The impact of land-use change on Cengklik Reservoir’s sedimentation rate

Purwanti Sri Pudyastuti*, Annisa Fathi Yakan, Jaji Abdurrosyid, Hermono S Budinetro

Civil Engineering Study Program, Faculty of Engineering, Universitas Muhammadiyah Surakarta, Jl. A. Yani, Tromol Pos I, Pabelan, Kartasura, Surakarta, Indonesia 57102
E-mail: *psp237@ums.ac.id

Abstract. The Cengklik Reservoir is operated for irrigation of rice fields in 3 sub-districts in Boyolali Regency, namely Sambi, Ngemplak, and Nogosari. At the present time, the volume of the Cengklik Reservoir has decreased and resulted in dryness during the dry season. One of the main causes is due to the high sedimentation rate. This research was conducted to evaluate changes in land use that resulted in sedimentation in the Cengklik Reservoir. Erosion prediction in this study uses USLE (Universal Soil Loss Equation) analysis. The amount of sediment obtained uses the standard erosion data from USLE calculations, namely by multiplying the amount of erosion by the SDR and the area of River Basin. The potential for erosion and sedimentation used land use data for 10 years, from 2009 to 2019. Based on the research, the amount of erosion and sedimentation in the Cengklik Reservoir was fluctuated with the highest amount occurring in 2016, with erosion of 9,292 tones/ha/year and sedimentation of 4304,154 tons/year. In general, erosion and sedimentation have increased from 2009 to 2019. The classification of erosion in the Cengklik Reservoir according to this study was categorized as light erosion. The trap efficiency used in this study was calculated using formulae based on the research of Heinemann (1981) using the Brune method for small reservoirs with an area of less than 0.5 km². In general, based on this study, the Trap Efficiency in Cengklik Reservoir was 95.254%.

1. Introduction

Land use change can affect the natural balance. The decreasing of green open space due to deforestation and land use change along with high rainfall intensity can trigger the losses of soil due to erosion. The soil losses due to soil erosion then will be conveyed by rain water and flowing into the river basin that can cause sedimentation in water bodies such as reservoir, lake, and river.

Cengklik Reservoir was built in 1926 until 1928 by Pura Mangkunegara and the Dutch colonial government. In the beginning, this reservoir functioned for the irrigation of Pura Mangkunegara rice fields. Today, the volume of water that can be stored in Cengklik Reservoir is decreasing. In 1970, the Cengklik Reservoir was able to accommodate a water volume of 12.7 million m³, but in March 2019, the volume of water that could be accommodated was only 1,483,100 m³. Thus, at the end of 2019, the Cengklik Reservoir has lost 87.64% of the volume of water since it was built. The impact due to the reduced capacity of Cengklik Reservoir water is that the irrigation is not optimal for thousands of hectares of rice fields in 3 districts namely Sambi,
Ngemplak, and Nogosari districts until the most pronounced impact is stopping the operation of Pura Mangkunegara Sugar Factory due to the lack of water supply for sugar cane plants.

This study aims to identify changes in land use to sedimentation rates. Land use that changes over time can affect the rate of sedimentation, for example in December 2018, most of the buffer zone turned into arid land, with a reservoir volume at that time of 3 million m$^3$ with the previous 2017 Cengklik Reservoir able to accommodate as much water 5.3 million m$^3$. This condition is exacerbated by limited dredging activity, that is only done once since it was built.

2. Research method

The study was conducted by analyzing secondary data obtained from related institutions such as Bengawan Solo River Basin Organization, local statistical bureau, and local environmental board in Boyolali District, Central Java, Indonesia. The secondary data required in this study were included topographical map, land slope map, rainfall data, reservoir capacity data, inflow data, and land use data. The rainfall data used in this study was the daily rainfall data from Cengklik reservoir rain gauging station in years 2009 – 2019. This study analyzed the soil erosion rate, sedimentation rate, and trap efficiency based on the data available. The approaches applied to analyze the data is described below.

2.1. Soil erosion rate

The rate of soil erosion was predicted using USLE (Universal Soil Loss Equation) method which has been widely used worldwide [1–15]. The USLE formula was developed by the USDA Agricultural Research Service in cooperation with USDA Soil Conservation Service [11] as shown in the equation below:

$$ A = R \cdot K \cdot L_S \cdot C \cdot P $$

(1)

$A =$ erosion (ton/ha/year), $R =$ rain erosivity factor (Kj/ha) = EI30, $K =$ soil erodibility factor, $L_S =$ length-slope factor, $C =$ crop management factor, and $P =$ erosion control practice factor.

