Numerical Model for Quantifying the Function of Soil Erosion and Sediment Transport Controls at Slope Agricultural Lands

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Abstract. The objective of this study was to build a numerical model that has the capability to account for the effect of various water and soil conservation practice scenarios in reducing erosion rate and sediment loads along slope cultivated lands. As further, inter-rill and rill erosion were implicitly represented by the raindrop and overland flow soil detachments. The observed surface runoff and sediment concentration data in response to incoming water from the rainfall within selected agricultural river catchments were used to evaluate the performance of spatially distributed, processed-based Hillslope Erosion and Sediment Transport Model (HESTM). As erosion and sediment yield from slope lands are primarily determined by rainfall, surface runoff, topography, vegetative canopy cover, ground surface cover, soil erodibility, and sediment properties. Thus, several scenario-based control strategies according to three clusters of water erosion and sediment control measures had been examined. They are agronomic measures and soil management; field management; and mechanical approach. Accordingly, scenario-based water and soil conservation practices were designed for setup numerical experiments of the model at selected water catchments located in the Upper Citarum and Cimanuk River basins, West Java which dominated by planted seasonal crops (carrot and potato). The study area was discretized into a spatial resolution of 30 x 30 m for considering heterogeneity and control measures function in rainfall-runoff-erosion-sediment process mechanisms.

Keywords: distributed model; runoff-erosion-sediment control; planted seasonal crops; water and soil conservation

1. Introduction

Surface runoff, soil erosion and sediment yield has important implications for agricultural land sustainability, water quality, and water resources. On the steep slopes and agriculture lands, surface runoff associated with soil erosion consequences to topsoil degradation, loss of agriculture productivity and increased export of sediment and contaminants to lower area. Likewise, rivers themselves, irrigation system, various hydraulic and water resources structures are suffering from sedimentation problems. Furthermore, soil erosion and transported sediment material affect the water quality of water bodies and increase the flood risk due to sedimentation. From these considerations, estimation and quantitative information in surface runoff, soil erosion, and sediment yield with time and space at a particular scale are very important for the solution of a number of problems [1]. Design of soil conservation and land-use planning, water quality and aquatic habitat management, and design of the dam and reservoir are some of the examples.
The problem, most of the areas prone to the water and sediment production are ungauged (no measurement and monitoring) sites because most of them are located in mountainous terrains, thus a question appeared in this study “which is the suitable model type to be used for predicting runoff-erosion-sediment of ungauged internal locations at a river catchment or slope unit?”. In terms of management practice, location of the runoff and erosion source areas, the volume of water, and sediment yields under certain management practice programs are some of the factors that should be quantified before deciding what sediment runoff control treatment is best suited for a problem. In addition, the processes controlling runoff and sediment are complex and interactive. This complexity results in the term “runoff-erosion-sediment processes” internal catchment area. The process is highly dependent on rainfall, topography, land use, soil type, and existing best management practices. Therefore, to develop and using a physically-based distributed rainfall-sediment-runoff model [2] for the above purpose is the best option.

Physically-based distributed model type features the capability to incorporate a variety of spatially varying process mechanisms on climate variable, topography, land-use, soil properties, and other forcing data input. Additionally, the distributed model applications can be intended for ungauged or poorly gauged sites [3]. Development and application of distributed model type especially in purpose for predicting and designing of runoff and erosion control that dealing with Indonesian cases have not appeared much in literature. Thus, the objective of this study was to construct a numerical distributed model type that has the capability to account for the efficiency of various water and soil conservation practice in reducing erosion rate and sediment yields along slope cultivated lands (or river catchments).

2. Materials and Method

![Figure 1](image-url)

Figure 1. The framework of runoff-erosion-sediment modeling at a grid-scale. The catchment area or a unit slope is discretized into the smallest scale as called “grid” which having a certain spatial resolution. The water and eroded sediment material is routed from one grid to other grids toward the lowest point (outlet) following flow direction information of each grid.

A physically-based distributed runoff-erosion-sediment model has been developed to simulate and predict the runoff generation, soil erosion, and sediment production generated from either any temporally-spatially varied rainfall event or continuous rainfall time series. The model name is Hillslope Erosion and Sediment Transport Model (HESTM). The modeling approach is deterministic, physically-based, spatially distributed and dynamical in time. Dynamic spatial of water movements, erosion or deposition patterns, and sedimentation rates can be predicted at any location inside of the catchment/unit slope. The concept of physically-based distributed runoff-erosion-sediment is shown in Figure 1. The target area modeled into the smallest scale of sub-catchment, namely “grid” which has a size of spatial resolution. Runoff generation and net erosion (either erosion or deposition) are initially
calculated from each grid. The model structure consists of three sub-modules: (1) rainfall-runoff; (2) soil detachment and sediment transportation; (3) the function (constants) of soil and water conservation practices. Thus, runoff-erosion-sediment simulation can be divided into two parallel phases, those are runoff generation and soil detachment.

