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Application of Remotely Sensed Data to Sediment Load Estimation by A Distributed Rainfall-Sediment-Runoff Catchment Model

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Abstract: This paper describes a physically-based distributed rainfall-sediment-runoff model for floods and sediment movement in a catchment scale. A grid-cell based kinematic wave runoff (KWR) model simulates surface and subsurface flows on each grid-cell, while soil transportation capacities of sheet erosion are calculated based on the unit stream power theory to model sheet erosion and deposit processes. Constructed model is applied to the Lesti River basin, which is located in the upper Brantas River basin, East Java, Indonesia. Land cover condition in the basin is studied with three different kinds of remotely sensed data including ADEOS/AVNIR, LANDSAT7/ETM+, and TERRA/MODIS. The verification indicated that the model well reproduces the sedimentation record during a rainy season from November 1995 to April 1996, which suggests the potential ability of the model.

1. INTRODUCTION

The integrated sediment management (ISM) in river basins, from upper streams to estuaries, has become increasingly important. The sediment problems have been dealt with independently in the areas, such as mountains, alluvial areas, plains, and estuaries. Local managements independently conducted affect sediment environment in other areas. In addition, human activities, such as land use change and dam construction, also affect the sediment movement in large scales over long terms. Therefore, the concept of integrated management dealing with sediment movement in whole basins has become recognized more important and realistic.

For ISM, it is necessary to establish methods to predict sediment movement both in basins and in streams. The advanced research on sediment transportation in a river stream has been conducted from a viewpoint of sediment hydraulics. In a catchment scale, however, there are still uncertainties in the prediction of sediment movement. The distributed runoff model, which has been studied in hydrology, makes water movement in basins clear by using spatially distributed information. This paper constructs a rainfall-sediment-runoff model by combining sediment yield, deposit, and transportation processes with the grid-cell based Kinematic Wave Runoff (KWR) model[1)]. Geographical Information System (GIS) and Remote sensing (RS) are useful tools in the modeling.

The constructed model is applied to the upper Brantas river basin, East Java, Indonesia. Covered with large amounts of volcanic ash, this area yields much sediment from cultivated lands, forests, and even urban regions. Surface flow in the areas covered by volcanic ash is the main cause that yields the sediment in the areas. The transportation capacity of the surface flow on each grid-cell must be considered to model the sediment yield and deposit processes. The transportation capacity is calculated based on the Unit Stream Power (USP) theory[2)]. The sediment yielded in slope cells follows a path dictated by the flow direction to the 'River' grid-cells on which bed load and suspended load are calculated.

2. LANDCOVER CLASSIFICATION BY REMOTELY SENSED DATA

Land cover condition in the Lesti River basin is studied using three kinds of remotely sensed data including ADEOS/AVNIR[3)] (16m resolution, July 1997), LANDSAT7/ETM+ (30m resolution, May 2002), and multiple scenes of TERRA/MODIS NDVI[4)] (250m resolution 16 days composite, from 2002 to 2003). Figure 1 shows two land cover classification maps based on ADEOS/AVNIR and LANDSAT7/ETM+. There is no significant difference between two scenes except for some erroneous area due to cloud cover and some area outside the Lesti River basin. Large-scale landuse change was not found inside the basin from 1997 to 2002. On the other hand, TERRA/MODIS NDVI (see Fig. 2) captured in different seasons indicate seasonal variability of vegetation cover. Figure 3 shows average NDVI values based on TERRA/MODIS images for each land cover class, which

