Rainfall-Runoff and Sediment Yield Modelling in Volcanic catchment using SWAT, a Case Study in Opak Watershed.

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Abstract. Understanding hydrological functions and sediment dynamics in a volcanic area will help decisions makers to a better rehabilitation and reconstruction processes including environmental restoration efforts. The volcanic material can provide the multiple functions; they can improve water quality by allowing water aeration along the river and work as a good aquifer that will keep the water in the groundwater storage. On the other hand, runoff in a volcano has the possibility to induce a more significant hazard. Lahar can cause bigger destruction. The general objectives of this paper were to develop a hydrologic model to characterise the water balance in a volcanic watershed to inform the relationship between rainfall and runoff. The Soil and Water Assessment Tool (SWAT) was chosen to test its applicability in an active volcanic watershed. By using this model, the hydrographs were simulated over the area. From the model, we found that Opak watershed consists of 83 sub-catchments. The highest erosion and sediment yield of the area from 2004 – 2013 were found on the sub-catchment number 83 with the total sediment yield is 147.8 ton/year The model achieved a reasonable fit after calibration. This work can provide information on simulated hydrologic processes and function on an active volcanic watershed using SWAT.

1. Introduction

Runoff is one of the essential hydrological variables in the study of hydrology. The study of runoff and its response to land-use and population changes has become a significant challenge on local and global scales [1–6]. Runoff can carry contaminants (chemical, biological, heavy metal etc.)[7–10] as well as sediment[11,12]. On the other hand, climate change will influence the runoff patterns. This condition will lead to stream degradation, erosion, flooding [13–15]. Understanding runoff patterns is a critical step in effective environmental management. From the runoff patterns, we can select the best management practices for watershed management. At this point, the model can play an important role in simulating runoff condition of a watershed. Hydrological watershed modelling has become a central tool for conceptualizing the runoff and subsurface water. From the model, we can simulate the water balance in a particular area. Besides understanding the water balances, we can use models to predict the impact of different management practices on a watershed response, sediment and contaminant transport[16–18]. SWAT model was developed in the 1980s. This model aimed to manage water supplies and assess the non-point source of pollution of an agricultural basin [19]. SWAT is
increasingly being applied to many watersheds, ranging from tropical to an arid area, from rural to urban watersheds.

This study aims to apply the SWAT model in the unique context of a volcanic watershed to test the model’s ability to perform. The result of this research will lead to a better understanding of hydrological processes in an active volcanic area. Therefore, better watershed management can be achieved base on the result of this model.

2. The Methods
The general objectives of this paper were to develop a hydrologic model to characterize the water balance in a volcanic watershed to inform the relationship between rainfall and runoff. The Soil and Water Assessment Tool (SWAT) was chosen to test its applicability in an active volcanic watershed. Using this model, the hydrographs were simulated over the area. The model achieved a reasonable fit after calibration. This work can provide information about simulated hydrologic processes and function on an active volcanic watershed using SWAT.

2.1. Study Area
The study area is located in the Merapi Volcano, Yogyakarta, Indonesia (Fig. 1). The Opak watershed is located between 7°32’54”-8°2’25” S and 104°15’24”–104°51’38”E, covering a surface area of 47,485.99 ha. It is located between 14-2660 msl. Average rainfall in this area is 2.319 mm/year, and the minimum rainfall recorded in this area was 1.206 mm/year. Geologically, Opak watershed consist of 6 formation, they are alluvium deposit, EMerapi Volcano Deposit, FormasiNgelanggran, FormasiSemilir, FormasiSambipitu, andold Merapi deposit.

