Assessment of Runoff, Sediment Yield and Nutrient Load on Watershed Using Watershed Modeling

Mohammad Sholichin\textsuperscript{1)}, Faridah Othman\textsuperscript{2)}, Shatirah Akib\textsuperscript{3)}

1. PhD PhD Student, Department of Civil Engineering, Universiti Malaya, Lembah Pantai, Kuala Lumpur, Malaysia; mochsholichin@perdana.um.edu.my; mocsholichin@yahoo.com
   Lecturer, Water Resources Department, Brawijaya University, Malang East Java Indonesia
2. Lecturer, Department of Civil Engineering, Universiti Malaya, Lembah Pantai, Kuala Lumpur, Malaysia; www fk.um.edu.my; faridahothman@um.edu.my
3. PhD Student, Department of Civil Engineering, Universiti Malaya, Lembah Pantai, Kuala Lumpur, Malaysia; www fk.um.edu.my; Shatirahakib@yahoo.co.uk

Abstract

The higher rate of soil erosion than normal erosion value due to illegal logging activities in conservation area become crucial problem of sediment in reservoir because it reduce of lifetime of dam purpose. Meanwhile, both over doses fertilizer use in agriculture activities and uncontrolled of wastewater pollution from urban/rural area increasing of pollution load in stream and it was as eutrophication hazard in reservoir. The main objective of this research are to assessment of runoff, sediment yield and nutrient load and to propose the statistical relationship relating sediment and nutrient loads to physiographic and hydrologic properties of the each sub watershed. For assessment of runoff, sediment yield and nutrient load on watershed, the watershed modeling was used. A Soil and Water Assessment Tool (SWAT) was choose to applied in this research due to successful for simulate the effect of non point and point source pollutant from watershed, in stream and river. Calibration for flow was performed from 1992 through 2000 and period 2001 to 2004 it was validated. Sediment and nutrient calibration was done from 2003 through 2005 at Sutami reservoir measurement data. The resulting statistical goodness-of-fit was evaluated with the Nash-Sutcliffe coefficient $R_{NS}^2 = 0.32$ and $R^2$ of the one-to-one line for monthly stream flow was 0.85. Highest estimated annual average sediment yields were 85.94 ton/ha/year and 62.07 ton/ha/years from Upper Lesti River and Amprong River basin. These two sub basin also had the highest estimated annual average sediment bound phosphorous loading which 1.15 kg/ha/yr and 1.00 kg/ha/yr, respectively. The highest of organic N loading are Upstream Brantas due to in this area dominate by agricultural area that assumed use overdoses of fertilizer. In Banggo river basin is highest of org P loading (4.20 kg/ha/yr) than another basin. This study showed that SWAT was able to assessment of runoff, sediment yield, and nutrients load successfully.

Key word: runoff, sediment yield, nutrient load, watershed model

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1. Introduction

Indonesia has the world’s four largest population (208.8 million) with over 92% being Muslim. The population is comprised of nearly 300 ethnic groups that speak about 538 different language and dialects (Board for Statistics Center 2005). Brantas River is a primary production of paddy stock in the country (Figure.1). It has an area of approximately 11,800 km² and make up 24.6% of East Java’s Land area. The basin is bounded by Mt Bromo (2,393m) and Mt Semeru (3,676 m) on east, a series of low ridges to the south, Mt Wilis (2,169m) and it’s ridge the west, and the Kedung low ridge and the Madura Strait on the north (Anjali bhat, et. al.,2005). The Brantas River plays a vital role in the economic regional, not only for East Java, but also national-wide. The main objective of watershed management in Brantas River are regulated and controlled for flooding, water supply, water quality etc. (Usman R, 1997). The focus of this study was presented of water quality on main stream of Upstream Brantas River related of difference characteristic of sub-basin (Metro, Lesti, Amprong, Kemanten etc). In upstream Brantas river basin is the starting point for review of source or water pollution both from point source and non point sour pollutant.

Water pollution of the Brantas River Basin occurs from both point and non-point source. Its water quality is poor and ecological health endangered especially in its lower reaches. The number of indigenous fish has decreased over the last twenty years and severe eutrophication problem exist particularly in the reservoirs. ( Schroeder F, and Diethard K, ). According by Hartanto, Water quality in Brantas River is often poor, leading to adverse impacts on both public health and economic development. Zones of particularly poor water quality include the reach immediately downstream of Malang Regency and the Lower Brantas – Surabaya. (Harnanto, .NET al., 2003). An operational of reservoir management has been importance played not only controlling of water quality but also reducing of concentration water pollutant in stream. On field observation with bio-monitoring in Upper Brantas River Basin indicated that water quality status of Brantas stream divided two condition; firstly, its was poor condition by Average Score Per Taxon (ASTP) value between 4,8 – 6,3, and secondly, its was very poor condition by Average Score Per Taxon (ASTP) value between 4,0 – 4,5 (Handayani, S., et al., 2003). In the middle of June 2001, Sutami reservoir, the biggest reservoir in Brantas River has been eutrophication problem due to receive a highest pollutant load from upstream area (chemical agriculture activities, urban area and industries). (Anonymous, Augustus 2002)