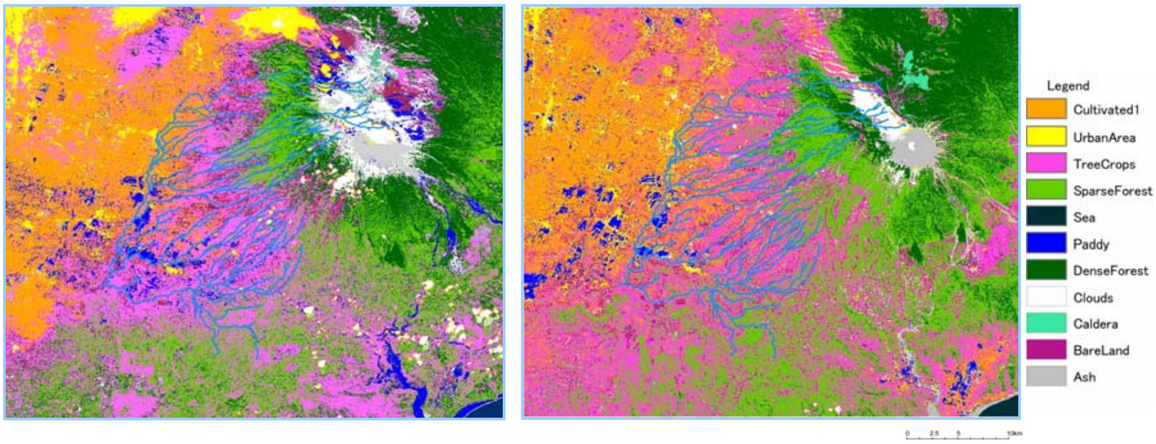

Figure 1. Land cover classification maps based on ADEOS/AVNIR captured in 1997 (left) and LANDSAT7/ETM+ captured in 2002 (right).

