Sediment export estimation from the catchment area of Lake Rawapening using InVEST model

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Abstract. Sedimentation is one of the main problems of the fifteen priority lakes in Indonesia, including Lake Rawapening. It has adverse impacts on lake, such as siltation that contribute to eutrophication and reduce the lake’s lifetime. Therefore, reducing sedimentation rate was set as one of the super-priority programs of the Lake Rescue Movement. Information on the spatial distribution of sediment export becomes important to implement the program effectively. This study aims to estimate the magnitude and the spatial distribution of sediment export from the catchment area of Lake Rawapening. The analysis was based on the Sediment Delivery Ratio sub-model. The results indicated that the total sediment export from the catchment area of Lake Rawapening is 501,628.6 tons/year. The largest export of sediment came from Galeh Sub-sub watershed, i.e., 161,091.7 tons/year (32.1% of the total sediment). However, Legi Sub-sub watershed has the highest average of sediment export per hectare, i.e., 42.9 tons/ha. High sediment export generally occurs in the upstream area with very steep slope, high rainfall, and dominated by dryland agriculture and vegetable farm land. Thus, efforts to reduce sediment export to Lake Rawapening should be focused on the hot-spot area, such as the upstream area of Legi Sub-sub watershed.

1. Introduction

Indonesia has around 840 lakes [1-3] and 521 of them have an extent of more than 10 hectares (ha) with the total area of about 491,724 ha [4]. Lake is a form of stagnant freshwater ecosystem (lentic) in the form of a basin area that functions to accommodate and store water from rivers, springs, groundwater and rainwater [1, 5]. Lake is one of the natural resources that have two functions, namely economic functions and ecosystem support functions [3]. Thus, the lake ecosystem has an important role in the life of humans and other living things. Lakes have various functions and benefits, where there are lakes with single function and lakes with multifunction [4]. The functions and benefits of the lake can be viewed in terms of direct benefits, ecological functions, production results, and their specificities, such as flood and drought control, transportation route, tourism, research and education, sediment anchoring, global climate control, water and energy supply, fisheries and agriculture support, as well as habitat for various flora and fauna [3].

Currently, many lakes in Indonesia and worldwide are facing severe environmental problems, for example soil erosion and sedimentation [6-15], two natural processes that are closely related [6]. Soil erosion is the displacement of soil from its formation by causative agents, such as raindrop, runoff, wind,
and gravity, and its deposition at a depressional and/or protected site [16]. Soil erosion rates within a landscape are affected by geology, topography, slope, climate, soil type and vegetation [17]. There are four stages involve in the process of soil erosion, i.e., detachment, breakdown, transport/redistribution and deposition of sediments [16, 17]. Therefore, sediment is the product of soil erosion, whether it occurred as upland surface erosion, hillslope and gully erosion, soil mass movement/landslide, streambank erosion, and bed erosion [17]. Sediment dynamics at the catchment scale are mainly determined by climate (in particular the rain intensity), soil properties, topography, and vegetation [18]. In addition, anthropogenic factors, such as urbanization and development, forestry practices (e.g., clear-cutting, land preparation), agricultural activities (land preparation and harvesting), dam construction and operation, are considered as the leading causes of erosion and sedimentation transfer [18, 19].

Sediment accumulation adversely impacts the quality of lake ecosystem. It degrades water quality, limits the available water supply, reduces flora and fauna biodiversity, damages drains and drainage channels that increase flood risk, disrupts energy supply from hydropower plant, and impedes economic and local community efforts [6]. High rate of sediment export causes the lake becoming shallower and narrower (lake size diminishment) due to siltation [8-10, 20]. Siltation decreases the function of lake ecosystem as a natural reservoir (reducing storage capacity) and accelerates the growth of water hyacinth and leads to eutrophication [11, 21]. Increasing sediment loading to lake ecosystem affects the conservation and management of aquatic biological diversity [22].