The main objectives of this study are to assessment of runoff, sediment yield and nutrient load and to propose the statistical relationship relating sediment and nutrient loads to physiographic and hydrologic properties of the each sub watershed. Hypothesis of this study are the increasing of wastewater effluent from point sources and over doses used of fertilizer on agricultural activities would be decreasing of water quality in stream and it’s some time make an eutrophication hazard in reservoir. Therefore, this study will concentrate on water quality in stream and reservoir due to difference pollutant load on each subbasin.

2. Research Methodology

2.1. Model description

The Watershed Water Quality Modeling, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998); Neitsch et al., 2002; http://www.brc.tamus.edu/swat), developed by the United State Department of Agriculture-Agriculture Research Service (USDA-ARS), was used in this study. SWAT was selected for this study because of its ability to simulate land management processes in larger Watersheds. SWAT is a physically based simulation model development to simulate continuous-time landscape processes and stream flow with a high level of spatial detail by allowing the river/watershed to be divided into subbasins or sub watersheds. Each subbasin is divided into several land use and soil
combination called Hydrologic Response Units (HRUs) based on threshold percentages used to select the land use and soil (Neitsch et al., 2002). SWAT model operates on daily time step and is designed to evaluate the impacts of different management condition (Point source and non point source pollutant) on water quality in large basins. Mayor components of the model include hydrology, weather, precipitation, soil type, erosion, crop growth, nutrient, pesticides, and agricultural management.

Surface runoff from daily rainfall is estimated with the modification of Soil Conservation Service (SCS) curve number method (USDA-SCS, 1972). In the curve number method, the daily rainfall is partitioned between surface runoff and infiltration as a function of antecedent soil moisture condition. Erosion and sediment yield are estimated for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The cannel sediment routing equation uses a modification of Bagnold’s sediment transport equation (Bagnold, 1977) that estimates the transport concentration capacity as a function of flow velocity. Once the sediment load in surface runoff is calculated, the amount of sediment released to the main channel is calculated:

\[
\text{sed} = (\text{sed}' + \text{sed}_{\text{stor},i-1}) \left(1 - \exp \left(-\frac{surlag}{t_{\text{conc}}} \right) \right)
\]

Where \( \text{sed}' \) is the amount of sediment load generated in the HRU on a given day (metric tons), \( \text{sed}_{\text{stor},i-1} \) is the sediment stirred of lagged from the previous day (metric tons), \( surlag \) is the surface runoff lag coefficient, and \( t_{\text{conc}} \) is the time of concentration for the HRU (hrs).

The fate and transport of nutrient in watershed depend on the transformations the compounds undergo in soil environment. SWAT model the complete nutrient cycle for nitrogen and phosphorous as well as the degradation of any pesticides applied in a HRUs. SWAT monitors five difference pools of nitrogen in the soil. Two pools are inorganic form of nitrogen, NH\(_4^+\) and NO\(_3^-\), while the other three pools are organic forms of nitrogen (Fig.1). Amount of NO\(_3^-\) transported with runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the soil layer. Organic N transport with sediment is calculated with a loading function developed by Mcelroy et al. (1976) and modified by William and Hann (1978). The concentration of organic in the soil surface layer, \( \text{conc}_{\text{orgN}} \), is calculated:

\[
\text{conc}_{\text{orgN}} = 100 \cdot \frac{(\text{orgN}_{\text{fresh,surf}} + \text{orgN}_{\text{sta,surf}} + \text{orgN}_{\text{act,surf}})}{\rho_b \cdot \text{depth}_{\text{surf}}}
\]

Where \( \text{orgN}_{\text{fresh,surf}} \) is nitrogen in fresh organic pool in the top 10 mm (Kg N/ha), \( \text{orgN}_{\text{sta,surf}} \) is nitrogen in the stable organic pool (Kg N/ha), \( \text{orgN}_{\text{act,surf}} \) is nitrogen in the active organic pool in the top 10 mm (Kg N/ha), \( \rho_b \) is the bulk density of the first soil layer (Mg/m\(^3\)), and \( \text{depth}_{\text{surf}} \) is the depth of soil surface layer (10 mm).