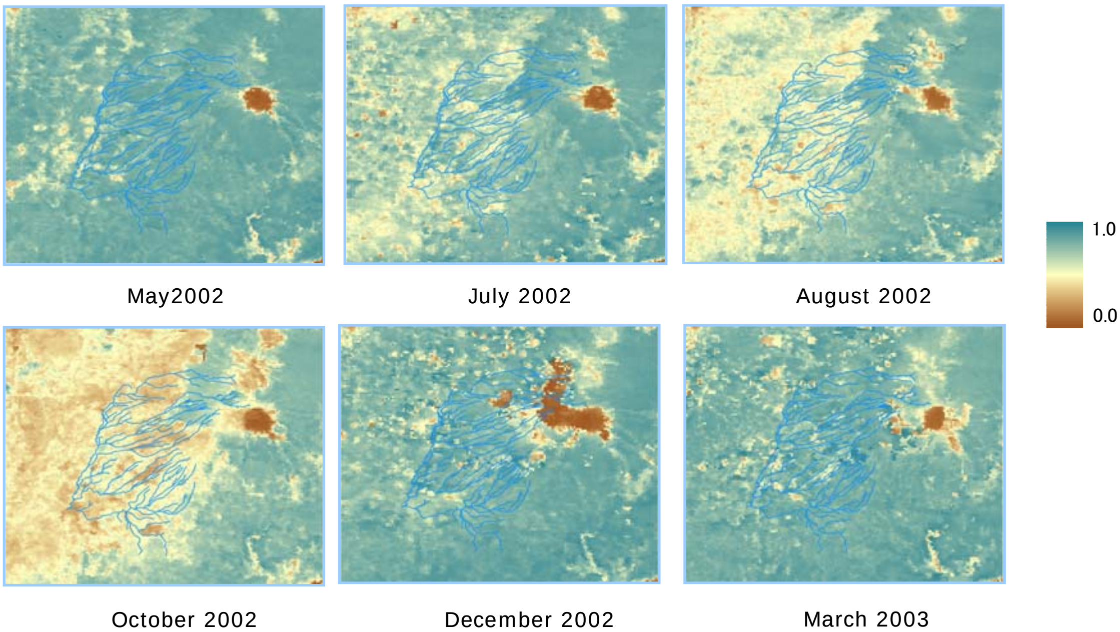

Figure 2. TERRA/MODIS NDVI images in different months

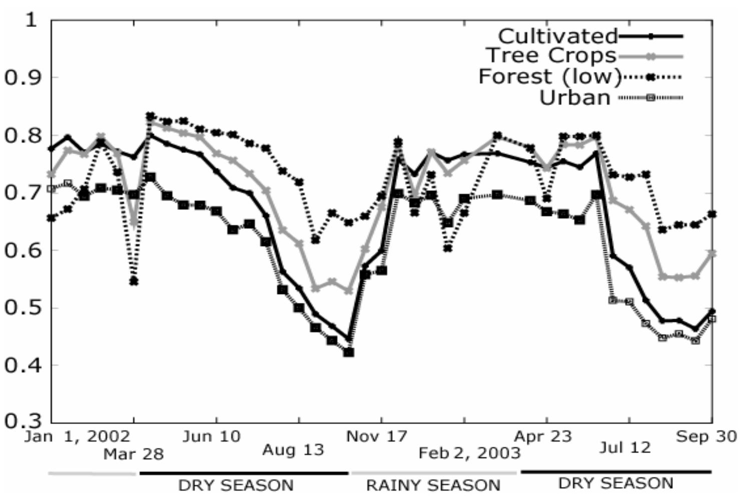

Figure 3. Seasonal trends of NDVI in land cover classes

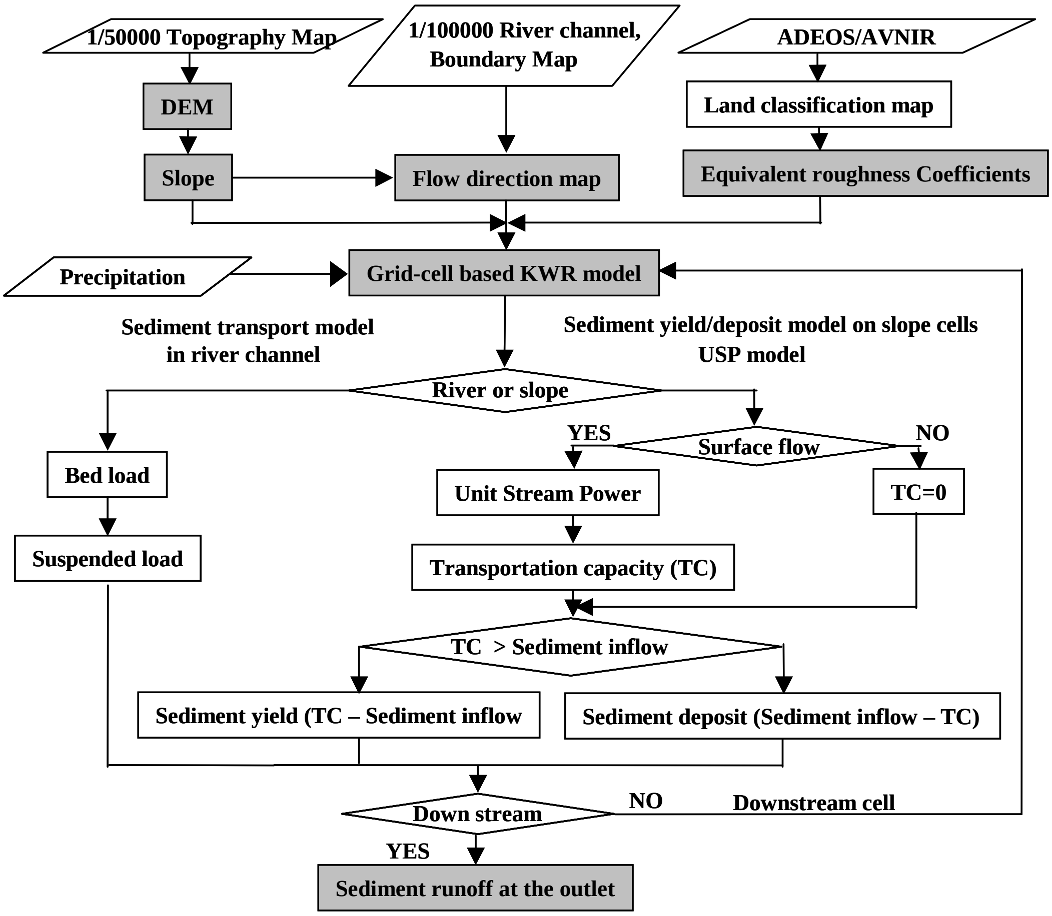

Figure 4 The flow of analysis

obtained from LANDSAT7/ETM+. NDVI becomes the lowest in the end of a dry season especially in cultivated land and in tree crops area, while forest areas maintain relatively high NDVI for all seasons. Though the inter and inner annual variability of vegetation activity as seen in remotely sensed data (Fig. 3) should be considered with the understanding of the effect of vegetation on sediment runoff processes, the authors have not addressed it yet for the rainfall-sediment-runoff modeling.

3. RAINFALL SEDIMENT RUNOFF MODEL

3.1 Application of GIS

Data sets of geographic information such as flow direction, slope and land cover on each grid-cell are needed for developing distributed hydrological models. In Indonesia, however, Digital Elevation Models (DEM) are not available. To overcome this disadvantage, this research uses GIS for generating a DEM. Digitizing contour lines on a 1:50,000 topographical map for the area of interest, GIS has generated a Triangulated Irregular Network (TIN) and transformed it to a 250 m-DEM. In this research, equivalent roughness indices are assigned to each grid-cell based on the land cover classification map from the ADEOS/AVNIR image (Fig. 1 left).

3.2 Sediment yield and deposit process model on slope cells

