points of collection in the study area.

2.6 Estimation of Cd contamination in soil loss

An analysis result of the average of soil loss from Equation (1) and Cd concentration calculated from IDW from Equation (5) were used as the parameter to estimate potential of Cd movement in soil loss. Potential of Cd movement in soil loss was calculated by the following Equation (6).

$$\mathrm{Pcd} = 0.16 \times \mathrm{A} \times \mathrm{CdIDW} \tag{6}$$

Where; Pcd=potential of Cd movement in soil loss (ton Cd/ha/year), A=average of soil loss (ton/ha/year), and CdIDW=Cd concentration calculated by IDW technique (mg Cd/kg soil).

The average of soil loss from RULSE model (parameter A) and Cd concentration from IDW technique (parameter CdIDW) were a spatial data. Both parameters and weighting value were applied by raster calculation to estimate the Cd contamination in soil loss.

3. RESULTS AND DISCUSSION

3.1 Soil loss estimation with RUSLE model

After analyzing five factors affecting sediment movement, each factor was then used to calculate the sediment movement of the Mae Tao watershed in all four scenarios with RUSLE model. The result of soil loss analysis with RUSLE model from four scenarios found a severe level of sediment movement (more than 125 ton/ha/year) as a critical level with high movement of soil and surface erosion affecting the ecosystem was found the most in Scenario 1 at 76.86 ha, which was the highest rate of erosion at 1,346.13 ton/ha/year. This was due to Scenario 1 covering the largest area of monoculture, namely corn, sugar cane, and soybean. C-factor and P-factor have been affected by LULC types therefore these factors were a high influence on the level of sediment movement. The second most critical was Scenario 3 at 21.04 ha. The least critical levels were found in Scenarios 2 and 4, both expressing the same numerical value of 19.16 ha (Figure 5). High levels of lost sediment occur in corn areas, including the middle of Mae Tao watershed, especially in Scenario 1. But some spatial soil erosion results differ in other areas, especially along the mainstreams (Somprasong and Chaiwiwatworakul, 2015). The different results can be identified by the computation of the C-factor and P-factor which are influenced by different LULC.