The Phosphorous (P) processes modeled by SWAT and he various pools of phosphorous in the soil are described in Neitsch et al., 2002. The amount of soluble P removed in runoff is predicted using labile P concentration in the top 10 mm of the soil, the runoff volume and phosphorous soil partitioning factor, that is, the ratio of P attached to sediment to P dissolved in soil water. (Santhi et al. 2005). In stream nutrient dynamics have been incorporated into SWAT using the kinetic routines from the in-stream water quality model, QUAL2E (Brown and Barnwell, 1987). The primary mechanism of phosphorous movement in the soil is by diffusion. Diffusion is the migration of ions over small distances.
(1-2 mm) in the soil solution in response to a concentration gradient. The amount of solution P transported in surface runoff is: 

\[ P_{surf} = \frac{P_{solution, surf} Q_{surf}}{\rho_b \cdot depth_{surf} \cdot K_{d, surf}} \]  

Where \( P_{surf} \) is the amount of soluble phosphorous lost in surface runoff (Kg P/ha), 
\( P_{solution, surf} \) is the amount of phosphorous in solution in the top 10 mm (kg P/ha), 
\( Q_{surf} \) is the amount of surface runoff on a given day (mm), 
\( \rho_b \) is the bulk density of the top 10 mm (Mg/m³), 
\( depth_{surf} \) is the depth of the surface layer (10 mm), and 
\( K_{d, surf} \) is the phosphorous soil partitioning coefficient (m³/Mg)

2.2. Study area

The Brantas river basin is located within the province of East Java Indonesia (see Figure 1). It has an area of approximately 11,800 km² and make up 24.6% of East Java’s Land area. The basin is bounded by Mt Bromo (2,393m) and Mt Semeru (3,676 m) on east, a series of low ridges to the south, Mt Wiwis (2,169m) and it’s ridge the west, and the Kedung low ridge and the Madura Strait on the north (Anjali bhat, et. al., 2005). In this paper, Upstream Brantas River was choosing to study as the first part of Research Plan (Figure 1). The main problem in upper Brantas River basin is erosion-sedimentation into reservoir, flood control and degradation of water quality due to pollutant load from both point and non point pollutant. On Brantas River basin have been build of 23 the online water quality monitoring station (WQMS) and 4 WQMS located in upstream area. (see Figure 2).

2.3. Model Input and Calibration

The Major input of SWAT model are GIS Data (topography, soil class, land use, station locations), Climate data (precipitation, air temperature, wind speed, relative humidity, solar radiation) and Land management (fertilization, crop rotation, plating, tillage, point source). (See figure 3.)

The Land use patterns were derived from the Department of Agriculture and Bakosurtanal, by different type of land cover. These data were received in the form of non digital map, therefore it was converted to digital map by AutoCad and AcrView GIS processed. (Figure 4). The Soil data were acquired from the Department of Agriculture. (Figure 5). The soil pattern of the basin is essential importance to the model, since in combination with the land uses determines the HRUs of the catchment and, to large extent, also determines runoff. The hydrological data patterns were derived

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from the Perum Jasa Tirta 1 agency. The hydrological data refer to daily precipitation and temperature, for period from 1992 to 2005.

Figure 3. Processing and display of AVSWAT 2000 model

Figure 4. Soil type in Upper Brantas river basin

Figure 5. Land use in Upper Brantas river basin
Model calibration and validation are necessary and critical step in any model application. For most models, calibration is an iterative procedure of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest. Model Validation is reality an extension of the calibration process. Its purpose is to assure that the calibration model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort. Calibration of the SWAT model has been done which tree steps, hydrology, sediment and nutrient. The resulting statistical goodness-of-fit was evaluated with the Nash-Sutcliffe coefficient (Strobl, 2002), $R^2_{NS} = 0.32$ (Fig. 6), and $R^2$ of the one-to-one line for monthly stream flow was 0.76 (Fig.7).