The grid-cell based KWR model simulates rainfall-runoff on each grid-cell, which has the same resolution as DEM (250 m). This model assumes that sediment is yielded when surface flow occurs. Surface flow has limitation for transporting sediment on each grid-cell, so that this research considers the transportation capacity of surface flow on each grid-cell in each time step to model sediment yield process as well as sediment deposit

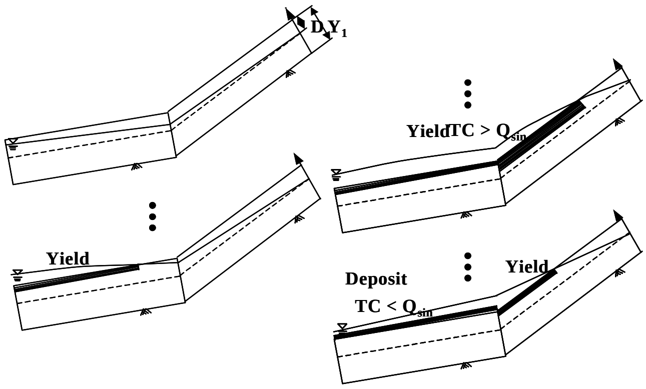

Figure 5. The concept of USP

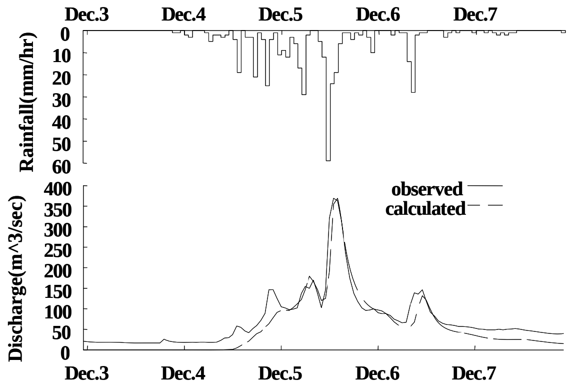

Figure 6. Simulation result in December

process physically. The transportation capacity is calculated by equation (1)[2], which is based on the USP theory. The grid-cell based KWR model simulates the mean velocity $\boldsymbol{V}$ and the discharge $\boldsymbol{Q}$ on each grid-cell with 1-hour time step. Transportation capacity (***TC***) is the product of the $\boldsymbol{C_t}$ and $\boldsymbol{Q}$ as in equation (2).

$$\log C_t = I + J\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \tag{1}$$

$$TC = C_t Q \tag{2}$$

If the volume of sediment supplied from upper grid-cells ($\boldsymbol{Q_{sin}}$) is bigger than the ***TC***, the volume of sediment of ***TC-SI*** will be yielded. On the other hand, the sediment from the upper grid-cells will be deposited with the volume of ***SI-TC*** when ***SI*** is bigger than ***TC*** because surface flow cannot move all of sediment from upper grid-cells[5].

