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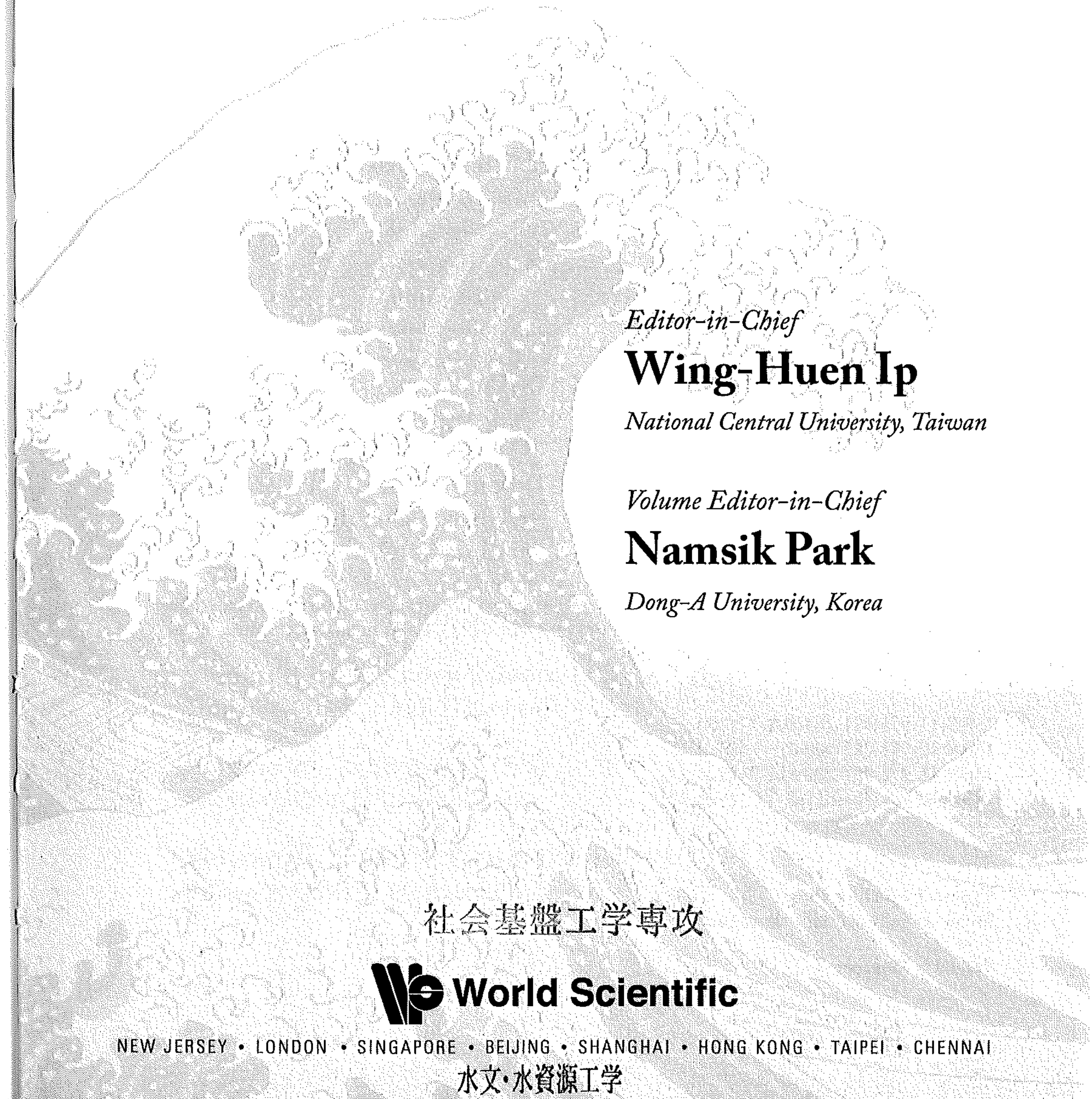

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A DISTRIBUTED-LUMPED MODEL FOR FLOOD AND SEDIMENT YIELD PREDICTIONS AT THE CATCHMENT SCALE

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This study proposes a lumping method for a physically-based distributed sediment runoff model. A distributed-lumped model obtained by the lumping method enables to predict flood and sediment yield on a real-time basis by considering hydrological and transport processes. First, model lumping of distributed kinematic wave rainfall runoff and erosion sediment transport equations is developed, which is the integration processes of spatially distributed equations assigned to each grid-cell over landscape. Then, lumped discrete relations between the variables, namely a stream discharge and a maximum sediment storage capacity is produced as a function of stored water volume in the catchment. Stream flow and sediment yield are predicted by using these discrete time-invariant relations and lumped continuity equations. The performance of distributed-lumped model was confirmed from the case study the Lesti River catchment, Indonesia.

