Soil erosion prediction in Cilebak – Cirasea Micro Watershed, Indonesia

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Abstract. Soil erosion impact on land degradation could threaten soil and water quality. In the mountainous area, soil erosion resulted in losses of topsoil, which containing high nutrients. The study area was located in Cilebak-Cirasea Micro Watershed, Bandung Regency, Indonesia. Landuses in this area were secondary forest (12%), upland agriculture (84%), and paddy field (4%). The objectives of this study were to assess soil erosion and study best management practices (BMP) effect to reduce soil erosion. Universal Soil Loss Equation (USLE) was used to estimate soil erosion with support from Geographic Information System (GIS). USLE parameters, which consist of erosivity, erodibility, slope length, steepness, crop, and soil management, were used to estimate soil erosion. BMP scenarios consist of application raised bed that parallel to contour lines and combination of raised bed that parallel to contour lines and straw mulch addition of 3 and 6 Mg ha\(^{-1}\) year\(^{-1}\). The result indicated that soil erosion rate under current condition was 45.4 Mg ha\(^{-1}\) year\(^{-1}\), which exceeding the tolerable soil loss. All BMP scenarios showed their effectiveness in reducing soil erosion. Proposed BMP to minimize soil erosion rate could probably be able to support government in arranging policies for maintaining or restoring crop productivity for sustainable agriculture.

1. Introduction

Agriculture land often has environmental issues of soil degradation due to intensification activities. Intensively soil degradation was caused by soil erosion, a form of physical soil degradation. Transporting of soil materials from surface layer could increase bulk density, decrease organic matter and fertility [1,2], also cause sedimentation in a reservoir or stream [3] that decrease its function.

Land deficient in organic matter and nutrient contents can not support crop productivity to reach the optimum result. The crop productivity will decline if no concern to provide some efforts to protect the soil from erosion [4,5]. Human activities accelerate soil erosion, which becomes problematic to the environmental sustainability and farmers’ welfare. Soil erosion in farming systems occurs as the effects of intensive tillage, frequent cultivation, and low input [6]. Soil erosion rates are generally high in the sloping areas [7] found in the mountainous regions.

The identification of watershed area potentially having high erosion is necessary to protect its hydrological function. Measuring soil erosion on a plot scale is quite expensive because it needs observations at a certain time. Assessment of soil erosion can be obtained through Universal Soil Loss Equation (USLE), which is a desk work-study, simple, and time efficient. Recently, USLE could be applied in watersheds scale with geographic information system (GIS) tool [8].

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Application of BMP effectively reduces soil erosion rate. BMP should be applied according to appropriate land topography, farmer’s preferences, and social-economic conditions. A study in Lampung showed a reduction of soil erosion with the application of agroforestry, cover crop, and contour system [9]. While a study in China showed that contour tillage and farming with a seasonal no-till ridge was able to reduce soil erosion by 31 and 70%, respectively [10].

Information on soil erosion rate is necessary to maintain environmental functions of hydrological systems and give the recommendation to stakeholders to decide policies. The objectives of this study were to predict soil erosion rate in a micro watershed and study BMP effect to reduce soil erosion rate.

2. Materials and methods

2.1. Study area
This study was located in Cilebak – Cirasea Micro Watershed, part of Citarum Watershed in West Java, Indonesia (figure 1). Geographically, the study area was located at 107°43'29.9'' to 107°44'04.1'' E and 7°08'50.6'' to 7°05'21.2'' S with a total area of 3.85 km². The altitudes ranged between 776 to 1,915 m above sea level. Total amount of rainfall in 2019 was 1,679 mm [11]. Land use in this area [12] consisted of secondary forest (12%), upland agriculture (84%), and paddy field (4%). Various vegetable crops (tomato, red chili peppers, cabbage, potato, and others) were planted in the upland agriculture landuse.