3.3 Sediment transportation model in river channels

A single channel is taken into account in each grid-cell of ‘River’ land cover class. The channel width is assumed to be 1 m to 25 m, which depends on the distance from the catchment’s outlet. Rainfall over the `River’ grid-cell is directly input to the channel as lateral inflow. The sediment that reaches to the `River’ grid-cell is transported in the channel to downstream as bed load and suspended load. The transportation depends on the discharge in the channel computed by the KWR model for channels.

The bed load $\boldsymbol{q_{bb}}$ is computed by equation (3) proposed by Ashida and Michiue[6].

$$q_{bb} = 17\sqrt{sgd^3}\,\tau_{*e}^{3/2}\left(1 - \frac{\tau_{*c}}{\tau_*}\right)\left(1 - \frac{u_{*c}}{u_*}\right) \tag{3}$$

where $\boldsymbol{s}$: specific gravity of sediment in water ; $\boldsymbol{g}$: gravity acceleration ; $\boldsymbol{d}$: grain size ; τ_{*e} : non-dimensional effective shear stress (=0.05) ; τ_{*c} : non-dimensional critical shear stress ; τ_* : non-dimensional shear stress ; u_{*c} : critical shear velocity ; and u_* : shear velocity.

The suspended load transport rate $\boldsymbol{q_{bs}}$ is expressed as the depth-integration of the product of the mean velocity and the concentration distribution as equation (4)[7].

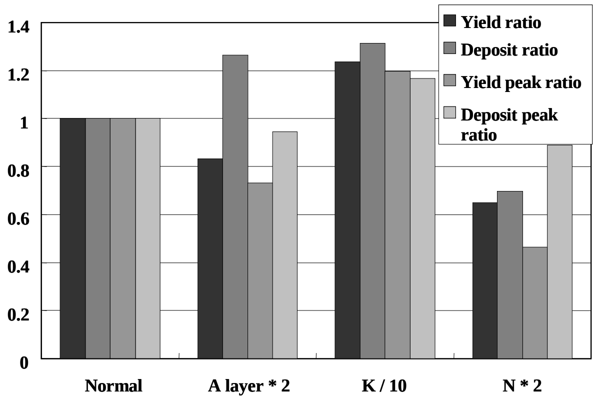

Figure 7. Comparison of the effects of parameters on sediment yield/deposit

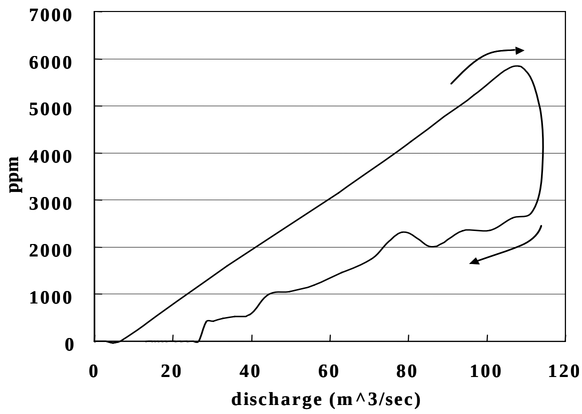

Figure 8. Sediment concentration hysteresis

$$q_{bs} = uC_a \frac{h}{6Z}\left(1 - e^{-6Z} e^{6Za/h}\right)$$
$$Z = \frac{\omega}{\beta \kappa u_*} \tag{4}$$

where $\boldsymbol{u}$: depth averaged velocity ; $\boldsymbol{C_a}$: concentration at the reference level ; $\boldsymbol{h}$: water depths ; a : reference level (0.05$\boldsymbol{h}$) ; $\boldsymbol{\omega}$: fall velocity ; $\boldsymbol{\beta}$: constant (= 1.2) ; and $\boldsymbol{\kappa}$: Karman's constant (= 0.4).