![Fig. 1: The study area in Opak watershed, Yogyakarta, Indonesia](image_url)
Table 1. Rainfall data in the study area

| Sub DAS Opak | Sub DAS | Nama Stasiun Hujan | Lokasi | Curah Hujan (mm) | CH Rate2 |
|-------------|---------|-------------------|--------|----------------|---------|
|             | Bedugan |                       |        | 2016.6         | 1597.83 |
|             | Bronggeng |                   |        | 2326.65         | 1933.6  |
|             | Cermawangi |                  |        | 2249.6         | 1934.6  |
|             | Karangploso |                 |        | 1811.1         | 1545.2  |
|             | Kepatihan |                     |        | 2015.7         | 1758.2  |
|             | Pumpung  |                       |        | 2263.6         | 1682.84 |
|             | Pantang  |                       |        | 1990.0         | 1597.83 |
|             | Tanjungiru |                   |        | 2347.9         | 1574.10 |

2.2. SWAT Model

SWAT (Soil Water Assessment Tool) model is a physically based semi distributed model that is able to simulate the runoff and sediment yield of a watershed [20,21], and assess the effect of land use change [22,23] and its effect on water quality [24]. The model based on the equation as follow[25].

\[
SW_t = SW_0 + \sum_{n=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \]

where \(SW_t\) is soil water capacity (mm), \(SW_0\) is initial water content (mm), \(R_{day}\) is rainfall (mm), \(Q_{surf}\) is surface runoff (mm), \(E_a\) is evapotranspiration (mm), \(W_{seep}\) is percolation (mm), \(Q_{gw}\) is ground water discharge (mm) and \(t\) is time (hari).

a. Surface runoff

SAWT Model calculate surface runoff base on SCS-CN. The equation is :

\[
Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad \text{…… 2}
\]

\[
S = 25.4 \left( \frac{100}{CN} - 10 \right) \quad \text{…… 3}
\]

where \(Q_{surf}\) is total surface runoff , \(R_{day}\) is number of rainy day, \(I_a\) is initial abstraction, \(S\) is retention and \(CN\) is Curve Number

b. Erosion and Sedimentation

Erosion and sedimentation is calculated using Modified Universal Soil Loss Equation (MUSLE).

\[
SED = 11.8 \cdot Q_{surf} \cdot q_{peak} \cdot \text{Area}_{HRU}^{0.54} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot L_{USLE} \cdot CFRG \quad \text{…… 4}
\]

Where \(SED\) is total sediment that leave the catchment, \(Q_{surf}\) total runoff, \(q_{peak}\) is peak discharge and \(Area_{HRU}\) is the area of HRU.

3. Results and discussions

Parametrization

a. Soil

The soil is one of the critical parameters in the SWAT Model. Since the information of soil in Indonesia is limited, pedogeomorphology approach was used in this research. We divided the area into 32 landform unit as the base map for soil mapping (table 2). Figure 2 shows the distribution of the soil in the study area.
| Landform Unit                                      | Soil coding |
|---------------------------------------------------|-------------|
| Bukit Sisa Formasi Semilir                        | HSD1        |
| Dataran Aluvial Gunungapi                          | PF1         |
| Dataran Kaki Fluvio - Koluvial                    | PDF2        |
| Gunungapi Merapi Tua                              | HVD1        |
| Kawah Gunungapi                                   | VV1         |
| Lembah Dataran Aluvial Gunungapi                  | PF2         |
| Lembah Kerucut Gunungapi                          | VF1         |
| Lembah Lereng Atas Gunungapi                      | VF2         |
| Lembah Lereng Tengah Gunungapi                    | VF3         |
| Lembahlereng kaki gunungapimerapi                 | PF3         |
| Lereng Atas Gunungapi                             | VVD1        |
| Lereng Atas Perbukitan Denudasional Breksi Andesit| MSD3        |
| Lereng Atas Perbukitan Denudasional Formasi Nglanggran| UD2|
| Lereng Atas Perbukitan Denudasional Formasi Semilir| MSD4        |
| Lereng Bawah Perbukitan Denudasional Formasi Semilir| MSD6        |
| Lereng Kaki Gunungapi                             | VVD2        |
| Lereng Kaki Koluvial                              | PDF3        |
| Lereng Kaki Perbukitan Denudasional Formasi Semilir| USD1        |
| Lereng Tengah Gunungapi                           | VVD3        |
| Lereng Tengah Perbukitan Denudasional Andesit     | MSD7        |
| Lereng Tengah Perbukitan Denudasional Formasi Semilir| UDF1        |
| Lereng Tengah Perbukitan Struktural Formasi Semilir| MSD8        |
| Puncak Perbukitan Denudasional Baturagung         | MSD9        |
| Puncak Perbukitan Denudasional Formasi Semilir    | USD2        |
| Puncak Perbukitan Struktural Formasi Semilir      | MSD10       |
| Puncak Igir Denudasional Formasi Nglanggran       | HD2         |
| Lembah Struktural Fluvio - Koluvial               | PF4         |
| Dataran Aluvial Struktural                        | PDF1        |
| Escarpment Baturagung                             | MSD1        |
| Kerucut Gunungapi                                 | VV2         |
| Kompleks Perbukitan Struktural Baturagung         | MSD2        |
| Lereng Tengah Perbukitan Denudasional Formasi Nglanggran| HD1|
b. Land-use