Rain erosivity (EI30) is calculated using the formulae below:

$$ EI30 = 6.21(Rain)^{1.21} \times (Days)^{-0.47} \times (max \cdot Rain)^{0.53} $$

(2)

Rain $=$ rainfall during the month (cm), Days $=$ the number of rainy days in the month, max.Rain $=$ maximum daily rain for the month (cm), The value soil erodibility factor is presented in Table 1, and the soil type map is shown in Figure 1.

| No. | Soil Classification          | K    |
|-----|------------------------------|------|
| 1   | Latosol (Inceptisol Oxic Subgoup) | 0.04 |
| 2   | Reddish yellow Mediteran (Alfisol) | 0.13 |
| 3   | Mediteran (Alfisol)           | 0.21 |
| 4   | Reddish yellow Podsolik (Ultisol) | 0.15 |
| 5   | Regosol (Inceptisol)          | 0.11 |
| 6   | Grumusol (Vertisol)           | 0.24 |
| 7   | Alluvial                      | 0.15 |

The length-slope factor ($L_S$) is determined using the Table 2 below.

In addition, the crop management factor ($C$) and erosion control practice factor ($P$) are determined based on Table 3 below.

The erosion criteria is defined based on Table 4.
Table 2: Slope Factor [8]

| Class | Slope (%) | LS value |
|-------|-----------|----------|
| I     | 0-8       | 0.40     |
| II    | 8-15      | 1.40     |
| III   | 15-25     | 3.10     |
| IV    | 25-40     | 6.80     |
| V     | >40       | 9.50     |

Table 3: $C$ value and $P$ value for various land uses [8]

| Land Use   | C   | P   |
|------------|-----|-----|
| Rice Field | 0.05| 0.02|
| Building   | 0.3 | 0.15|
| Fields     | 0.45| 0.25|
| Plantation | 0.45| 0.25|
| Forest     | 0.02| 0.6 |
| Body of water | 0  | 0   |
Table 4: Erosion Criteria [8]

| No. | Erosion (ton/ha/year) | Level | Criteria     |
|-----|-----------------------|-------|--------------|
| 1   | <15                   | I     | Very light   |
| 2   | 15-60                 | II    | Light        |
| 3   | 60-180                | III   | Medium       |
| 4   | 180-460               | IV    | Heavy        |
| 5   | >460                  | V     | Very heavy   |

2.2. Sedimentation
Sedimentation is the result of erosion processes, whether in the form of surface erosion, trench erosion, or other types of erosion. The result of sediment is the amount of erosion that occurs in the catchment area which is measured at a certain time and place [1, 2]. The sedimentation can be predicted based on the erosion value using equation below:

\[ Y = E(\text{SDR})W_s \]  

\[ Y = \text{Sedimentation}, \text{SDR} = \text{Sediment Delivery Ratio}, \text{and } W_s = \text{the area of river basin}. \]

2.3. Trap Efficiency
To calculate the percentage of the amount of sediment left behind, it can be calculated using the method by [12, 13].

\[ T_E = \frac{-22 + \frac{199.6 \times C}{0.012 + 1.02 \times I}}{2} \]  

\[ T_E = \text{trap efficiency}, C = \text{reservoir capacity, and } I = \text{inflow}. \]

3. Result and discussion
Soil erosion is predicted using USLE method which consists variables i.e. rainfall erosivity, soil erodibility, length-slope factor, land cover, and land conservation factor. The component that used in rainfall erosivity calculation are maximum rainfall data, rainfall day, and average rainfall. The rainfall data used for calculation was the rainfall data from Cengklik reservoir rain gauging station in years 2009 - 2019. The result of the rainfall erosivity factor is presented in Table 5.

Table 5: Rainfall Erosivity in Cengklik Reservoir Catchment Area

| Year | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|------|------|------|------|------|------|------|------|------|------|------|------|
| Rainfall Erosivity (kJ/ha) | 38.61 | 53.72 | 95.95 | 112.67 | 150.01 | 92.67 | 56.51 | 370.13 | 211.45 | 59.24 | 118.75 |

Based on Figure 1, the majority of soil composition at Cengklik Reservoir catchment area is dark grey grumusol and reddish brown mediteran. That type of soil, based on Table, has soil erodibility factor 0.45.

Furthermore, for the slope factor, the analysis needs to look at the slope map first and then pairing the slope data from slope map with the slope data from table 2 to know the value of the slope factor. the slope in Sambi sub-district area colored with dark blue, light blue and also has little yellow category. Then the slope is around less than 2% until 15%, with dominant slope around 2 - 8%. Based on the slope factor table above, with the slope around 2 – 8% then LS value is 1.40.
For the crop management factor (C) and erosion control practice factor (P), the analyses was based on the land use data from the Boyolali Statistical Board. There are some land use data type in this research, namely rice field, building, fields, meadow, forest, and water body. Table 6 below is presented the summary of soil erosion calculation using USLE method and the sedimentation in Cengklik Reservoir. From the calculation, the average trap efficiency in Cengklik Reservoir is 95.254.