Scenario 1 Scenario 2

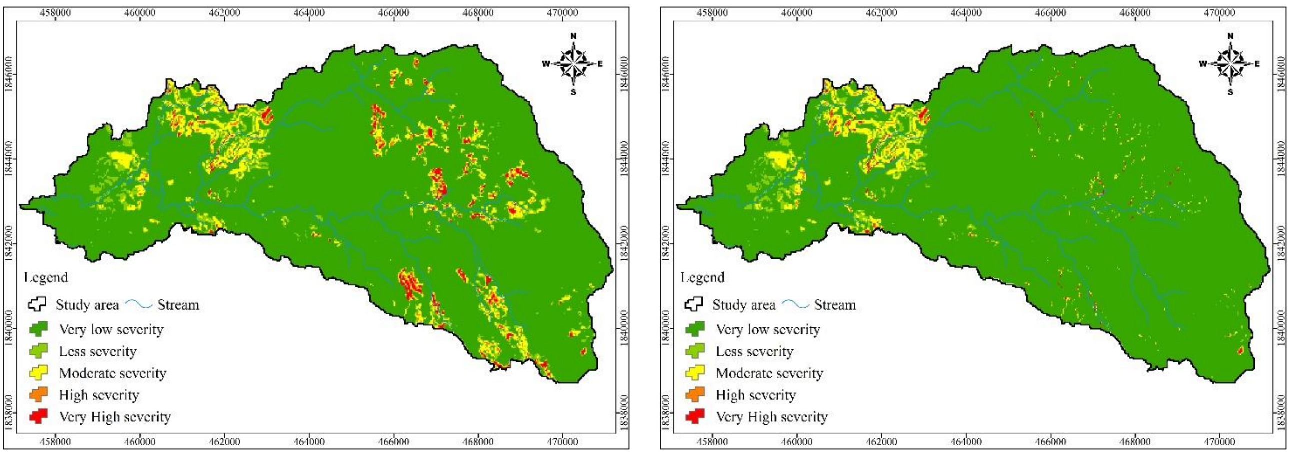


Figure 5. Soil loss estimation of each scenario

Scenario 3 Scenario 4

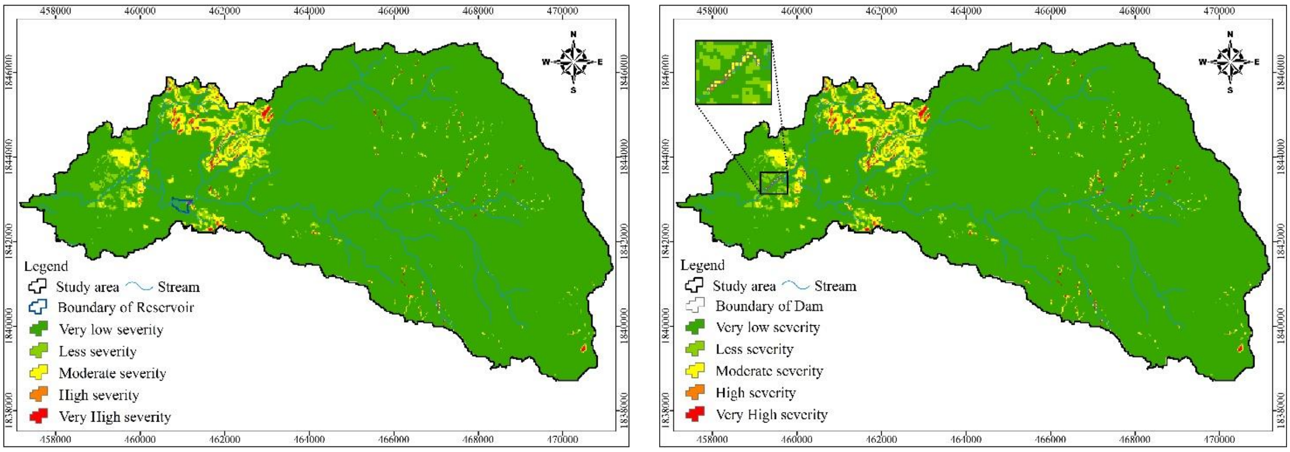


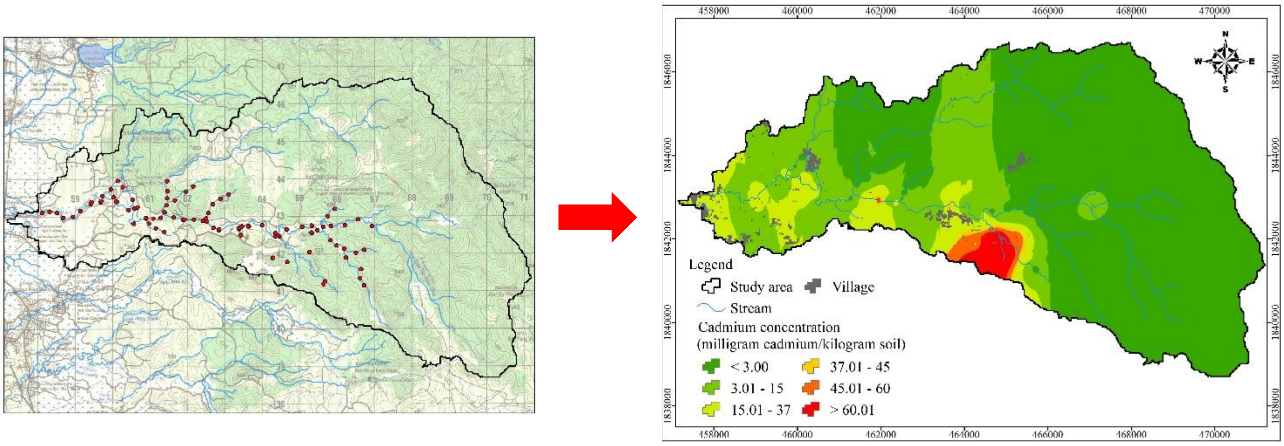
Figure 5. Soil loss estimation of each scenario (cont.)

For this study, observed soil sediment data from field surveying was not performed. However, the observed soil sediment data and the sediment yield results from RUSLE model simulation were well correlated with a correlation higher than 0.9 (Chuenchum et al., 2020).

