Analysis of erosion and sedimentation in predicting the life time of the Cieunteung Retention Basin

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Abstract. The high rates of erosion and sedimentation as the impacts of changes in land use cause the problem of sedimentation. The aim of this research is to analyse erosion and sedimentation in the Upper Citarum sub-basin, which will impact the life time of the Cieunteung retention basin. The SWAT model was used to simulate the hydrological process and erosion mechanism by using the formula of MUSLE. Based on the results of simulation data, the highest average erosion equalled 1,094 tons/ha/year in 2013 while the lowest average erosion equalled 71.16 tons/ha/year in 2009. The results of SWAT model calibration in 2008-2018 were $R^2 = 0.89$ and $NS = 0.95$, which means the model performance is categorized as very good. The simulation results showed the anticipative indicators of watershed disaster, as the erosion hazard index in terms of land cover and the coefficient of river regime in terms of water availability, have a very close relationship and positive correlation with the average of $R^2 = 0.8$. The incoming sediment to the Cieunteung retention basin is 105,418 ton/year or 72,551.961 m$^3$/year. By using sediment trap efficiency with a value of 4.37%, this research estimated that the dead storage capacity of 113,670.3 m$^3$ will be filled with sediments in 35.87 years. Furthermore, the long-term retention basin conservation effort by land terracing can reduce total sediments by 22% to 81,948 tons in 2018, and thus the life time of the Cieunteung retention basin becomes 46.15 years.

Keywords: erosion, sedimentation, SWAT model, retention basin, life time of retention basin.

1. Introduction

The Cieunteung retention basin has the roles of reducing flooding in Bandung Regency and supplying raw water to the City of Bandung. Aside from its important role for human life, the high rates of erosion and sedimentation at the Upper Citarum basin impact the volume of incoming sediment to the retention basin, which will disrupt retention in the basin. Land conservation at the Upper Citarum sub-basin, as an effort to reduce the rate of erosion and sedimentation, needs to be performed to increase the life time of the Cieunteung retention basin.

The objective of this study is to analyse the life time of Cieunteung retention basin based on sedimentation using the SWAT model. The SWAT model was chosen because the model can simulate with limited applicable data, especially for a large watershed. This paper also discusses the correlation...
between the erosion hazard index cover and the coefficient of river regime for each watershed in the Upper Citarum.

2. Material and Methods

2.1 Erosion

“Erosion is performed by ice, water, wind, or gravity. Erosion happens when rains, runoff, or floods flowed and the soil particles are picked up and moved. The types of erosion are sheet and rill erosion, tunnel erosion, and streambank erosion” [1].

The simulation of an erosion using the SWAT model is with the Modified Universal Soil Loss Equation (MUSLE):

\[
S_{ed} = 11.8 \cdot (Q_{surf} \cdot Q_{peak} \cdot \text{area}_{hru})^{0.56} \cdot k_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot L_{SUSLE} \cdot C_{FRG}
\]  

(1)

where \(S_{ed}\) is soil erosion load (metric tons), \(Q_{surf}\) is surface runoff volume (millimetre of water per hectare), \(Q_{peak}\) is peak runoff rate (cubic metre per second), \(\text{area}_{hru}\) is HRU area (hectare), \(k_{USLE}\) is the soil erodibility factor, \(P_{USLE}\) is the support practice factor, \(C_{USLE}\) is the cover and management factor, \(L_{SUSLE}\) is the topographic factor, and \(C_{FRG}\) is the coarse fragment factor [2].

2.2 Sedimentation

Strand & Pemberton (1982) stated that “Factors that determine sediment yield in a catchment area are the volume and intensity of rainfall, geology formation and soil type, land cover, topography, erosion at the upstream area, runoff; characteristics of sediments such as size of sediment particles and characteristics of the hydraulic channel” [3].

2.3. Watershed

According to Minister of Public Works and Housing Regulation No.02/PRT/M/2013, “Watershed is a land area that is an integral part of a river and its tributaries, which has the functions to collect, store, and channel water from rain to the lakes or to the sea naturally. Its boundary on land is the topography separator and its boundary in the sea is waters that are still impacted by land activities” [4].

2.4. Retention Basin

According to Minister of Public Works and Housing Regulation No.12/PRT/M/2014, “Retention basin is a drainage infrastructure to collect and absorb rainwater in an area” [5].