We divided the land-use in the Opak watershed into 12 type of land-uses. Sawah dominated the study area by 40.22%. Other land-use are open water (0.39%), shrub (3.32%), building (0.53%), Forest (0.99), settlement (25.31%), bareland (sand) (0.05%), grass (1.69%), mix garden (9.08%), rainfed farm (2.83%), bareland (sand and stone) (0.17) and agriculture area (15.52%). Table 3 shows the land-use of the study area. Figure 3 shows the land-use distribution.

| Type of landuse         | Luas (Ha) |
|-------------------------|-----------|
| Open water              | 161.15    |
| Shrub                   | 1317.67   |
| Building                | 218.36    |
| Forest                  | 405.26    |
| Garden                  | 3725.43   |
| Bareland (sand)         | 20.65     |
| Settlement              | 10380.72  |
| Grass                   | 692.64    |
| Sawah                   | 16493.36  |
| Rainfed Sawah           | 1158.57   |
| Bareland (sand and stone)| 67.74    |
| Dryland agriculture     | 6366.13   |
Runoff and Sediment yield in Opak Watershed

From the model, we found that Opak watershed consists of 83 sub-catchment. Based on the SWAT model, we found that there are 5176 HRUs. The highest erosion and sediment yield of the area from 2009 – 2013 were found on the sub-catchment number 21 with the total sediment yield is 87.25 ton/year. While the other sub-catchment number 22, 26, 30, 32, 34, 41, 42 and 44 is considered as high and very high. Figure 4 shows the sediment yield in each sub-catchment while figure 5 shows the distribution of the sub-catchment as well as the sediment yield of the study area.
### Table 4. Surface Runoff's on each Sub Basin

| Sub Basin | Runoff (mm/year) | Class   | Sub Basin | Runoff (mm/year) | Class   | Sub Basin | Runoff (mm/year) | Class |
|-----------|------------------|---------|-----------|------------------|---------|-----------|------------------|-------|
| 1         | 265              | Very Low| 17        | 999              | Medium  | 33        | 161              | Very Low |
| 2         | 512              | Low     | 18        | 693              | Low     | 34        | 236              | Very Low |
| 3         | 441              | Very Low| 19        | 832              | Medium  | 35        | 246              | Very Low |
| 4         | 739              | Low     | 20        | 844              | Medium  | 36        | 175              | Very Low |
| 5         | 657              | Low     | 21        | 1641             | Very High| 37       | 150              | Very Low |
| 6         | 467              | Low     | 22        | 217              | Very Low| 38        | 239              | Very Low |
| 7         | 507              | Low     | 23        | 700              | Low     | 39        | 259              | Very Low |
| 8         | 380              | Very Low| 24        | 669              | Low     | 40        | 175              | Very Low |
| 9         | 669              | Low     | 25        | 163              | Very Low| 41        | 207              | Very Low |
| 10        | 589              | Low     | 26        | 209              | Very Low| 42        | 242              | Very Low |
| 11        | 1086             | High    | 27        | 154              | Very Low| 43        | 232              | Very Low |
| 12        | 344              | Very Low| 28        | 144              | Very Low| 44        | 263              | Very Low |
| 13        | 620              | Low     | 29        | 155              | Very Low| 45        | 174              | Very Low |
| 14        | 896              | Medium  | 30        | 203              | Very Low| 46        | 203              | Very Low |
| 15        | 1144             | High    | 31        | 772              | Medium  | 47        | 211              | Very Low |
| 16        | 727              | Low     | 32        | 243              | Very Low|           |                  |       |