2.2. Assessment of soil erosion
Assessment of soil erosion was conducted by using Universal Soil Loss Equation (USLE). Previously, this equation was adopted for field-scale size [13]. This equation could also be applied in watershed scale along with GIS tools such as ArcMap. The equation of USLE:
where $A$ is assessment of soil erosion loss ($\text{Mg ha}^{-1} \text{year}^{-1}$), $R$ is the erosivity factor ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$), $K$ is the soil erodibility factor ($\text{Mg ha}^{-1} \text{h}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$), $LS$ is topography factor of slope length and steepness (dimensionless), $C$ is the crop management factor (dimensionless), and $P$ is soil support practice or soil conservation factor (dimensionless).

Soil erosion rate is assessed by overlaying map of USLE parameters and processed by raster calculator in ArcMap software 10.4.1. The information on soil erosion will be provided based on pixels with a size of 30 m.

2.2.1. Erosivity factor ($R$). $R$ factor is the potential of precipitation that results in soil erosion. Energy kinetic from water drops could detach soil aggregate in surface area; therefore, soil particles easily loose and eroded. The $R$ factor was calculated by using Bols equation [14]:

$$R_m=6.119\text{Rain}^{1.21}\times\text{Days}^{0.47}\times\text{MaxP}^{0.53}$$ (2)

where $R_m$ is monthly erosivity factor, $\text{Rain}$ is total monthly precipitation (cm) in the observed months, $\text{Days}$ is number of precipitation day in the observed months, and $\text{MaxP}$ is maximum precipitation (cm) in the observed months.

Precipitation data in 2019 (figure 2) was obtained to calculate $R$ factor using this above equation. Dry season having less precipitation occurred from June to October, while rainy season occurred from January to May and November to December.

2.2.2. Erodibility factor ($K$). $K$ factor reflects in soil sensitivity to erosion. Soil properties such as texture, structure, permeability, and organic matter describe the sensitivity of soil to erode. $K$ factor was determined by this following equation [13,15]:

$$100K=(2.71 \times M^{1.14} \times (10^{-4}) \times (12-OM)+3.25\times(s-2)+2.5\times(p-3))/7.59$$ (3)

where $M$ is (the percentage of very fine sand + silt) $\times$ (100 - percent clay), $OM$ is the percentage of organic matter, $s$ is code of soil structure while $p$ is code of soil permeability class.

Figure 2. Precipitation in 2019.
The soil within this area was classified as Typic Eutrudepts, which had silty clay texture, 3% organic carbon, coarse granular structure, and good drainage. Soil properties data for calculating $K$ value were collected from the Indonesian Center for Agricultural Land Resources Research and Development [16].

2.2.3. Length and slope factor (LS). $LS$ factor reflects of topography role in soil erosion. Digital elevation model (DEM) data was processed to obtain information regarding topography impact on soil redistribution in watershed scale.

$LS$ factor in this study was processed by ArcMap 10.4.1 with extension terrain – hydrology from System for Automated Geoscientific Analyses (SAGA), and calculated by Desmet and Govers equations [17]:

$$L_{i,j} = (A_{i,j-in} + D^{m+1}) - A_{i,j-in} = \frac{D^{2m+2} * X_{i,j}}{X_{i,j}^{22.13^m}}$$

where $L_{i,j}$ is topography factor of slope length for the grid cell that have coordinates $(i,j)$, $A_{i,j-in}$ is contributing area which have position at the inlet of a grid cell with coordinates $(i,j)$ (m²), $X_{i,j}$ is $\sin \alpha_{i,j} + \cos \alpha_{i,j}$, and $\alpha_{i,j}$ is aspect direction for the grid cell that have coordinates $(i,j)$, $D$ is the grid cell size (m), and $m$ is slope length exponent. The equation used for calculating slope length exponent (m):

$$m = \frac{\beta}{(\beta+1)}$$

$$\beta = \frac{\sin \Theta}{3 * \sin^3 \Theta + 0.56}$$

where $\Theta$ is slope in degrees, $\beta$ is ratio of rill erosion to interrill erosion.

2.2.4. Crop and soil management factor (CP). Crop factor represents the effect of crop towards soil erosion. The values of $C$ factor vary depending on vegetation cover. $C$ factor for secondary forest and paddy field were 0.005 and 0.05, respectively [18]. $P$ factor represents soil management that affects on reducing soil erosion. $P$ factor for secondary forest and paddy field land uses, were set as 1 due to no soil practices (table 1). Therefore, $CP$ factor values of secondary forest and paddy field were 0.005 and 0.05, respectively.