1. Introduction

The Brantas River, 320 km length with 39 tributaries and a catchment area about 11,800 km^2, is the second largest river located in East Java. The Lesti River catchment (351.3 km^2), a tributary catchment in the Upper Brantas River basin is selected as study area. At the confluence point of the Lesti River and the Brantas main reach, the Sengguruh dam was constructed in 1988 for water resources and hydropower generation. Its original gross storage in 1989 was 22.4 million m^3 and reduced to 5.5 million m^3 in 1993. Unexpectedly, most of the gross storage has been already filled with the large amount of sedimentation from the Lesti River.[1] In order to protect the capacity of the reservoir and manage water resources from sedimentation caused by flood events, it is necessary to predict water and sediment inflows to the reservoir.

Many complex distributed models have been developed to understand the spatial dynamic sediment yield and transportation at the catchment scale. A physically-based distributed sediment runoff model considers multiple sources of sediment transport, namely soil detachment by raindrops and soil detachment by overland flow developed by the authors.[2] However, the direct applications of the model to the real-time flood and sediment yield predictions are still limited because of the high computational requirement especially when stochastic algorithms are included. Thus, the model originated from a physically meaningful model structure and parameter with less computational requirement has a great potential to be used to the real-time flood and sediment predictions on coping with predictive uncertainty. It due to the most of proposed uncertainty assessment approaches conduct Monte Carlo type simulations with long time-consuming process.

One of the potential ways to step forward and overcome the high computational burden is by structural lumping of physically-based distributed models as pointed out by various researchers.[3,4] The lumping kinematic wave equation of a physically-based distributed sediment runoff model is addressed in the study. This paper focuses on (1) proposing a new method to lump a physically-based distributed sediment runoff model at the catchment scale and (2) subsequently constructing a distributed-lumped model as a new type of lumped sediment runoff model which preserves the physical meaning of the hydrologic and sediment transport processes. The paper describes the overall model structures and the lumping method, as well the reliable application of the model at the Lesti River catchment, Indonesia. Mathematical formulation of the physically-based distributed sediment runoff model and its distributed-lumped version are provided following section.

2. Physically-Based Distributed Sediment Runoff Model

The hydrological model[5] considers three principal water flux pathways within a catchment: subsurface flow through unsaturated flow (capillary pore), subsurface flow through saturated flow (non-capillary pore), and surface overland flow. Based on stage-discharge relationship,[6] after the water depth is greater than the surface soil layer, the net rainfall will accumulate as surface water and begin to flow as overland flow. Subsurface and surface flows in both land surface and river channel networks are computed as one-dimensional kinematic wave equation. In a given rainfall event, rainfall is directly added to subsurface or surface flow according to the water depth, depending on the rainfall occurring in a grid-cell.

The stage-discharge, $q - h$, relation for both surface and subsurface flows:

$$q = \begin{cases} v_m d_m (h/d_m)^\beta, & 0 \le h \le d_m \\ v_m d_m + v_a(h - d_m), & d_m \le h \le d_a \\ v_m d_m + v_a(h - d_m) + \alpha(h - d_a)^m, & d_a \le h \end{cases} \tag{1}$$

$$\nu_m = k_m i, \quad \nu_a = k_a i, \quad k_m = k_a/\beta, \quad \alpha = \sqrt{i}/n$$

where q is discharge per unit width, h is water depth, i is the slope gradient, k_m is the saturated hydraulic conductivity of the capillary soil layer, k_a is the hydraulic conductivity of the non-capillary soil layer, d_m is the depth of the capillary soil layer, d_a represents the depths of the capillary and non-capillary soil layers, β is the exponent constant of unsaturated flow, v_m and v_a are the flow velocities of unsaturated and saturated subsurface flows, respectively, and n is the roughness coefficient based on the land cover classes.

A sediment transport algorithm was newly added to the hydrological model. Soil erosion and deposition are described in terms of processes occurring on hillslopes. The sediment transport algorithm includes multiple sources of sediment transport, namely soil detachment by raindrops (d_r) and soil detachment or deposition driven by overland flow (d_f).