### Table 5. Sediment yield on each Sub Basin

| Sub Basin | Sediment (ton/ha/year) | Class   | Sub Basin | Sediment (ton/ha/year) | Class   | Sub Basin | Sediment (ton/ha/year) | Class |
|-----------|------------------------|---------|-----------|------------------------|---------|-----------|------------------------|-------|
| 1         | 1.60                   | Very Low| 17        | 7.66                   | Very Low| 33        | 0.85                   | Very Low |
| 2         | 2.88                   | Very Low| 18        | 1.96                   | Very Low| 34        | 9.73                   | Very Low |
| 3         | 1.99                   | Very Low| 19        | 2.01                   | Very Low| 35        | 0.63                   | Very Low |
| 4         | 1.49                   | Very Low| 20        | 1.85                   | Very Low| 36        | 0.74                   | Very Low |
| 5         | 1.14                   | Very Low| 21        | 87.25                  | Very High| 37       | 0.59                   | Very Low |
| 6         | 6.22                   | Very Low| 22        | 23.48                  | Low      | 38        | 0.59                   | Very Low |
| 7         | 1.01                   | Very Low| 23        | 1.96                   | Very Low| 39        | 0.59                   | Very Low |
| 8         | 1.77                   | Very Low| 24        | 5.22                   | Very Low| 40        | 5.62                   | Very Low |
| 9         | 1.98                   | Very Low| 25        | 4.74                   | Very Low| 41        | 12.02                  | Very Low |
| 10        | 1.51                   | Very Low| 26        | 29.11                  | Low      | 42        | 15.48                  | Very Low |
| 11        | 1.29                   | Very Low| 27        | 1.57                   | Very Low| 43        | 0.67                   | Very Low |
| 12        | 1.78                   | Very Low| 28        | 0.69                   | Very Low| 44        | 7.92                   | Very Low |
| 13        | 1.98                   | Very Low| 29        | 4.52                   | Very Low| 45        | 0.74                   | Very Low |
| 14        | 1.79                   | Very Low| 30        | 15.40                  | Very Low| 46        | 4.08                   | Very Low |
| 15        | 1.29                   | Very Low| 31        | 2.36                   | Very Low| 47        | 0.79                   | Very Low |
| 16        | 1.85                   | Very Low| 32        | 11.81                  | Very Low|           |                        |       |
4. Conclusion
Soil, land use, topography and rainfall hold a significant role in runoff and sediment dynamic within a watershed. An area with limited data like Indonesia needs other approaches to obtain better hydrological modelling results. Pedogeomorphology is one of the best methods to tackle the absent of soil information. Land-use from the topographic map updated with Google Earth image can be very useful, while the topographic features can be obtained from some global dataset. From the model, by avoiding the sediment from lahar, we found that the sediment from an active volcano is smaller compared to a structural old volcanic mountain. Catchment 21 that falls on the structural old volcanic mountain have 87.25 ton/ha/year, while from the active volcano is less than 20 ton/ha/year. Therefore, we can conclude that the watershed management in Merapi based on its land-use is good while in the structural old volcanic mountain of Batur Agung need more effort.

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