3.2 Cadmium contamination estimation in the sediment

3.2.1 Spatial concentration of Cadmium

The field data of measured Cd concentration from the study areas found that 50.5% of total points had more than the regulatory standard concentration of 3 mg Cd/kg soil. All the data collected in this study was put into the function of the GIS for analyzing the spatial concentration of Cd. The results showed that an area that exceeds the European Economic Community's maximum permissible (EEC MP) level, was found west of the Mae Tao watershed covering about 2.12 ha. Cd concentration exceeding the standard set in place by the Enhancement and Conservation of National Environment Quality Act (more than 37 mg Cd/kg soil) was found in an area of about 640 ha located in the middle of the Mae Tao watershed-originally a mining area. Nonetheless, the average Cd concentration in the Mae Tao watershed was found to be 13.64 mg Cd/kg soil, which exceeds all of the standards according to the EEC MP criterion. The range with more than 60.01 mg Cd/kg soil had an average Cd concentration as high as 110.93 mg Cd/kg soil. This concentration of Cd is considered as an amount that could affect the ecosystem as well as the human residents living in the area (Figure 6). Moreover, rice field soil samples collected in the study area had Cd levels of 3.40-284 mg Cd/kg soil, 94 times the EEC MP concentration in soil (Simmons et al., 2005). In additional, high Cd concentration from IDW were found near the residential area west of the Mae Tao watershed, with a range of Cd concentrations from 0-200 mg/kg. (Somprasong and Chaiwiwatworakul, 2015).



(a) 101 points of measured Cd concentration from the study areas (b) spatial concentration of Cd from IDW

Figure 6. Locations of measured Cd concentration (a) and concentration of Cd from IDW (b)

3.2.2 Cadmium contamination from soil loss

After analyzing the spatial concentration of Cd with GIS, the criteria range was determined by separating the levels of Cd contamination from soil loss into three levels: 1) high level of Cd contamination with more than 30 ton/ha/year; 2) medium level of Cd contamination with 3-30 ton/ha/year; and 3) low level of Cd contamination with less than 3 ton/ha/year. These criteria were used for a determination of Cd contamination from the range of soil loss (Figure 7). Cd contamination estimates also due to erosion occurred in the mining production area. In addition, there is significant evidence that the upstream area of the basin has the potential to release Cd during incidents of erosion (Somprasong and Chaiwiwatworakul, 2015). The total Cd concentrations in sediment were increased when passing the zinc mines (Thamjedsada and Chaiwiwatworakul, 2012).