Soil detachment by raindrops is given by an empirical equation in which the rate is proportional to the kinetic energy of effective rainfall. From observation of rainfall characteristics in the study area,[7] d_r is given as

$$d_r = \mu\ k\ k_e = \mu\ k\ 56.48\ r \tag{2}$$

where μ is the soil erodibility, k is a tuning parameter, k_e is the total kinetic energy of the rainfall, and r is the rainfall intensity.

The concept of sediment transport capacity was used to determine soil detachment or deposition by overland flow. Sediment transport capacity of overland flow is defined as the maximum value of sediment concentration to transport; d_f represents the sediment yield by surface flow shear stress[8]:

$$d_f = \alpha(T_c - c)h_s \tag{3}$$

where α is the detachment/deposition efficiency factor, h_s is the overland flow depth, and T_c is the maximum sediment concentration transport capacity. Following the T_c value, if the current sediment concentration c is lower than this capacity, erosion occurs; otherwise an excess of soil deposition exists.

The transportation capacity was calculated based on the unit stream power theory that can be applied for sediment transport in open channels and surface land erosion.[9] Hence T_c is estimated as

$$T_c = \log c_t = I + J \log((vi - v_{critical}\ i)/\omega) \tag{4}$$

where $v * i$ is the unit stream power (where v is the flow velocity and$i$ is the slope gradient), $c_{critical*}i$ is the critical unit stream power ($v_{critical}$ is the critical flow velocity), ω is the sediment fall velocity calculated by Rubey's equation, as well I and J are the dimensionless parameters.

The catchment is divided into an orthogonal matrix of square grid-cells (i.e. 250m $\times$ 250m), assumed to represent homogeneous conditions according to the digital elevation model (DEM). This allows the use of DEM to derive flow direction map to define the interaction between the objects which simulate sediment runoff at each grid-cell. Runoff generation, soil erosion or deposition are computed for each grid-cell and are routed between grid-cells using the kinematic wave model following the water flow direction, which defines the routine order for the water flow and sediment transport propagation.

The physically-based distributed sediment runoff model is a suitable tool allowing for the simulation and investigation of hydrological process, sources of erosion and deposition within internal location of the catchment (Fig. 1).

3. Distributed-Lumped Sediment Runoff Model Derived from the Lumping Method

A method to lump a physically-based distributed rainfall runoff model[4] was used and extended for erosion and sediment transport model. The lumping method has been developed to produce a distributed-lumped model as a new type of lumped sediment runoff model version. The original distributed model is used to derive a lumped relation between water storage volume, discharge, and maximum sediment storage of the catchment by considering spatial distribution of topographic variables, water content, and sediment

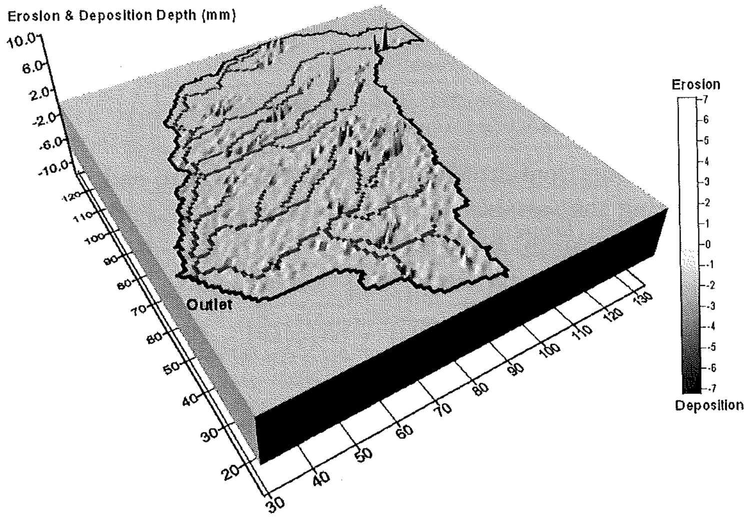

Fig. 1. Spatial distribution of erosion and deposition sources for internal location of the catchment after rainfall event on September 13–15, 2004 at the study site.

concentration transport capacity. The method proves that lumped version is derived from the distributed version. The objective of the development is not only to improve the computational efficiency but more importantly to construct a lumped formulation of the hydrologic and sediment transport equations at catchment scale by keeping the physical meaning of the distributed model. All the represented dominant processes are preserved in the lumping procedures.