2.4. Pollution source Identification and Assessment

The pollution sources of upstream Brantas river, which drain to Sutami reservoir, can be categorized as: non point source pollution (agrochemical diffusion) and point sources (sewage, industrial, etc). In the study case area, the source pollution is from domestic solid wastewater. The number of people which live in upstream Brantas are 2,5 million and 55% from it’s directly throw away to river body. Domestic solid wastewater contains organic matter, bacterial, Nutrient (N & P), etc. In the human solid wastewater contains 14.5 g. N/person/day and 1.9 g. P/person/day and human urine contain 7 g. N/person/day and 2 g. P/person/day, respectively. Therefore the nutrient load on watershed approximately were 30 Ton N/day and 5, 5 ton P/day.
The second source pollution is from industries. According from PJT report, 17 industries located in Upstream Brantas river basin are sugar factory 2 units, tapioca factory 5 units, leather industry 3 units and 7 units the other type. Potential pollutant load from industry into Sutami reservoir assume 35 ton BOD/day. The third source pollutant is from chemical agriculture activities. An usually, farmer use of type fertilizer for Urea [CO(NH$_2$)$_2$], TSP [Ca(H$_2$PO$_4$)$_2$], KCL and ZA. A fertilizer used on rice field normally are 300 kg/ha for Urea, 100 kg/ha for TSP and 75 kg/ha for KCL, respectively. By assume, fertilizer looses on water residue are 45% /kg- N for urea and 1.2 % /kg P for TSP. Therefore, the pollutant load on Sutami reservoir assumes 10.2 ton N/day and 3.1 ton P/day respectively.

3. Result and Essay

According for data collection along field survey and analysis in laboratory, water quality in Brantas river decrease for 5 years period especially at 2002 that eutrophication attach in sutami reservoir. (Figure 8 and figure 9).

![Figure 8. Water Quality monitoring at Pendem station](image)

![Figure 9. Water Monitoring at Sengguru reservoir](image)

Table 1. Annual Average Estimates Of Sediment Yield and Nutrient Load for Each Basin Based On Period 1995 to 2006 Simulation

<table>
<thead>
<tr>
<th>Sub Basin</th>
<th>Sub Basin Name</th>
<th>Area (Km$^2$)</th>
<th>Rainfall (mm)</th>
<th>Sh. Runoff (mm)</th>
<th>GW flow (mm)</th>
<th>Sed. Yield (ton/ha)</th>
<th>Org. N (Kg/ha)</th>
<th>Org. P (Kg/ha)</th>
<th>Sol. P (Kg/ha)</th>
<th>Sed. P (Kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Banggo River</td>
<td>214.32</td>
<td>2,043.92</td>
<td>876.67</td>
<td>124.28</td>
<td>7.88</td>
<td>28.51</td>
<td>4.26</td>
<td>0.64</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>Upstream Brantas</td>
<td>174.76</td>
<td>1,786.52</td>
<td>491.88</td>
<td>131.78</td>
<td>27.33</td>
<td>29.50</td>
<td>4.10</td>
<td>0.83</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>Amprong River</td>
<td>926.71</td>
<td>1,836.52</td>
<td>787.90</td>
<td>119.38</td>
<td>62.02</td>
<td>13.25</td>
<td>2.23</td>
<td>0.63</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>Ketung Banteng</td>
<td>82.33</td>
<td>1,791.53</td>
<td>510.76</td>
<td>119.80</td>
<td>4.33</td>
<td>19.55</td>
<td>2.95</td>
<td>0.63</td>
<td>0.70</td>
</tr>
<tr>
<td>5</td>
<td>Metro River</td>
<td>257.52</td>
<td>1,944.35</td>
<td>508.91</td>
<td>104.39</td>
<td>17.19</td>
<td>27.31</td>
<td>4.84</td>
<td>0.83</td>
<td>1.03</td>
</tr>
<tr>
<td>6</td>
<td>Manten River</td>
<td>206.29</td>
<td>1,900.67</td>
<td>804.92</td>
<td>79.26</td>
<td>1.75</td>
<td>10.23</td>
<td>1.67</td>
<td>0.64</td>
<td>0.70</td>
</tr>
<tr>
<td>7</td>
<td>Lower Lesti River</td>
<td>249.48</td>
<td>1,816.44</td>
<td>813.35</td>
<td>86.10</td>
<td>3.19</td>
<td>11.69</td>
<td>1.95</td>
<td>0.63</td>
<td>0.84</td>
</tr>
<tr>
<td>8</td>
<td>Upper Lesti River</td>
<td>249.58</td>
<td>1,363.83</td>
<td>546.80</td>
<td>65.83</td>
<td>85.95</td>
<td>14.48</td>
<td>2.38</td>
<td>0.62</td>
<td>1.15</td>
</tr>
<tr>
<td>9</td>
<td>Ginteng River</td>
<td>196.14</td>
<td>1,920.69</td>
<td>661.44</td>
<td>76.08</td>
<td>7.68</td>
<td>29.09</td>
<td>2.97</td>
<td>0.84</td>
<td>0.90</td>
</tr>
</tbody>
</table>