The rainfall-runoff sub-module was based on a kinematic wave approach and simulates three lateral flow mechanisms, including subsurface and surface flows [4]. The model simulates: (1) subsurface flow through capillary pores; (2) subsurface flow through non-capillary pores; and (3) surface flow of the soil surface. Accordingly, then a soil erosion and sediment transport algorithm was newly added to obtain soil erosion and sediment sub-module. Runoff generation, soil erosion, and deposition are computed for each grid as DEM (i.e 90-m spatial resolution) and are routed between grid following overland flow direction defined according to the kinematic wave approach. The soil erosion and sediment transport algorithm include multiple soil erosion process mechanisms, which are soil detachment by raindrop (DR) and soil detachment driven by overland flow (DF). Herein, soil detachment processes associated with inter-rill and rill erosion are implicitly simulated as raindrop splash and surface flow detachment, respectively. The basic assumption of this model is that the sediment is yielded when overland flow occurs. The eroded sediment is transported by overland flow to river channels. Soil detachment and transport is handled with the continuity equation representing \( DR \) and \( DF \) as:

\[
\frac{\partial(h_c C)}{\partial t} + \frac{\partial(q_s C)}{\partial x} = e(x,t) \tag{1}
\]

\[
e(x,t) = DR + DF \tag{2}
\]

where \( C \) is the sediment concentration in the overland flow (kg/m\(^3\)); \( h_s \) is the water depth of overland flow (m); \( q_s \) is the discharge of overland flow (m\(^3\)/s); and \( e \) is the net erosion (kg/m\(^2\)/hr).

In this study, the concept of Transport Capacity (TC) of overland flow has been used in determining the net erosion over each grid. The transportation capacity is calculated based on the Unit Stream Power (USP) theory that can be applied for sediment transport in open channels and surface land erosion [5]. The sediment transport rate using the USP approach could be determined as a function of flow discharge, average flow velocity, energy slope, and shear stress. Herein, the USP theory contributing to TC defined as a product of the overland flow discharge and velocity, slope dimension, and shear stress of each grid. In addition, through USP concept is accomplished that TC depends on the particle settling velocity, shear velocity, grain size, kinematic viscosity of the water, and water density. Small particles such as clay and silt move mostly in suspension and easily carried by the flow while the sand fraction moves as bed-material and more difficult to move by flow (Figure 2). Net erosion in the form of either erosion or deposition gained by overland flow over a grid is...
assumed to be proportional to the TC deficit. Following the TC approach; if actual sediment concentration from upper grids is lower than this capacity, then erosion occurs, otherwise soil deposition excess takes place.

The runoff-erosion-sediment continuity equation (Equation 1) was solved numerically using the Mac-Cormax finite difference scheme. Once the flow variables are obtained by the Lax-Wendroff scheme, Equation (1) can be explicitly solved for sediment concentration \( C \), and erosion and deposition can be estimated and routed through the flow direction and channel network. Mac-Cormack scheme is another scheme that introduces assistant grids as a two-step Lax-Wendroff scheme. The general concept of the time and space derivatives of \( C \) at a grid using the Mac-Cormack scheme is approximated in Figure 3.

![Figure 3. Mac-Cormax box for solution of the runoff-erosion-sediment continuity equation](image)

The model has been designed to be applicable for multi scales, from a lope unit scale, single river catchment, multi river catchments, and to national scale. The model is especially constructed for the tropical region and agricultural landscapes dominated by steep to middle slopes. To apply the model, spatial information related to meteorological components, hydrotopography (DEM, slope, flow direction, flow accumulation, river networks), soil type and its property, and land-use are the minimum data is requested for the model input.

To assess and accounting the function of selected soil and water conservation practices intended to control the runoff, soil erosion, and sediment then a sub-module has been added to the model. Simple empirical equation and trapping efficiency value that describes the control function at a particular location or grid can be inserted as the module.

### 3. Results and Discussion

#### 3.1 Model Calibration and Validation

The performance of the physically-based distributed runoff-erosion-sediment model described in the previous section can best be illustrated by applying the model to the total runoff response and yielded sediment in actual catchments, in this case, the Upper Citarum River catchment is selected for the model calibration, using long-term simulations. Model calibration was done by adjusting the model parameters in order to obtain the best fit between the model output and the observed data. Adjustment of the final parameters was undertaken by performing Monte-Carlo-type simulations, on the basis of best model performance. The year 2010 was selected as the calibration period. Sediment discharge data from the Nanjung Station (the main inlet of Saguling Reservoir) was used to calibrate the model output. The GSMaP (Global Satellite Mapping for Precipitation) Re-analysis Products with spatial resolution 11-km, distributed in and around the basin, was utilized to account for the distribution of rainfall.
Observed and simulated cumulative water and sediment yield at Nanjung Station are summarized in Figure 4, in which each panel shows the result of calibration. The results depicted in Figure 4 indicate that after calibration, the model yielded comparable results with respect to long-term daily cumulative streamflow and sediment yields. The model generally predicted the overall shape of hydrographs of cumulative water and sediment yields reasonably well. The performance of the streamflow model was evaluated using the Relative Error (RE). The RE values for the calibration period resulted in low values (1–10%), indicating that the model can effectively predict hydrological responses. The model satisfactorily reproduced the observed sediment yield at the Saguling Reservoir inlet, which was estimated to be about 7.0–8.0 million tons year⁻¹.