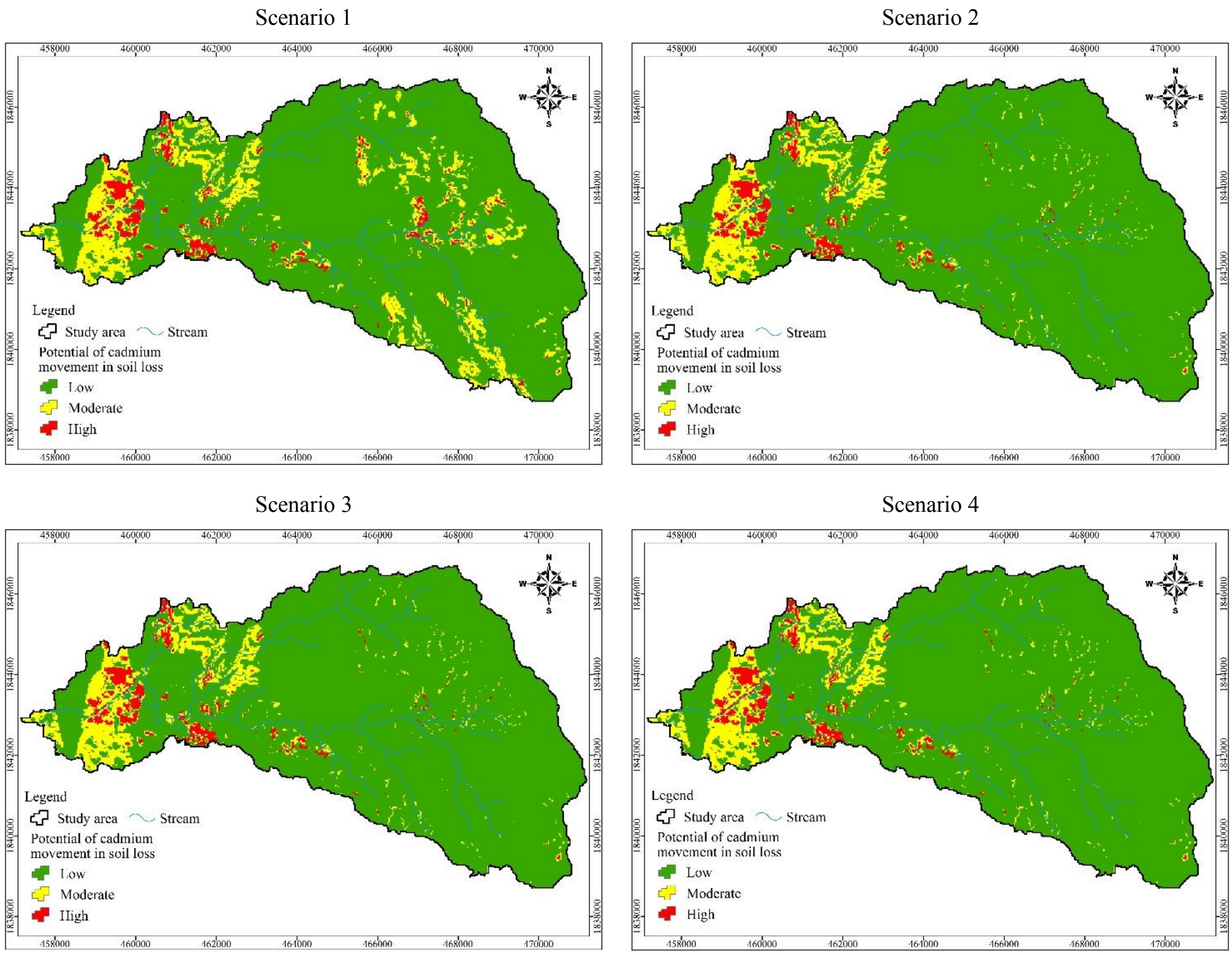


Figure 7. Cd contamination from soil loss of each scenario

A high level of Cd contamination from soil loss (more than 30 ton Cd/ha/year) was found mostly in the east and middle areas of the Mae Tao watershed. Scenario 1 had the highest Cd contamination from soil loss, which was about 187.20 ha. Scenario 4 was the second-most contaminated at about 158.40 ha, while Scenario 2 was contaminated at about 156.80 ha. Scenario 3 yielded the least contaminated at about 156.32 ha (Table 2). From this result, it can be concluded that Scenario 3 is the best measure to decrease Cd contamination of the soil loss in Mae Tao watershed. RUSLE model can certainly aid in implementation of soil management and conservation practices to reduce the soil erosion (Ganasri and Ramesh, 2016) and also help to locate the severe soil loss areas for suitable conservation practices (Ostovari et al., 2017).

Moreover, an area exceeding a high level of Cd contamination from soil loss (more than 30 ton Cd/ha/year), was analyzed with land used in the Mae Tao watershed. The results of the four scenarios of this study found that a high level of Cd contamination was found mostly in the corn plantation area (104,995.63 ton/year in Scenario 3) (Table 2), as well as the sugar cane (13,758.86 ton/year in Scenario 3) and cassava plantation areas (11,977.18 ton/year in Scenario 3). This result revealed that soil loss and Cd Contamination problems were highly influenced by monoculture.

Table 2. High level of Cd contamination (CC) in each LULC

Land use/land cover	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Area (ha)	Total of cc (ton/year)	Area (ha)	Total of cc (ton/year)	Area (ha)	Total of cc (ton/year)	Area (ha)	Total of cc (ton/year)
Corn	133.86	120,522.95	106.37	104,968.64	106.08	104,995.63	107.95	104,987.90
Sugar cane	10.09	11,453.11	8.81	13,758.86	8.81	13,758.86	8.81	13,758.86
Cassava	14.29	14,589.88	11.21	11,881.87	11.15	11,977.18	11.14	11,898.20
Soybean	6.65	7,315.42	7.46	9,358.64	7.39	6,606.22	7.39	6,606.22
Water body	5.67	11,569.15	4.72	5,892.86	4.72	5,892.86	4.65	5,928.45
Village	7.35	12,839.04	7.73	10,539.61	7.73	10,539.60	7.73	10,539.60
Mining area	1.54	2,138.39	1.81	2,537.99	1.81	2,537.99	1.81	2,537.99
Para rubber	0.09	70.69	-	-	0.02	35.79	0.02	21.52
Paddy field	7.11	8,817.81	7.73	9,065.96	7.73	9,065.96	7.65	9,175.93
Papaya	0.99	871.35	0.94	514.21	0.94	514.21	0.95	514.21
Total	187.65	190,187.80	156.78	168,518.64	156.33	165,924.32	158.11	165,968.89

4. CONCLUSION

The application of RUSLE model, satellite data, and GIS could be effective techniques to assess the suitable measures for environmental management, especially soil pollution. The results of this study demonstrated the pattern of Cd contamination from soil loss in the each LULC area and could explore Cd contamination in remote areas. The results highlight the advantage of the methods selected in this study. However, regarding the limitation of this study, it would be helpful if observed soil sediment data was collected by field surveying to examine the result from RUSLE model in further study.

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