In the study area, farmers in upland agriculture dominantly applied raised beds in the same direction to slope. Soil practice of raised beds directed to slope is the conventional approach of farmers in cultivating vegetables. $CP$ factor of raised bed with vegetable crop planting (chilli pepper) directed to slope had value 0.88 [19].

| Soil practice                                      | $P$   | $CP$   |
|---------------------------------------------------|-------|--------|
| No soil practice                                   | $1^a$ |        |
| Straw mulch 3 Mg ha$^{-1}$ year$^{-1}$             | 0.5$^a$ |        |
| Straw mulch 6 Mg ha$^{-1}$ year$^{-1}$             | 0.3$^a$ |        |
| Vegetable crop with raised bed directed to contour lines | 0.88$^b$ |        |
| Vegetable crop with raised bed parallel with contour lines | 0.48$^b$ |        |

$^a$Hamer [18].
$^b$Hidayati, Erfandy, and Suyitno [19].
2.3. Best Management Practices (BMP)

The application of BMP could reduce soil erosion. Simulations were applied in upland agriculture because this land use contributes to high soil erosion compared to secondary forest and paddy field. Simulation scenarios of BMP in the study area are as follows:

1. Application raised bed parallel with contour lines
2. Application raised bed parallel with contour lines and straw mulch 3 Mg ha\(^{-1}\) year\(^{-1}\)
3. Application raised bed parallel with contour lines and straw mulch 6 Mg ha\(^{-1}\) year\(^{-1}\)

Adoption of mulch was selected as BMP because this practice was able to be applied in study area and easily adopted by farmers, but did not reduce planting area. Through applying BMP, soil erosion rates could decline to maintain sustainable agriculture.

3. Results and discussion

3.1. Assessment of soil erosion

R factor value, which represents the erosive potential of rainfall to cause surface runoff, was 1,475 MJ mm ha\(^{-1}\) h\(^{-1}\) year\(^{-1}\). K factor value in study area based on soil properties was 0.0129 Mg ha h ha\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\) while LS factor value ranged from 0 to 9 (figure 3). CP factor distribution was presented in Figure 3.

![Figure 3](image_url)

Figure 3. (a) LS factor map, (b) CP factor map, and (c) soil erosion map.
Soil erosion results in study area ranged from 0 to 150.7 Mg ha\(^{-1}\) year\(^{-1}\) with average erosion of 45.4 ± 45.5 Mg ha\(^{-1}\) year\(^{-1}\) (figure 3). Soil erosion resulted by smallholder potato farming system for one cropping season in Kenya was 55.1 Mg ha\(^{-1}\) [20]. Measurement of soil erosion in Philippine on cropping sequences of cabbage – corn – potato, fallow – cabbage – potato, sweet pepper – fallow – cabbage, potato – cauliflower – sweet pea had resulted in 26.6, 34, 13.4, and 52.5 Mg ha\(^{-1}\) year\(^{-1}\), respectively [21].

Soil erosion rate will create severe environment if its value is higher than tolerable soil loss (TSL). TSL is soil tolerance limit to soil degradation, which is influenced by some parameters such as soil erosion rate, social and economic condition, and soil depth [22]. The value of TSL is varied spatially according to parent material, land use, climate, and geographic position [23]. The rate of soil erosion resulted in the study area was of 45.4 Mg ha\(^{-1}\) year\(^{-1}\) exceeding TSL value of 10 Mg ha\(^{-1}\) year\(^{-1}\) [24] in Indonesia, while the TSL values in India ranged between 2.5 – 12.5 Mg ha\(^{-1}\) year\(^{-1}\) [25]. The average soil erosion rate being higher than TSL value indicates that the soil is vulnerable to soil degradation.