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A summary of the annual average nutrient concentration output of the SWAT model for this study is provided in table 2. The highest concentration of sediment is 1.600 mg/l in upper Lesti River but it lower concentration of NO3 for 9.24 mg/l. Kedung Banteng basin that located in down stream have highest of mineral Phosphorous concentration (1,06 mg/l).
Table 2. Annual Average Estimates of Nutrient Concentration in outlet stream for Each Basin Based on Period 1995 to 2006 Simulation

<table>
<thead>
<tr>
<th>Outlet No.</th>
<th>Sub Basin Name</th>
<th>Area (Km²)</th>
<th>Flow m³/sec</th>
<th>Sed Conc</th>
<th>Org N</th>
<th>Org P</th>
<th>NO3</th>
<th>NH3</th>
<th>Min P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Banggo River</td>
<td>214.32</td>
<td>8.24</td>
<td>95.53</td>
<td>6.09</td>
<td>0.81</td>
<td>13.54</td>
<td>2.13</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>Upstream Brantas</td>
<td>174.96</td>
<td>5.32</td>
<td>404.80</td>
<td>7.54</td>
<td>0.99</td>
<td>13.50</td>
<td>2.92</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>Amprong River</td>
<td>326.71</td>
<td>10.39</td>
<td>175.60</td>
<td>3.87</td>
<td>0.53</td>
<td>11.35</td>
<td>2.25</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>Kedung Banteng</td>
<td>82.33</td>
<td>57.85</td>
<td>161.00</td>
<td>2.83</td>
<td>0.29</td>
<td>15.51</td>
<td>1.67</td>
<td>1.06</td>
</tr>
<tr>
<td>5</td>
<td>Metro River</td>
<td>257.52</td>
<td>8.02</td>
<td>260.90</td>
<td>6.61</td>
<td>0.90</td>
<td>16.38</td>
<td>2.30</td>
<td>0.76</td>
</tr>
<tr>
<td>6</td>
<td>Manten River</td>
<td>266.29</td>
<td>30.20</td>
<td>115.70</td>
<td>3.21</td>
<td>0.36</td>
<td>11.37</td>
<td>2.58</td>
<td>0.92</td>
</tr>
<tr>
<td>7</td>
<td>Lower Lesti River</td>
<td>249.48</td>
<td>16.87</td>
<td>81.78</td>
<td>3.48</td>
<td>0.50</td>
<td>11.59</td>
<td>2.05</td>
<td>0.83</td>
</tr>
<tr>
<td>8</td>
<td>Upper Lesti River</td>
<td>249.58</td>
<td>5.28</td>
<td>1,690.00</td>
<td>5.62</td>
<td>0.94</td>
<td>9.24</td>
<td>2.12</td>
<td>0.94</td>
</tr>
<tr>
<td>9</td>
<td>Genteng River</td>
<td>106.14</td>
<td>4.07</td>
<td>86.89</td>
<td>4.59</td>
<td>0.66</td>
<td>20.80</td>
<td>1.57</td>
<td>0.51</td>
</tr>
</tbody>
</table>

In upstream Brantas basin, the concentration of organic N are 7.94 mg/l more high than Manten river basin, its can be understanding because upstream Brantas river dominate by agriculture and Manten river basin dominated by non agriculture (domestic) area. The lowest concentration of NO3 and NH3 were 9.24 mg/l and 1.57 mg/l at upstream Lesti River and Genteng river basin, respectively.

Conclusion and Suggestion

The development of ArcView_GIS has facilitated the prediction of soil loss and nutrient transport in spatial distributed manner; range of data types can be incorporated to provide an integrated approach to catchment erosion and nutrient study. Arc View SWAT model was developed to predict the impact of land management practice on water, sediment and agricultural chemical yields in large complex watershed with varying soil, land use and management condition over long time of time. To order a good results, SWAT model much been calibration and validation carefully.

Banggo sub basin is highest of rainfall 2.043 mm and surface runoff 876.67 mm, respectively, but it is not the highest of sediment yield. The highest sediment yield is 85.94 ton/ha/year in Upper Lesti river basin due to maximum erosion rate in this area. This sub basin also the highest of sediment phosphorus which 1.15 kg/ha/year, but the highest of organic P loading which 4.20 kg/ha/yr are in Banggo river basin.

The concentration of organic phosphorous (range 0.36 – 0.99 mg/l) in all sub basin is over of the standard regulation in C class. The concentration of organic nitrogen (range 9.34 – 20.80 mg/l) in all sub basins is lower of the standard regulation in C class.

In the next simulation, modification of difference fertilizer used and management tillage in agriculture would be done. Simulation of SWAT model can also done which difference of divided of each sub basin which smaller than 200 km². The minimum of secondary data information especially of nutrient load was obstacle to good result of simulation of SWAT model.

Literature


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