The fundamental assumption of the lumping method is that the rainfall runoff process of the catchment system reaches the steady state condition with spatially uniform rainfall input. From this assumption, discharge flux can be expressed as the product of rainfall intensity and the upslope contributing areas. Then, the relation between total stored water and the outflow discharge in each grid cell is theoretically derived by integration processes of spatially distributed equations assigned to each grid cell over the landscape:

$$q(x) = q(0)/w + r\int_0^x (x)\ dx = r\ U/w + rx \tag{5}$$

where U is the upslope contributing area, x is the horizontal distance from the upstream end of a grid cell, and w is the width of the grid cell.

The stored water volume of a grid cell, s, is given as

$$s = w \int_{0}^{L} h(x)\ dx \tag{6}$$

where L is the horizontal distance at the downstream end of a grid cell. By substituting the variable of integration from x to q using the relation given by Eq. (5), Eq. (6) becomes

$$s = \frac{w}{r} \int_{q(0)}^{q(L)} f(q)\ dq = \frac{w}{r}\left[F(q(L)) - F(q(0))\right] \tag{7}$$

It is assumed that q is a function of h and can be analytically integrated with h. If the value of q is known from Eq. (5), and h is numerically obtained using Eq. (1), then $F(q(x))$ can be calculated.[10]

The stored water at the catchment scale, S_w, can be calculated by summing the s from each grid cell as follows:

$$S_w = \sum_{i=1}^{N} s_i \tag{8}$$

where N is the total number of grid cells for a whole catchment. Finally, q at the outlet is linked to S_w as a function of the topographic and physical characteristics of each grid cell, as well as effective rainfall intensity.

The sediment transport process is affected by the dynamic spatial distribution of overland flow. For lumped representation of the catchment, soil detachment or redeposition depends on the balance between the current sediment concentration and maximum sediment storage capacity. The maximum sediment storage variable is produced from lumping distributed erosion-sediment transport equations as

$$S_s^{\max} = \frac{\sum_{i=1}^{N} (T_c s_{ws})_i}{S_w} \tag{9}$$

where s_{ws} is the surface water stored in each grid cell if $h > d_a$. Variable T_c is then calculated using Eq. (6). According to the relation between the current sediment storage, S_s, and S_w for each time-step calculation, the value of c from the hillslope area can be solved by

$$c = \frac{S_s}{S_{ws}} \tag{10}$$

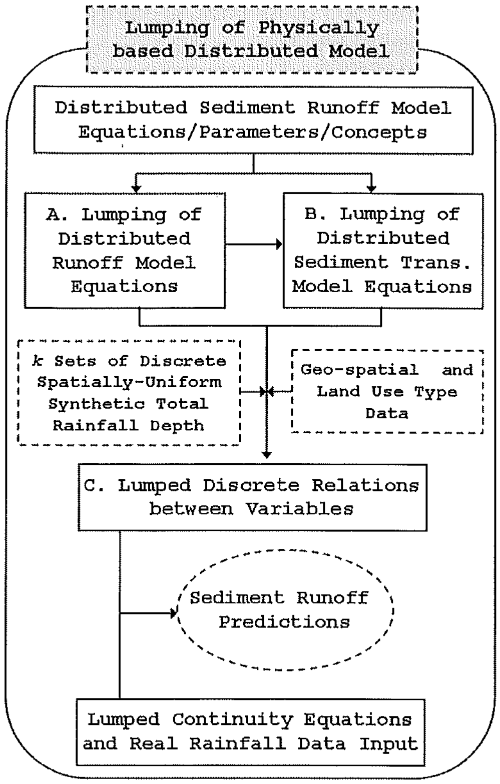

Fig. 2. Schematic diagram of the procedures to develop a distributed-lumped sediment runoff model based on the lumping method.

where S_{ws} is the total stored water surface of the catchment. For each time-step calculation, c is assumed to be uniform over the catchment and is the variable of lumped continuity.

In brief, the procedures to develop the distributed-lumped sediment runoff model version (see Fig. 2) may be summarized as follows:

1. Based on the original distributed equations and their physically meaningful parameterization, lumping process of the distributed model is done by spatially integrating kinematic wave runoff and sediment transport equations for each grid-cell over the entire catchment system.
2. Obtain the lumped discrete relations between the variables, namely the stream discharge, the total water stored amount, and the maximum sediment storage capacity. It may be conducted by spatially distributed

information on land use, soil properties, geomorphology and topology, as well for k sets of different synthetic rainfall intensity (i.e. from 1, 2,... to 500 mm/hr). Finally, it prepares the lumped relations in the "look-up" table form, which is time-invariant values and considered as parameters of the lumped model. Thus the innovative aspect of this method is these lumped model parameters (Fig. 3) can be derived directly from the distributed model without adding any calibration or parameterization. This feature can solves the major disadvantage of traditional lumped models, which lacks physical background of the parameters.