4. APPLICATION TO THE LESTI RIVER BASIN

4.1 The Lesti River basin

The model is applied to the Lesti River basin (625 km^2) located in the upper Brantas River basin (12,000 km^2), which is the second largest river in Java Island, Indonesia. The Lesti River basin is covered with volcanic soil because of Mt. Semeru eruption. The Sengguruh dam, which is located at the junction of the Lesti River and the Brantas River, was constructed in 1988 for water resources and power generation, but the 85 % of gross storage (21.5 million m^3) has been filled with the sedimentation in 8 years after the dam construction[8)]. Since the sedimentation at the Senggruh dam and river channels is one of the major cause for decreasing the dam life and increasing the risk of flood, the prediction of sediment movement in a catchment scale such as sediment deposit at the reservoir and changes in river morphology caused by sediment transport is most important task before planning any mitigation measures.

4.2 Rainfall runoff analysis

To verify the result, the simulated rainfall runoff is compared with the observed data, measured from December 3 to December 5 in 1995. The surface soil (volcanic ash) layer depth and permeability (or hydraulic conductivity) are assumed to be uniform and constant in the whole basin. The runoff coefficient and equivalent roughness coefficient have been decided according to the land cover classification. Let the condition be referred to as "Normal". Figure 6 shows an example of simulated hydrograph, which agrees well with the observed one.

4.3 The sediment yields and deposits differences according to the parameters

According to the simulation, 334 million m^3 of sediment was yielded under the condition of "Normal". The surface soil layer depth, permeability and equivalent roughness coefficient represent the land cover and the geological conditions of each grid-cell in distributed hydrological modeling. Here, total sediment yields and deposits, peak sediment yields and deposits from the whole basin are examined with the different conditions in surface layer depth, permeability, and roughness coefficient. Figure 7 shows the results when the surface layer depth is twice as thick as the "Normal" condition. The amount of sediment yield becomes 0.83 of "Normal" condition. Less amount of sediment will be yielded under the assumption of doubled surface layer depth because surface flow seldom occurs on thicker surface layers. When the permeability is one tenth of the "Normal" condition, both total amount of sediment yield and peak sediment yield increase because slower subsurface flow increases the possibility of occurring the surface flow. This result explains that on the field covered with volcanic ash (small *k* value), surface flow is easy to occur and more soil to be eroded.

4.4 Sediment concentration hysteresis

Figure 8 shows the sediment concentration hysteresis at the outlet with a triangular precipitation (max 11 mm/h, total 134 mm). The figure explains that the sediment concentration is higher when the precipitation increases than when it decreases. The model can express the physical process that if high concentrated surface flow occurs once, the sediment yield rate decrease, and, finally decreasing precipitation makes the yielded sediment deposit on the fields.

4.5 Sediment runoff analysis in a rainy season from 1995 to 1996

Sediment runoff analysis is conducted with the "Normal" soil condition by inputting observed precipitation in a rainy season from November 1995 to April 1996. The upper two panels in Figure 9 show the hyetograph, the cumulative sediment runoff at the outlet, and the cumulative total sediment yield. Roedjito and Harianto[8)] reported that annual sedimentation at the Sengguruh dam reservoir is around 1 million m^3, while simulated sediment runoff at the outlet in the rainy season is about 65 million m^3. The simulation is relatively proper, if the following reasons are considered. The simulation period is not a year but 6 months, the outlet decided in this model application is located about 10 km upstream along the Lesti River from the Sengguruh dam, and the simulated sedimentation does not include the sedimentation coming from the Brantas river. The lower panel in Figure 9 shows the cumulative sediment yield and deposit, explaining that the sediment volume of 428 million m^3 had been yielded and 148 million m^3 had been deposited after the rainy season in the whole basin; therefore, the sediment of about 300 million m^3 had entered into river channel. The volume of eroded material at the cultivated hillslope of Mt. Semeru is found to be larger than other places, which is analogous phenomenon to the natural physical process of sediment erosion.