Numerous models have been developed to simulate sediment transport at various scales. [23] provided a thorough review on the erosion/sediment transport models based on several criteria, including model output, input data, model structure, predictive accuracy, and model limitations. Generally, the models were classified into three main groups, i.e., empirical, conceptual, and physics-based models. Empirical models are the simplest models, which are based on the analysis of observation data. The models require less data and computational compared to conceptual dan physics-based models [23]. Another review on hillslope and watershed scales erosion and sedimentation transport models was provided by [24], which focus on the physically-based models. In this review, the detail characteristics of the physically-based models were explained. Recently, [25] published a review on watershed-scale water quality and nonpoint source pollution models, including models that simulate sediment. A total of 14 models were evaluated and classified into three categories based on the model complexity, i.e., simple models, medium-complexity models, and complex models. [23] stated that the most suitable model depends on the intended use and the catchment’s characteristics.

The 1st and the 2nd Indonesian Lakes National Conference (ILNC I and II), which took place in Bali and Semarang in the year of 2009 and 2011, respectively, resulted in an agreement on Sustainable Lake Management in fifteen lake ecosystems, including Lake Rawapening [3, 26]. Based on the agreement, the management and rescue of the lake ecosystem will be carried out in stages according to the severity of the damage and the impact of the damage on people’s lives [26]. In more detail, the determination of priority lakes to be immediately addressed is based on several criteria, namely: (1) the level of damage (sedimentation, pollution, eutrophication, high water quality and quantity degradation), (2) various uses of the lakes, (3) strategic value of the lakes, (4) the level of biodiversity, and (5) the level of disaster risk [3]. Considering that sedimentation is one of the main causes of lake ecosystem degradation, thus countermeasures of lake sedimentation become a super priority program of Lake Rescue Movement [13-15]. To support the implementation of the program effectively, it is important to gather information on the magnitude and the spatial distribution of sediment export at the catchment level. It needs to be carried out due to limited available resources for the implementation of lake sedimentation countermeasure program. This study aims to estimate the magnitude and the spatial distribution of sediment export from the catchment area of Lake Rawapening as one of the fifteen priority lakes.
2. Materials and Methods

2.1. Study Site
The study was conducted at the catchment area of Lake Rawapening, i.e., Rawapening Sub-watershed. Lake Rawapening is one of the fifteen priority lakes set at the 2009 INLC I in Bali [27]. This was caused by high sedimentation rate, partly triggered by the increasing residential and industrial areas in the catchment area of Lake Rawapening [8, 28]. Lake Rawapening catchment, which is upstream of the Tuntang Watershed, consists of nine sub-watersheds, namely: (1) Rengas, (2) Panjang, (3) Torong, (4) Parat, (5) Sraten, (6) Ringis, (7) Kedung Ringin, (8) Legi and (9) Galeh [27, 29]. In terms of government administration, the catchment area of Lake Rawapening covers seventy two subdistricts/villages spread over eleven districts in Semarang Regency and Salatiga City with a total area of about 27,130.59 ha [29]. The elevation ranges from 494 to 2,865 meters above sea level (masl). The map of the research location is presented in Figure 1.

Naturally, Lake Rawapening was formed through the eruption of Ungaran Tua Volcano, where basalt lava flows from the eruption blocked Kali Pening in the Tuntang area which resulted in the submergence of the Kali Pening valley [30, 31]. The valley eventually became a natural reservoir and was known as Lake Rawapening. The function of Lake Rawapening is as a barrier and reservoir for surface water flow, so that it can be used for agricultural irrigation, hydropower, raw water and water for industry, tidal paddy fields, inland fisheries, flood control in downstream areas, tourism, handicrafts, organic fertilizer from peat, and mushroom cultivation facilities [32].

2.2. Methods
The calculation of the sediment export that enters Lake Rawapening was carried out using the Sediment Delivery Ratio (SDR) sub-model, which is part of the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) model developed by the Natural Capital Project, Stanford University, University of Minnesota, the Nature Conservancy, and World Wildlife Fund [18, 33]. SDR is a spatial model that calculates the amount of sediment export to water bodies on a pixel scale according to the spatial resolution of the Digital Elevation Model (DEM) data input used. For each pixel, the SDR sub-model calculates the amount of soil eroded and the SDR, i.e., the proportion of soil loss that actually reaches the outlet. This approach was proposed by [34]. The annual soil loss was calculated using the Revised Universal Soil Loss Equation (RUSLE) approach [35].

Figure 1. Map of the study area depicting the elevation and the sub-sub watershed boundary (Rawapening Sub watershed)
2.3. Data
This study is a GIS (geographic information system) - based study using spatial and nonspatial data collected from relevant institutions and published literature. The data needed in this study is presented in Table 1.