3. Streamflow and sediment concentration are predicted and updated using lumped continuity equations and real rainfall intensity. They related to each of discrete relations which summarized in the "look-up" table. Lumping of original distributed model leads to transforming the water flow and suspended sediment transport routing processes into a cascade of non-linear reservoirs represents the cacthment as a whole of the form as shown in Fig. 4. It transforming kinematic wave routing process into storage routing process as lumped continuity equations.

4. Model Evaluation and Discussions

The sediment runoff models both the distributed and lumped have been applied to the Lesti River catchment shown in Fig. 5. The parameter values of the original distributed model version: roughness coefficient n (0.001–0.3 $m^{-1/3}s$); depth of capillary and non-capillary soil layer d_a (0.08–1.2 m); depth of the capillary soil layer d_m (0.04–0.8 m); hydraulic conductivity of the non-capillary soil layer K_a (0.015 m/sec); exponent constant of unsaturated flow β (8); median of grain size D_{50} (0.062 mm); soil detachability k (0.004 kg/J); and detachment/deposition efficiency factor α (0.98).

Figures 6 shows a comparison between the values of simulated streamflow and sediment concentration at the outlet (Tawangrejeni station) for two scenarios of soil thickness with the same rainfall intensity and total depth calculated through the distributed and the lumped models. The evaluation results suggest that in the case when soil thickness is shallow (Case 1), the discrepancy of estimated values for both the streamflow and sediment concentration by the lumped and distributed models is generally less than that of the case the soil is thicker (Case 2).

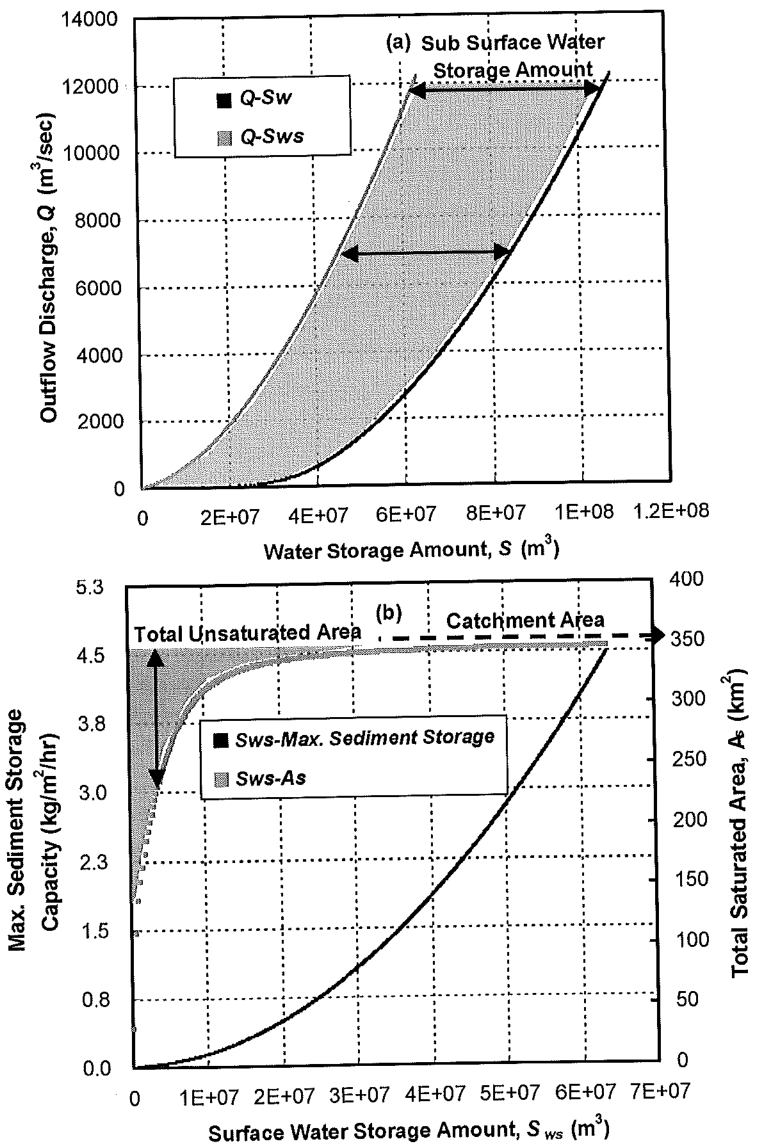

Fig. 3. (a) Plots of lumped discrete relations between variables of $Q - S_w$ and $S_{ws} - S_w$; and (b) discrete relations between $S_s^{max} - S_{ws}$ and $A_s - S_{ws}$ for 1150 different sets of rainfall intensity.