2.5. SWAT Model

“SWAT is a river basin, or watershed, scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long period of time. The model is physically based on computational efficiency, uses readily available inputs and enables users to study long-term impacts”[2]. “SWAT uses two phases for simulation of hydrology. The first phase is the land phase where the land phase controls the amount of water, sediment, nutrients, and pesticides and the routing phase that moves towards the main channel in each sub-watershed. The second phase is the routing phase that defines the movement of water, sediment, and so on through the channel network of the watershed into the outlet” [2].

2.6. SWAT Model Calibration Techniques

“During the calibration process, model parameters were subjected to adjustments, in order to obtain model results that correspond better to the measured datasets. The goodness-of-fit between the simulated and measured runoff and sediment yields was evaluated using the coefficient of determination (R²) and the Nash-Sutcliffe coefficient of efficiency” [6].
\[
NS = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{cal})^2}{\sum_{i=1}^{n}(Q_{obs} - \bar{Q}_{obs})^2}
\]  
(2)

Here, \(NS = \) the Nash-Sutcliffe efficiency of the model; \(Q_{obs}\) and \(Q_{cal}\) = the observed and simulated values, respectively; and \(\bar{Q}_{obs}\) = the average observed value.

\[
R^2 = \left[ \frac{\sum_{i=1}^{n}(Q_{obs} - \bar{Q}_{obs})(Q_{cal} - \bar{Q}_{cal})}{\sqrt{\sum_{i=1}^{n}(Q_{obs} - \bar{Q}_{obs})^2 \sum_{i=1}^{n}(Q_{cal} - \bar{Q}_{cal})^2}} \right]^2
\]  
(3)

Here, \(Q_{obs}\) = the observed data; and \(\bar{Q}_{obs}\) = the average observed data; \(Q_{cal}\) = simulated data and \(\bar{Q}_{cal}\) = the average of simulated data.

2.7. Erosion Hazard Index

Erosion hazard index was obtained by dividing the actual value of erosion with the allowable erosion value (T) in that area.

\[
IE = \frac{E}{TSL}
\]  
(4)

Here, \(IE = \) Erosion hazard index; \(E = \) actual value of erosion rate (tons/ha/year); \(TSL = \) allowable value of erosion (tons/ha/year).

| No | Level of Erosion | Erosion Hazard Index |
|----|------------------|----------------------|
| 1  | Low              | IE ≤ 1.0             |
| 2  | Moderate         | 1.0 < IE ≤ 4.0       |
| 3  | High             | 4.0 < IE ≤ 10.0      |
| 4  | Very high        | IE > 10.0            |

Source: Arsyad (2010) [7]

2.8. Coefficient of River Regime

“Coefficient of River Regime is a comparison between maximum discharge \(Q_{max}\) and the minimum discharge \(Q_{min}\) in a sub-watershed” (Directorate-General regulation related to forestry sector, 2009) [8].

\[
KRS = \frac{Q_{max}}{Q_{min}}
\]  
(5)

Here, \(Q_{max} = \) average of maximum daily discharge in a year (m³/s); \(Q_{min} = \) average of minimum daily discharge in a year (m³/s).

| No | Condition of watershed | Coefficient of River Regime |
|----|-------------------------|-----------------------------|
| 1  | Healthy                 | <50                         |
| 2  | Moderate                | 50-120                      |
| 3  | Bad                     | >120                        |

Source: Ministry of Forestry Decree No. P.04/V-SET/2009
2.9. Sediment Trap efficiency

According to the Bureau of Reclamation, “Trap efficiency is defined as the ratio of deposited sediment to the total sediment inflow, which depends upon the falling velocity of various sediment particles, water flow velocity of reservoir, and size, depth, operation system, and form of a reservoir”.

\[ \eta = 100 \left( 1 - 1(1 + ax) \right)^n \]  
(6)

Where:
- \( \eta \) = Trap efficiency (%);
- \( x \) = Ratio of reservoir capacity to water inflow discharge;
- \( a \) = constant, \( a = 100 \), the average, \( a = 65 \), the minimum, \( a = 130 \), the maximum;
- \( n \) = constant, \( n = 1.5 \), the average, \( n = 2.0 \), the minimum, \( n = 1.0 \), the maximum [9].