Then, the same calibrated model parameter is used in the next model application. Using the same parameters from the calibration period, the model was run for the validation period at the Cibodas River, an agricultural sub-catchment in the Upper Cimanuk River basin, West Java. The model validation was performed at a 2-minute time step with the grid size of 30 m x 30 m. So, here the model setup used higher spatio-temporal resolution compared to the calibration period. The calibration result with its performance index values (Nash-Sutcliff coefficient of Efficiency, NSE; and RE) presented in Figure 5. Wherein, the predicted river discharge (runoff) and sediment concentration are compared with the observed ones. The model is generally successful in representing broad trends of water discharge and sediment concentration in the validation phase.

3.2 Model Application to Detect Hot-spots Area of Erosion & Deposition

Locations of the surface runoff, erosion, and deposition source areas at the internal location of the target area as well as the delivered sediment yield under certain landscape management are some
information that should be quantified before deciding what runoff-erosion-sediment control treatment such as through soil and water conservation is best suited for a problem. The measurement of erosion and sediment-runoff rates in the fields are some of the limitations, while direct surface measurements are preferable, these are often difficult to obtain from an observational, logistical, and instrumental point of view. In this context, the developed physically-based distributed runoff-erosion-sediment, HESTM model provides the necessary tool to provide such as the hot spot locations spatially at the internal area that contributes to highly produce runoff volume, erosion rate, and deposition rate. **Figure 5** shows the map of average river discharge, total eroded, and deposited soil in response to a rainfall extreme event at the Cibitung River, in the Upper Citarum River basin. This kind of information can be used in the identification of priority locations; and selection of appropriate water and soil conservation techniques.

![Diagram of river discharge and sediment](image)

Debit Aliran = River Discharge (m³/sec)
Total Erosi = Eroded Volume (m³)
Total Deposisi = Deposited Volume (m³)
3.3 Model Application to Account the Function (Reduction) of Runoff, Erosion & Sediment Controls

The model has been used for assessing the reduction function of selected control measures in controlling surface runoff, soil erosion, and sediment yields, such as using alley cropping system, terrace, and “rorak” farming systems. The scenario of control measures plans performed at Cibodas Sub-Catchment, which located in the Upper Cimanuk River Basin, West Java. Existing land-use condition and spatial information of the slope (Figure 7) is used as the basic information in drilling scenario-based control measures as listed in Table 1. The estimated result in the percentage reduction of the total runoff volume and eroded soil over the catchment as well as sediment yield at the river outlet compared to the existing land-use condition can be seen in Table 2.

![Figure 6. Application of the module runoff-erosion-sediment (HESTM) model at the ecohydrology demo site location (Cibitung River catchment, the Upper Citarum River basin) for quantification and prediction of spatial distributions on river flow regimes (top-left); hot-spots of high soil erosion rate (top-right); and hot-spots of high soil deposition rate (below-center) as a response to rainfall with particular duration. Accordingly, the priority locations and its type ecotechnology or hydro-technique for reducing surface runoff, soil erosion, and trapping sediment transportation could be identified.](image)

![Figure 7. Spatial slope (%) information (kemiringan lereng in bahasa) of the Cibodas River sub-catchment in the Upper Cimanuk River basin, West Java as basic information in designing soil and water conservation practices.](image)

| Slope Criteria | Control Strategy Plan | Description |
|----------------|-----------------------|-------------|
| Slope > 45%    | Planted seasonal crops (i.e carrot and potato) replaced by annual crops (perennial trees/forest); | ![Image](image) |
| Slope 25-45 %  | Planted seasonal crops combined with terrace system and using vertical mulching; | ![Image](image) |
Table 2. Estimated % reduction in response to various control plans of soil & water conservation practice

| Component                | Reduction (%) |
|--------------------------|---------------|
| Surface Runoff           | -22.93%       |
| Total Eroded Soil        | -47.32%       |
| Sediment Yield           | -39.34%       |

4. Conclusion

A numerical model to represent the process mechanism of rainfall-runoff-erosion-sediment transportation and its control measures function in various scales (from a unit slope to river catchment scale) has been developed. Herein, a physically-based and the distributed model type was selected as the common platform in the model development. The model output performance in reproducing the observed water and sediment yields at some selected agricultural river catchments has been evaluated, and it shows good performance. The model has the potential capability to account for the efficiency of various water and soil conservation measures in reducing the rate (or volume) of surface runoff, eroded soil, and produced sediment yield. Detailed model development and application with a high temporal and spatial resolution at one cultivated slope unit will be the main concern for the further step of this study.

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