Table 1. The data needed in the sediment export modeling using the SDR submodel

| Data                                | Source                                                                 | Remarks                                                                                      |
|-------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Digital elevation model (DEM)       | NASA-JAXA                                                              | obtained from the ALOS PALSAR RTC DEM image with a spatial resolution of 12.5 m              |
| Rainfall erosivity index (R)        |                                                                        | obtained through spatial interpolation of the kriging technique on 10-year rainfall data 2008-2017 |
| Annual rainfall                     | PuSDATARu (Pusat Sumber Daya Air dan Tata Ruang) Central Java           |                                                                                               |
| Soil erodibility (K)                | BBWS (Balai Besar Wilayah Sungai) Pemali Juana                         | based on the soil type map scale 1:250,000                                                   |
| Land cover/use                      | BPPTPDAS (Balai Penelitian dan Pengembangan Teknologi Pengelolaan Daerah Aliran Sungai) | obtained from updated RBI (Rupa Bumi Indonesia) map from BIG (Badan Informasi Geospasial) scale 1:25,000, year 2015 |
| Watershed/subwatershed boundaries   | BPDASHL (Balai Pengelolaan Daerah Aliran Sungai dan Hutan Lindung) Pemali Jratun |                                                                                               |
| Biophysical table                   | InVEST documentation                                                   | Containing:                                                                                   |
|                                     |                                                                        | a. lucode: code (integer) for each class of land cover/use according to the name of each class of cover/land use. |
|                                     |                                                                        | b. usle_c: soil cover management factor for erosion modeling, 0 to 1 in decimal format.        |
|                                     |                                                                        | c. usle_p: soil conservation factor for erosion modeling, 0 to 1 in decimal format.            |
| Flow accumulation threshold         | InVEST documentation                                                   | the minimum number of pixels flowing into a pixel to be considered as part of the river network (default value is 1000) |

2.4. Data Analysis
The data analysis in this study was based on the method of SDR sub-model [18, 33]. The total catchment sediment load/export, \( E \) (ton/ha/year), was calculated using equation 1.

\[
E = \sum E_i
\]
\( E_i \), which is the sediment load from a given pixel \( i \) (ton/ha/year) was calculated using equation 2.

\[
E_i = usle_i \times SDR_i
\]  

(2)

The amount of annual soil loss on pixel \( i \), \( usle_i \) (ton/ha/year), was estimated using RUSLE proposed by [35] as in equation 3.

\[
usle_i = R_i \times K_i \times LS_i \times C_i \times P_i
\]  

(3)

where \( R_i \) is the rainfall erosivity \((MJ \cdot \text{mm} \cdot \text{ha} \cdot \text{hr})^{-1}\), \( K_i \) is the soil erodibility \((\text{ton} \cdot \text{ha} \cdot \text{hr}(MJ \cdot \text{ha} \cdot \text{mm})^{-1}\)), \( LS_i \) is the slope length-gradient factor, \( C_i \) is the crop-management factor and \( P_i \) is the support practice factor.

The sediment delivery ratio for a given pixel, \( SDR_i \), was derived from the conductivity index (IC) following [36] as in equation 4.

\[
SDR_i = \frac{SDR_{\text{max}}}{1 + \exp \left( \frac{IC_0 - IC_i}{k} \right)}
\]  

(4)

where \( SDR_{\text{max}} \) is the maximum theoretical SDR, set to an average value of 0.8 [36], and \( IC_0 \) and \( k \) are calibration parameters that define the shape of the SDR-IC relationship (increasing function). Details on the processing steps of the SDR sub-model can be found in [18, 33].

3. Results and Discussion

3.1. Sediment export from the catchment area of Lake Rawapening

Based on the results of the analysis using the SDR sub-model, it can be observed that the total sediment export from the catchment area of Lake Rawapening is 501,628.6 tons/year. The largest export of sediment came from Galeh Sub-sub watershed, which amounted to 161,091.7 tons/year or 32.11% of the total sediment export. The other three sub-sub watersheds with high sediment exports are Panjang (127,307.9 tons/year or 25.38%), Parat (78,395.4 tons/year or 15.63%), and Legi (74,862.8 tons/year or 14.92%). Ringis Sub-sub watershed has the lowest sediment export, i.e., 1,310.9 tons/year or 0.26%. The sediment yield found in this study is much lower compared to that found by [27] and [37], i.e. 3.7 million tons in 2011 and 4.2 million tons in 2017, respectively. Difference in method used to estimate the sediment export contributes to the large discrepancy of the results. Sediment exports for each sub-sub watershed are presented in Figure 2.