3.2. Best Management Practices (BMP)

Soil erosion affects on a decrease in crop yield [5]; therefore, it is necessary to reduce soil erosion and maintain soil properties in order to support crop growth through the application of soil conservation practices. Low adoption of soil conservation practices was determined by misleading information that soil conservation caused poor drainage, reluctance farmers to reduce planting area, and costly [26].

All simulation scenarios of BMP showed reduced soil erosion. Simulation of adoption raised bed parallel to contour lines decreased soil erosion to become 24.9 Mg ha\(^{-1}\) year\(^{-1}\) with standard deviation of 19.3 Mg ha\(^{-1}\) year\(^{-1}\). By applying this conservation method, soil erosion reduced by 45.3% (figure 4). Raised beds parallel contour lines will reduce surface runoff, result in lower soil erosion rate. Besides, the structure of raised bed could promote water infiltration into the soil. Previous study stated that soil management in potato farming system on raised beds parallel contour lines results in soil erosion rate of 12.7 Mg ha\(^{-1}\) in one cropping season [27]. Study in Central Mexico revealed that raised bed planting could increase soil quality properties and support sustainable crop production [28]. As raised bed parallel to contour lines reduced soil erosion effectively, so that the farmers in Talun Berasap Village, Jambi Province paid high preferences to adopt this practice when it was disseminated to them [29].

**Figure 4.** Current condition and BMP practices; Scenario 1 = raised bed parallel to contour lines; Scenario 2 = raised bed parallel to contour lines with straw mulch 3 Mg ha\(^{-1}\) year\(^{-1}\); Scenario 3 = raised bed parallel to contour lines with straw mulch 6 Mg ha\(^{-1}\) year\(^{-1}\).
Scenario 2 of applying 3 Mg ha\(^{-1}\) year\(^{-1}\) straw mulch in raised bed parallel to contour lines reduced soil erosion by 72.4% (figure 4) with average value of 12.5 \(\pm 9.53\) Mg ha\(^{-1}\) year\(^{-1}\). Scenario 3 of applying 6 Mg ha\(^{-1}\) year\(^{-1}\) straw mulch in raised bed parallel to contour lines had the highest effect in reducing soil erosion by 83.3% (figure 4) with average of 7.6 \(\pm 5.6\) Mg ha\(^{-1}\) year\(^{-1}\). The application of straw mulch could improve soil properties. Mulumba and Lal [30] stated that mulch application on the field has effects on enhancing porosity, aggregate stability, moisture retention, and available water capacity. Research in Rwanda by Nzeyimana [31] resulted that mulch application could reduce bulk density and soil erodibility, and also enhanced soil organic carbon and wet aggregate stability. Combination soil practices of mulch from left cover crop and chicken manure with reduced-tillage could reduce soil erosion rate and surface runoff [32]. A study in Germany has shown that chopped straw mulch practice could declined soil erosion [33] in potatoes farming system. Besides, mulch has roles in reducing potato virus Y (PVY) attack [34].

4. Conclusions

The current condition of study area had soil erosion rate of 45.4 Mg ha\(^{-1}\) year\(^{-1}\) which exceeds tolerable soil loss. Application of BMP in upland agriculture land use could reduce soil erosion rate. The highest effect in reducing soil erosion was shown by the application of raised bed parallel to contour lines with 6 Mg ha\(^{-1}\) year\(^{-1}\) straw mulch. This practice reduced soil erosion by 83.3% and resulted in the soil erosion rate below the TSL value. Adoption of this practice could reduce nutrient loss, prevent environmental degradation, and support sustainable crop productivity.

Farmers play important role in achieving sustainable agriculture. They should apply BMP in their planting crop to conserve soil quality properties. Land management without soil conservation practices leads to poor soil performances which need high input of fertilizer. This will count on high production costs and reduce farmers’ profit.

Information on the areas with high erosion and current soil management practices could support stakeholders to make appropriate policies. The government should encourage farmers by making policies for applying smart agriculture in order to support sustainable agriculture. Information on BMP helps stakeholders to implements conservation practices to maintain environment functions in the study area of Cilebak – Cirasea micro watershed. It is required the concerns from government in establishing smart agriculture areas that stand for the environment side and increase farmers’ livelihoods.

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