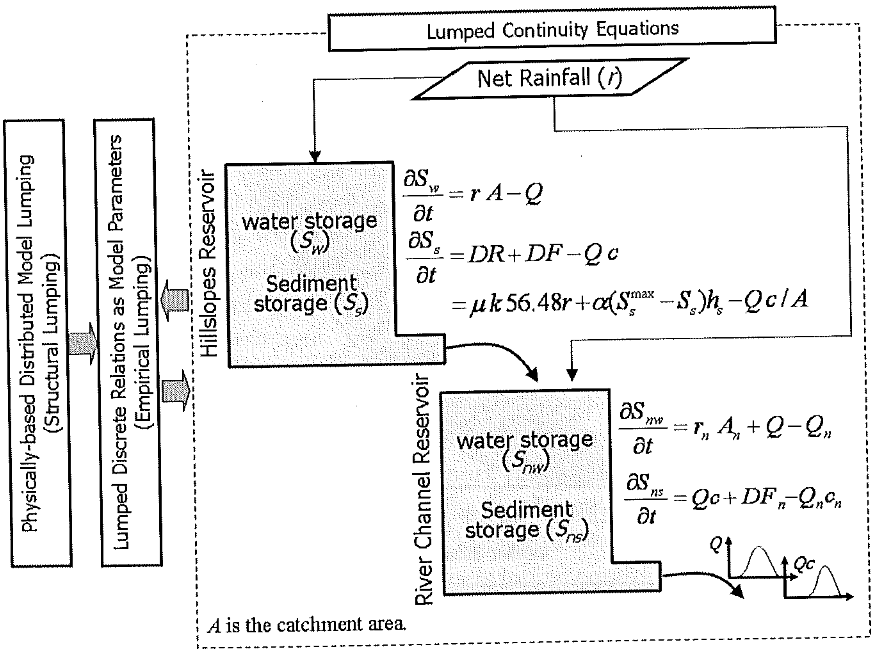

Fig. 4. Conceptual scheme of the new lumped sediment runoff model structure.

The difference increases with the soil thickness, where the lumped model results generally have a tendency to underestimate streamflow and sediment concentration at the rising limb, and over estimate at the falling limb of hydrograph and sedimentgraph. This difference is due to the assumed steady state condition in deriving the lumped model. In Case 2, at the beginning time of event, the catchment system does not reach a steady state yet, rainfall stored in the soil layer flows is rather slow, and therefore streamflow is insensitive to rainfall intensity. Afterwards, the soil layers are easily saturated and once the water depth at the most area of catchment exceeds the capacity of the capillary soil layer, streamflow rises up suddenly. This implies it was not correct for the event to assume the steady state condition at the beginning of the simulation in Case 2. Thus the second discrete relation of $Q - S_w$ for the lumped model shows some difference from the distributed one. Another possible reason is that in the distributed model, the setting of initial conditions causing some parts of the catchment are already saturated (i.e. river channel area) and overland flow happens thus the rising limb of the hydrograph is faster than the lumped