| Year | Total Area (Ha) | Erosion (ton/year) | Total Erosion (ton/ha/year) | Class | Sedimentation (Y) |
|------|----------------|--------------------|-----------------------------|-------|-------------------|
| 2009 | 4480.6         | 3490.17            | 0.7790                      | very light | 360.804           |
| 2010 | 4480.6         | 4856.24            | 1.0840                      | very light | 502.024           |
| 2011 | 4480.6         | 8673.59            | 1.9360                      | very light | 896.651           |
| 2012 | 4480.6         | 10185.00           | 2.2730                      | very light | 1052.896          |
| 2013 | 4480.6         | 13556.70           | 3.0260                      | very light | 1401.452          |
| 2014 | 4479.6         | 8374.51            | 1.8690                      | very light | 865.925           |
| 2015 | 4479.6         | 5106.56            | 1.1400                      | very light | 528.019           |
| 2016 | 4479.6         | 33449.60           | 7.4670                      | very light | 3458.695          |
| 2017 | 4480.6         | 19109.58           | 4.2650                      | very light | 1975.492          |
| 2018 | 4480.6         | 5354.03            | 1.1950                      | very light | 553.484           |
| 2019 | 4340.97        | 10243.93           | 2.3600                      | very light | 1093.049          |

![Erosion and Sedimentation in Cengklik Reservoir (2009 - 2019)](image)

**Figure 2:** The relation between soil erosion and sedimentation in Cengklik Reservoir

4. Conclusion and suggestion
Based on the analysis of this study, it can be concluded that: Effect of the land use change can influence the erosion and sedimentation rates. It can be seen in the USLE calculation. From the USLE calculation, it gave result that: The erosion of Cengklik Dam was fluctuating, with the highest value in 2016, that is 7.467 ton/ha/year and the lowest value was 0.779 ton/ha/year which occurred in 2009. The sedimentation based on the erosion value was also fluctuating, with the highest value in 2016, that was 3458.695 ton/year and the lowest value was 449.00 ton/year in 2009. Total sedimentation from 2009 until 2019 is 12688.491 ton/year Trap Efficiency in Cengklik dam is 95.254% based on the Brune Method for small reservoir calculation. This study
has limited land use data, therefore for better further research, it is suggested that the complete land use map and data should be provided.

Acknowledgments
The authors would like to thanks Universitas Muhammadiyah Surakarta for giving support and funding therefore the study could be conducted and published.

References
[1] Alie, Misy Efrodina R. 2015. Kajian Erosi Lahan Pada DAS Dawas Kabupaten Musi Banyuasin – Sumatera Selatan.
[2] Asdak, Chay. 2001. Hidrologi dan Pengelolaan Daerah Aliran Sungai. Yogyakarta : Gadjah Mada University Press
[3] Cahyono B K et al. 2017 Perhitungan Kecepatan Sedimentasi Melalui Pendekatan USLE dan Pengukuran Kandungan Tanah dalam Air Sungai yang Masuk ke Dalam Waduk Sermo
[4] El Jazouli et al. 2017 Soil erosion modeled with USLE, GIS, and remote sensing: a case study of Ikkour watershed in Middle Atlas (Morocco). Geosci. Lett. (2017) 4:25. https://doi.org/10.1186/s40562-017-0091-6
[5] Falcao C J L M et al 2019 Estimating potential soil sheet Erosion in a Brazilian semiarid county using USLE, GIS, and remote sensing data. (Environ Monit Assess 2020 192: 47) https://doi.org/10.1007/s10661-019-7955-5.
[6] Febrianingrum N D et al (no date) Pengaruh Perubahan Penggunaan Lahan Terhadap Sedimen di Sungai Lesti.
[7] Li, Jian, et al. 2017. Estimating the Sediment Trap Efficiency and Lifespan of Cascaded Reservoirs in the Upper Yangtze River Basin , China.
[8] Mahawati F I et al. 2015 Sedimentasi di DAS Bah Bolon Akibat Tata Guna Lahan.
[9] Marhendi, Teguh, et al. 2018 Prediksi Peningkatan Sedimentasi dengan Metode Angkutan Sedimen (Studi Kasus Sedimentasi Di Waduk Mrica).
[10] Mulu A and Dwarakish G S 2015 Different Approach for Using Trap Efficiency for Estimation of Reservoir Sedimentation. An Overview (Aquatic Procedia 4 2015 847 – 852) https://doi.org/10.1016/j.aqpro.2015.02.106
[11] Ponce V M 1989 Engineering Hydrology Principles and Practices (New Jersey: Prentice Hall) p 538
[12] Revel N M T K et al 2015 Estimation of Sediment Trap Efficiency in Reservoirs -An Experimental Study- ENGINEER - Vol. XLVIII, No. 02, pp. 43-49 (The Institution of Engineers, Sri Lanka)
[13] Sarminingsih A 2018 Kajian Perubahan Tataguna Lahan Terhadap Tingkat Bahaya Erosi di DAS Dengkeng
[14] Simons, Daryl B and Fuat Sentruk. 1977 Sediment Transport Technology. USA : Water Resources Publication
[15] Utami A K et al 2019 Kajian Sedimentasi pada DAS Sail Pekanbaru dengan menggunakan SIG dan Metode USLE