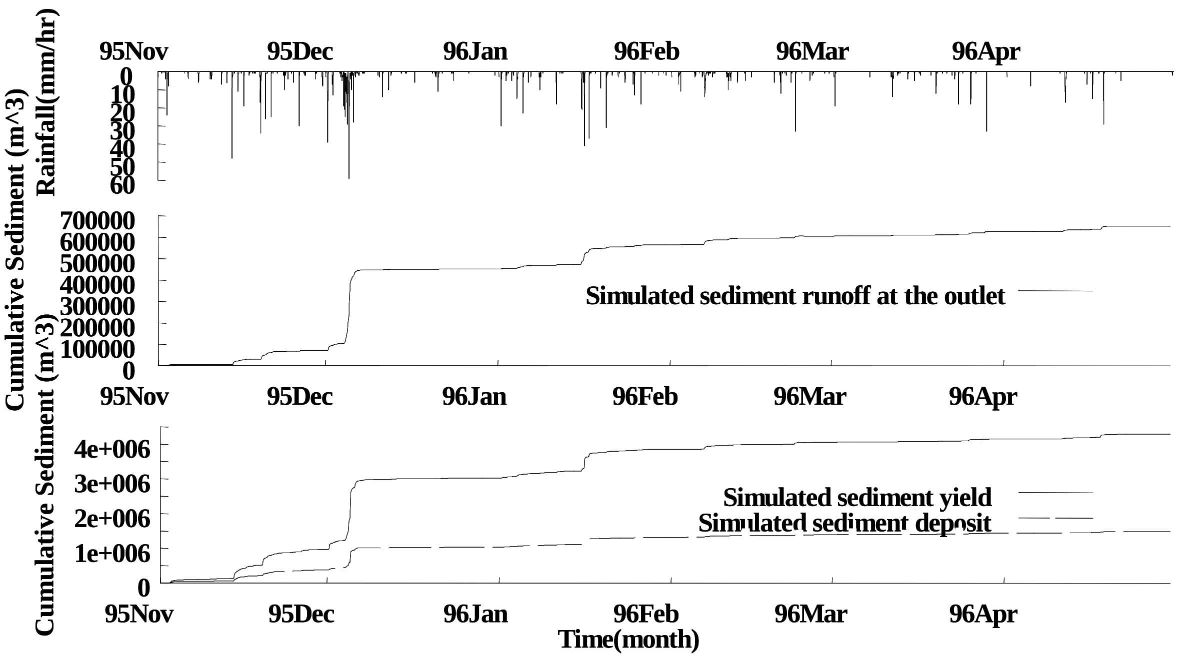

Figure 9. Rainfall sediment runoff analysis in a rainy season from 1995 to

5 CONCLUSIONS

With the aid of GIS and remote sensing, this paper applied the distributed rainfall-sediment-runoff model to the Brantas River basin, Indonesia. The model calculated sediment movement on each grid-cell based on water energy, which contributed to sediment transportation, without introducing any sediment movement parameters. Simulating water movement can simultaneously express the spatially distributed sediment movement processes depending upon land cover and geology. The sensitivity of model parameters, such as equivalent roughness coefficient, surface layer depth, and permeability to the sediment yields was also investigated. As a result, the places, with small permeability, thin surface layer, and small equivalent roughness, yielded larger amounts of sediment. These conditions would often be found in the deforested mountain areas covered with fine volcanic ash as in the Lesti River basin. The verification indicated the model's good performance that reproduced the actual sedimentation record during a rainy season. Further, it was noted by the simulations that the erosion rate at the cultivated hillslope of Mt. Semeru was higher than that in other places. As mentioned in Section 2, further research is necessary to understand variability of vegetation activity, which would significantly affect sediment runoff processes.

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