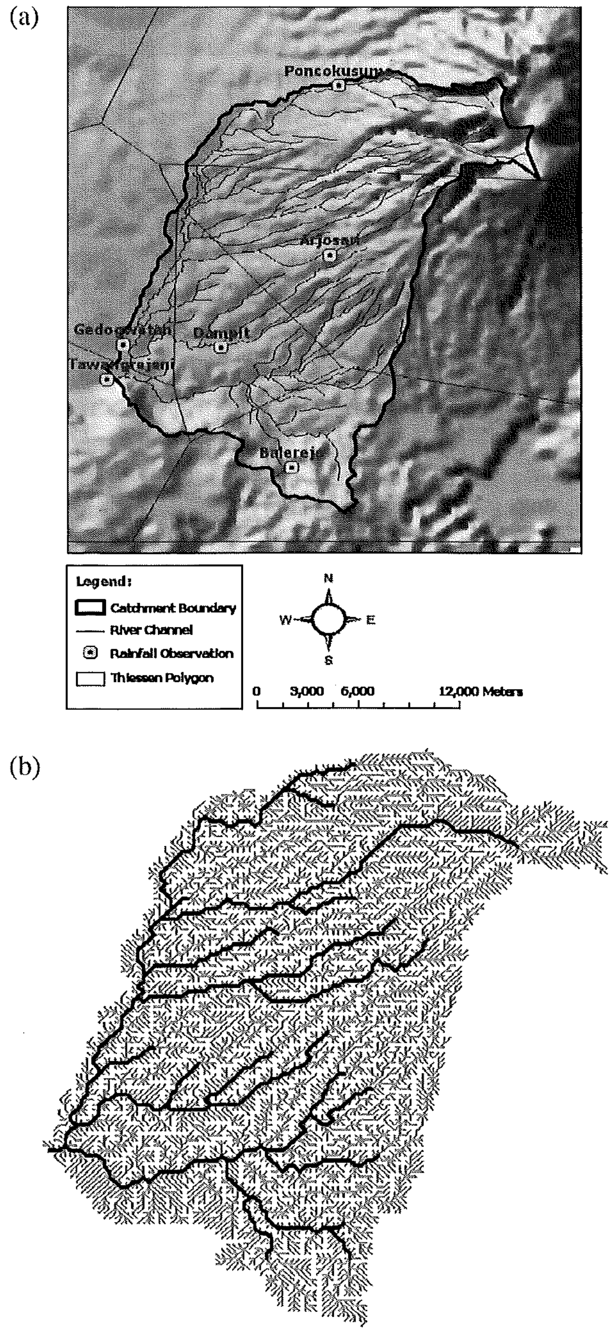

Fig. 5. (a) Lesti River catchment: river system, catchment boundary, and rainfall observation sites; and (b) its flow direction map.