![Figure 2](image-url)
Based on the area of each sub-sub watershed, the largest average of sediment export came from Legi Sub-sub watershed, i.e., 42.93 tons/ha/year, followed by Panjang and Galeh sub-sub watersheds with an average of 28.30 and 27.76 tons/ha/year, respectively. The high values of sediment export in these sub-sub watersheds generally occur in the upstream area with very steep slopes, high rainfall, and dominated by dryland agriculture or vegetables farm lands. Ringis Sub-sub watershed with a flat terrain condition and land covers dominated by irrigated paddy fields, settlements, and gardens has the lowest average of sediment export, i.e., 0.91 ton/ha/year. Variation of sediment exports at the catchment area are affected by natural factors, such as climate (in particular rainfall intensity), soil properties, topography and vegetation, as well as anthropogenic factors such as agricultural activities [18, 19]. In this case, land covers and soil properties determine the amount of soil erosion produced and the ability of sediment retention. Land cover changes within catchment area determine the temporal dynamics of sediment rate that enter lake body [6, 8, 27, 28]. Increasing the extent of land cover with low sediment retention capacity will increase the sediment export to lake ecosystem. On the contrary, it was reported that conversion from agricultural land to forest land, which has higher sediment retention capacity, decreased the sedimentation rate by 88.28% [6]. The average of sediment export in each sub-sub watershed can be seen in Figure 3. The land cover/use classes in the catchment area of Lake Rawapening is presented in Figure 4.

Figure 3. Average of sediment export for each sub-sub watershed in the catchment area of Lake Rawapening

Figure 4. The land cover/use classes in the catchment area of Lake Rawapening
3.2. Spatial Distribution of Sediment Export from The Catchment Area of Lake Rawapening

Based on the results of the analysis, the catchment area of Lake Rawapening has sediment export values ranging from 0 to 274.16 tons/pixel/year (0 to 17,546.24 tons/ha/year) with an average value of about 0.29 ton/pixel/year or 18.6 tons/ha/year (pixel size 12.5 m x 12.5 m). The distribution of sediment exports in the catchment area of Lake Rawapening is dominated by low export values (Figure 5). This is because the catchment area of Lake Rawapening is dominated by mixed private forest, paddy fields, and settlements that have low soil erosion. High sediment exports mainly occurred on upstream land with steep slope and high rainfall intensity which are utilized for vegetable farm and dryland agriculture. These type of land uses involve land preparation process and yield harvesting that expose the soil to rainfall and lead to soil erosion. In addition, high sediment export also occurred on upstream shrublands with sparse vegetation cover and close to stream. Apart from being determined by the land cover class (which determines the magnitude of erosion and retention capacity), the amount of sediment export is also determined by the distance to the stream network [17]. Erosion sources close to rivers will have relatively higher export values because the chances of being retained by land cover are lower in relation to time travel of sediment load to stream. Thus, the sediment load will be rapidly flowed into the river to the lake body. The spatial distribution of sediment exports in the catchment area of Lake Rawapening is presented in Figure 5.

![Spatial distribution of sediment exports in the catchment area of Lake Rawapening](image)

4. Conclusion

Erosion and sedimentation due to degradation of the catchment area have caused a serious problem to Lake Rawapening. High sedimentation rate that enters Lake Rawapening creates siltation that reduce the functions and benefits of Lake Rawapening and shorten its lifetime. Eventually, it will negatively impact the peoples who depend on the existence and services of Lake Rawapening. Therefore, efforts should be undertaken to overcome the erosion and sedimentation problems. Considering that vegetable farm and dryland agriculture at the upstream area contribute high sediment export, it is important to provide agricultural extension services to farmers to raise their awareness related to application of soil and water conservation measures. Government resources for countermeasures of lake sedimentation should be allocated to hot-spot areas, such as Legi Sub-sub watershed which has high sedimentation export per unit area.
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