2.10. Life time of Reservoir Estimation

To estimate the life time of a reservoir, the following empiric equation (Linsley & Franzini, 1979) is utilized:

\[ T = \frac{V}{(L \cdot S \cdot E)} \]  
(7)

Where:
- \( T \) = Life time of reservoir (years);
- \( V \) = dead storage capacity (m³);
- \( L \) = Area of watershed (km²);
- \( S \) = Erosion intensity = Vs/L; \( Vs \) = The volume of sediment passing through reservoir (m³/year);
- \( Ws \) = The amount of sediment passing through reservoir (ton/years);
- \( \gamma_s \) = Bulk density of sediment (tons/m³);
- \( E \) = sediment trap efficiency of reservoir (%)

2.11. Land Conservation Effort

The following are the methods of land conservation that can be implemented as alternative conservation for long-time periods:

1) Strip Cropping
2) Contour Cropping
3) Terracing

“Terracing is applied by reducing the slope length of land so that it can hold water until it seeps into the soil. Terracing also can reduce both the amount and velocity of water moving across the soil surface and increase water infiltration so that soil loss due to water erosion can also be reduced”. (Arsyad, 2010). Types of terraces include level terraces, ridge terraces, contour terraces, and bench terraces.

2.12 Data Collection

This quantitative research needs secondary data obtained from related institutions, which include:

1. Digital elevation model
2. Land use/cover data
3. Soil data
4. Observed AWLR data
5. Weather data (Rainfall and Climatology)
6. Water level elevation of Cieunteung retention basin
7. Technical data of Cieunteung retention basin
8. River network and watershed boundary map

3. Results and Discussion

3.1 Location of the Research

3.1.1 Upper Citarum Basin. The catchment area of the Upper Citarum basin is located in the Province of West Java. It is geographically located at 6° 42’ 46” – 7° 14’ 43” SL and 107° 22’ 37” – 107° 57’ 19” EL.

3.1.2 Cieunteung Retention Basin. The project of this retention basin is located in Baleendah Sub-District, Bandung Regency and geographically located at 6° 59’ 31.98” SL and 107° 37’ 37.04” EL.
In this step, the process begins with delineating the watershed, determining the stream digitation process, and defining AWLR at Dayeuhkolot as the main outlet from stream channel outlets. Topography was defined by a DEM from DEMNAS with a resolution of 8.33 m that describes the elevation of any point in a given area at a specific spatial resolution. UTM 1984 map projection was used for zone 48, and WGS 1984 was the reference datum. Then, the DEM was converted into the ASC file format and clipped using Upper Citarum Basin boundaries. Next, the DEM was imported into SWAT. The results of Upper Citarum sub-basin delineation is 19 sub-sub-basins, as presented in Figure 3 and Table 4.

3.2 SWAT Operation Model

Watershed Delineation. In this step, the process begins with delineating the watershed, determining the stream digitation process, and defining AWLR at Dayeuhkolot as the main outlet from stream channel outlets. Topography was defined by a DEM from DEMNAS with a resolution of 8.33 m that describes the elevation of any point in a given area at a specific spatial resolution. UTM 1984 map projection was used for zone 48, and WGS 1984 was the reference datum. Then, the DEM was converted into the ASC file format and clipped using Upper Citarum Basin boundaries. Next, the DEM was imported into SWAT. The results of Upper Citarum sub-basin delineation is 19 sub-sub-basins, as presented in Figure 3 and Table 4.
Table 3. Sub-sub basins by SWAT delineation

| Sub-Sub CA | Area (ha) | Sub-Sub CA | Area (ha) |
|------------|-----------|------------|-----------|
| 1          | 5727.14   | 11         | 4487.97   |
| 2          | 11415.52  | 12         | 18618.75  |
| 3          | 33.24     | 13         | 5208.22   |
| 4          | 86.27     | 14         | 479.65    |
| 5          | 16.61     | 15         | 3919.10   |
| 6          | 14518.88  | 16         | 770.80    |
| 7          | 290.11    | 17         | 9465.24   |
| 8          | 4125.58   | 18         | 23406.64  |
| 9          | 6110.92   | 19         | 20581.90  |
| 10         | 4029.31   |            |           |
| Sub CA     |           | 133291.8   |

**Hydrology Response Unit (HRU).** It is known that the soil, land use, and topography influence evapotranspiration, infiltration, surface flow, interflow, and groundwater in all river basins; additionally, they are dynamic variables causing HRU changes from time to time. The results of the overlay process described land use (Fig. 4a), soil type distribution (Fig. 4b) and slope in each area of the basin (Fig. 4c). HRU distribution in the ARCSWAT 2012 toolbar was executed to process the Hydrology Response Unit distribution from each area of the basin until the table database is created. In this study, multiple HRUs with 0% land use, 0% soil, and 0% slope thresholds were used. The 19 sub-sub basins were further divided into a total of 1271 HRUs. Characteristics of sub-catchment and HRUs were calculated and used in the SWAT simulation.