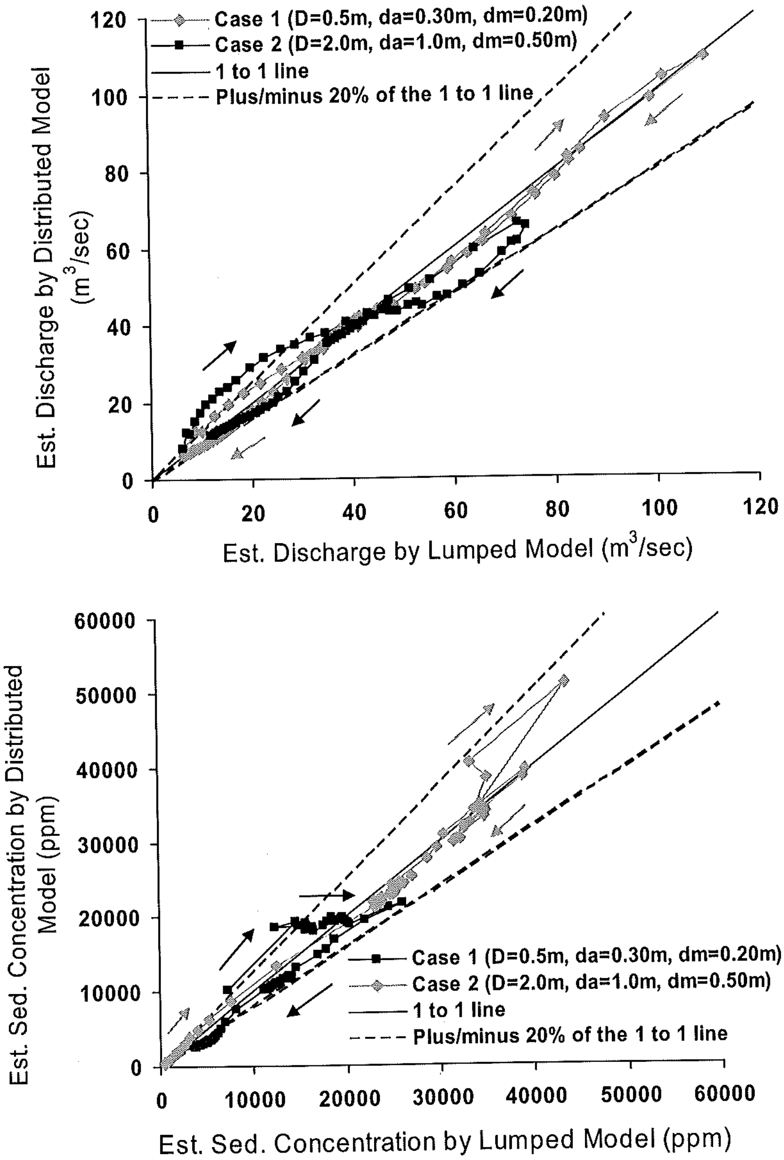

Fig. 6. Comparisons of hysteresis loops of outflow discharge and sediment concentration for various cases of soil thickness (D) through original distributed model and its lumped model version.

Table 1. Sim
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Variables
Runoff (m^3)
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Table 1. Simulated cumulative streamflow and sediment concentration for two simulation cases.

Variables	Cases	Distributed model	Lumped model	Difference (%)
Runoff (m^3)	Case 1	2724.20	2776.63	1.56
	Case 2	2192.48	2293.90	4.63
Sediment yield (kg)	Case 1	1517.05	1548.86	2.10
	Case 2	856.45	909.13	6.15

one. On the contrary, the capacity of non-capillary layer $d_a - d_m$ in Case 1 is smaller as compared to Case 2. The catchment system rises up to dynamic steady state condition, and lumped model results show better performance belonging to the original distributed model than in Case 2.

The above experiments showed that the lumped model version, structured according to the proposed lumping method, produces acceptable results. Within the range of possible soil depths, the difference is small and does not cause severe problems for the application. In addition, the lumped model successfully reduced the computational burden. Simulation time of the lumped model was about 1/37 of that of the original distributed model. Table 1 summarizes the differences in cumulative total runoff and sediment yield calculated by lumped and distributed models, which are all lower than 7%.

Figure 7 plots computed streamflow discharges and sediment concentrations by the lumped model compared to the observed data. The simulation results of the lumped model shows good agreement with the observed one.

5. Conclusions

The Lumping method of a physically-based distributed sediment runoff model has been developed. The advantage of the method is that the lumped model preserves hydrological and sediment transport processes, as well the model parameters derived from the original distributed model does not require additional calibration. From the case study in Indonesian river catchment, we confirmed both distributed model and the newly developed lumped model can indicate the reliable application compared to the observed streamflow discharge and sediment concentration. The discrepancy between the two models increases as the soil layer becomes

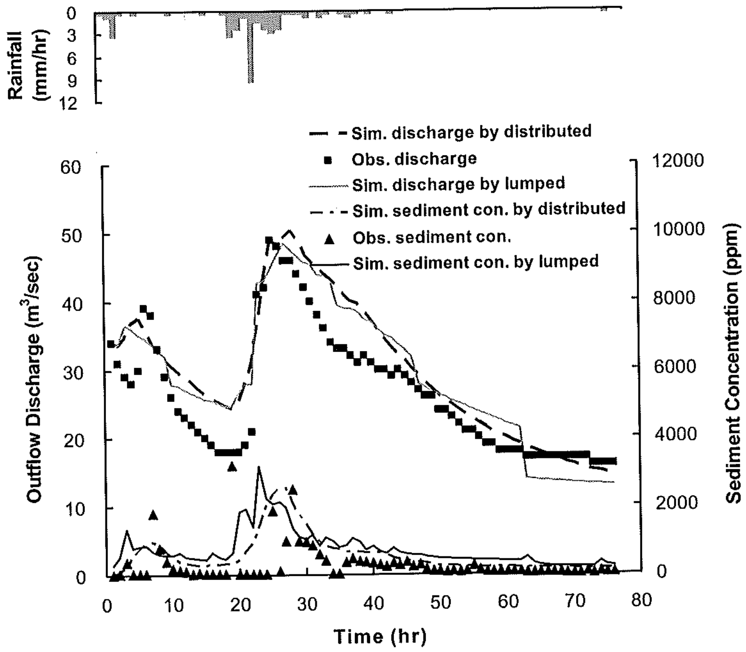

Fig. 7. Event sediment runoff observation and simulation at the catchment outlet in 2003.

thicker, rainfall amount decreases, and the spatial-temporal variability of input rainfall intensity become more significant. These are mainly due to the steady state assumption that lies under the lumping method. The proposed distributed-lumped sediment runoff model is an effective way, particularly for the practical applications on the real-time basis in combination with stochastic analyses.

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