![Figure 4. Distribution of areas: (a) HRU of land use, (b) HRU of soil type, (c) HRU of slope](image)

**Weather Data.** The data of rainfall and climatology are required by the SWAT model for finding the hydrological balance. The data were obtained from 8 rainfall gauges that are located within the basin (Table 4), covering the period from January 2005 to December 2018. The daily weather data were prepared in the appropriate file format, as a DBF database file that is required by the model, and imported into the model.

**Running SWAT.** The SWAT program was executed from 1-1-2015 until 31-12-2018 on a monthly basis. The first three years of the modelling period were used as NYSKIP as a “model warm-up”.
Table 4. Data of weather gauges

| No | Gauges                  | Time periods |
|----|-------------------------|--------------|
| 1  | 701075                  | 2005-2014    |
| 2  | 701078                  | 2005-2014    |
| 3  | Dago-Pakar (701079)     | 2005-2018    |
| 4  | Cibiru (701080)         | 2005-2018    |
| 5  | Rancaekek (701081)      | 2005-2018    |
| 6  | Pasir Jambu (701082)    | 2005-2018    |
| 7  | Cipaku-Paseh (701083)   | 2005-2018    |
| 8  | Cibeureum (701084)      | 2005-2018    |

Visualization of result data. The results of simulation of monthly data using time-series datasets from 2008 to 2018 showed that the maximum discharge was 373 m$^3$/s while the minimum discharge was 5.385 m$^3$/s. By comparing the simulation flow data with the observed AWLR data at Dayeuhkolot using the SWAT Calibration Helper, the results showed that the determination coefficient ($R^2$) value equalled 0.01 and NS equalled -33.87. Based on those values, the model was categorized as unacceptable and needed to be calibrated.

Calibration of the SWAT Model. Data for the period from 2008 to 2018 were used for calibration. Model parameters were subjected to adjustments with the fitted value, in order to obtain a close agreement of the average monthly simulated and measured values. The model adequately predicted for this study area during calibration, with $R^2$ and NS values of 0.89 and 0.95. This means that the simulated monthly data matched well with measured monthly data and the model is categorized as very good.

3.3 Erosion Hazard Index and Coefficient of river regime

Erosion Hazard Index and coefficient of river regime were estimated in each of the 19 sub-basins of the Upper Citarum. 30 tons/ha/year was chosen as the tolerable erosion value for estimating erosion index, because the soil layer of the Upper Citarum sub-basin is more than 90 cm in depth. Erosion hazard index was categorized based on the result of erosion rate.

Before determining the coefficient of river regime, the maximum and minimum discharge values in a year (m$^3$/s) needed to be obtained for each of the 19 sub-sub basins. The correlation between these two parameters of anticipative indicators of watershed disaster has a very close relationship, with a positive correlation and an average of $R^2$ = 0.8 in the period of time from 2008 to 2018. This means that as the value of the erosion hazard index increases, this is be followed by an increase in the coefficient of river regime and vice versa. This can happen because the two parameters for watershed...
disaster indicator, in terms of land cover and water availability, are equally affected by the amount of surface runoff.

Table 5. The values of erosion hazard index (IBE) and coefficient of river regime (KRS)

| Sub-sub basin | Erosion Rate (tons/ha/yr) | IBE | Criteria | Discharge (m³/s) | KRS | Condition |
|---------------|---------------------------|-----|----------|-----------------|-----|-----------|
|               |                           |     |          | Q_max | Q_min |       |           |
| 1             | 87.78                     | 2.93| Moderate | 14.16 | 0.323 | 43.89  | Healthy  |
| 2             | 108.21                    | 3.61| Moderate | 28.24 | 0.602 | 46.94  | Healthy  |
| 3             | 16.48                     | 0.55| Low      | 42.47 | 1.904 | 22.31  | Healthy  |
| 4             | 2.55                      | 0.08| Low      | 186.2 | 7.137 | 26.09  | Healthy  |
| 5             | 22.65                     | 0.76| Low      | 100.4 | 1.625 | 61.78  | Moderate |
| 6             | 1.41                      | 0.05| Low      | 25.2  | 1.075 | 23.44  | Healthy  |
| 7             | 8.81                      | 0.29| Low      | 128.8 | 6.005 | 21.45  | Healthy  |
| 8             | 6.61                      | 0.22| Low      | 8.776 | 0.375 | 23.43  | Healthy  |
| 9             | 82.26                     | 2.74| Moderate | 119.3 | 2.631 | 45.34  | Healthy  |
| 10            | 56.96                     | 1.90| Moderate | 11.93 | 0.761 | 15.68  | Healthy  |
| 11            | 34.65                     | 1.16| Moderate | 24.47 | 0.266 | 92.17  | Moderate |
| 12            | 0.63                      | 0.02| Low      | 15.8  | 1.007 | 15.69  | Healthy  |
| 13            | 51.90                     | 1.73| Very high | 124.7 | 3.653 | 34.14  | Healthy  |
| 14            | 7.80                      | 0.26| Very high | 82.75 | 1.581 | 52.34  | Moderate |
| 15            | 8.79                      | 0.29| Very high | 6.01  | 0.573 | 10.49  | Healthy  |
| 16            | 0.59                      | 0.02| Low      | 99.45 | 1.886 | 52.72  | Moderate |
| 17            | 971.02                    | 32.37| Very high | 33.47 | 0.23  | 145.78 | Bad      |
| 18            | 557.22                    | 18.57| Very high | 80.99 | 0.76  | 106.58 | Bad      |
| 19            | 625.79                    | 20.86| Very high | 70.15 | 0.502 | 139.74 | Bad      |

Figure 6. Correlation between the erosion hazard index (IBE) and coefficient of river regime (KRS) in 2018 with $R^2 = 0.758$ and the equation $KRS = 33.14 + 3.96$ (IBE).
3.4 Estimating the life time of the Cieunteung retention basin

The life time of Cieunteung retention basin was estimated based on the data from 2018.

- Dead storage capacity (C) = 113,670.3 m$^3$ (Total volume form elevation +653.7 masl to +656.2 masl)
- Inflow discharge (Iw) = 10.26 m$^3$/s (31536000s) = 32359360 m$^3$
- C/Iw = 113,670.3/32359360 = 3.51 (10$^{-4}$)

Thus, the calculation of trap efficiency is:

$$\eta = 100 \left(1 - \frac{1}{1+ax}\right)^n$$

$$= 100 \left(1 - \frac{1}{1+(130 \times 0.000586)}\right)^1$$

$$= 4.37\%$$

The length of the life time of the retention basin is determined by the time it takes for the dead storage capacity to be filled with sediments. Based on simulation data from SWAT, the amount of sediments entering sub-sub basin 7 (the location of the Cieunteung retention basin) was obtained from the results of SED_OUT in the RCH file.

With a bulk density of 1.453 ton/m$^3$, the volume of sediments is:

$$Q_s = \frac{\text{debit sedimen (tons/year)}}{\text{Bulk Density (tons/m$^3$)}} = \frac{105418 \text{ tons/year}}{1.453 \text{ tons/m}^3} = 72551.961 \text{ m}^3/\text{years}$$

$$T = \frac{V}{Q_s \times \eta} = \frac{113670.3 \text{ m}^3}{72551.961 \left(\frac{\text{m}^3}{\text{yr}}\right) \times 4.37\%} = 35.87 \text{ years}$$
Thus, the dead storage capacity would be filled with sediment in 35.87 years.

3.5 Land Conservation Efforts

The alternative land conservation implemented in this study is the long-term conservation by land terracing. Land terracing can reduce soil loss due to erosion by decreasing the value of the P factor. Changes in the value of P depend on the slope of the land. The creation of terraces is applied to all types of land use with slopes < 25% except residential and forest.

Figure 8 shows the location of terraces, symbolized in green, where the level of shading describes the slope of the land. The results of terrace creation successfully reduced the total volume of sediments by 22% from 105,418 tons/year to 81,948 tons/year. With a decrease in the sediment volume, the life time of the Cieunteung retention basin indirectly increased from 35.87 years to 46.15 years.

4. Conclusion

- The maximum average erosion rate equalled 1,904 tons/ha/year in 2013, categorized as very high, while the minimum average erosion rate equalled 71.16 tons/ha/year in 2009, categorized as moderate. The results were obtained from simulation using the SWAT model. The comparison between simulated and observed monthly flow data for 11 years (January 2008 to December 2018) show values of $R^2 = 0.89$ and $NS = 0.95$, which means the model is categorized as very good.
- The correlation between erosion hazard index (IBE) and coefficient of river regime (KRS) shows a very close relationship and positive correlation with the average of $R^2 = 0.8$ from 2008 to 2018. As the value of the erosion hazard index increases, this is followed by an increase in the value of the coefficient of river regime and vice versa.
- The life time of the Cieunteung retention basin based on the time sediments will fill the capacity of dead storage is 35.87 years, with the value of trap efficiency being 4.37% and sedimentation equaling 72,551.961 m$^3$/year.
- Alternative land conservation through the creation of terraces successfully reduces sedimentation by 22% from 105,418 tons/year to 81,948 tons/year, and thus the life time of the Cieunteung retention basin will also increase to 46.15 years.

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