STUDY ON SEDIMENT YIELD AND TRANSPORT PROPERTIES USING A DISTRIBUTED RUNOFF MODEL

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ABSTRACT

The objective of this research is to improve prediction performance of a distributed rainfall and sediment runoff model for better reservoir sedimentation management. The authors construct an analytical model for dealing with sediment production from slope failure and transport process, and it became possible to estimate sediment inflows by torrential rain. However, it had left the challenges to understand the dynamics of each sediment origin. This paper clarifies the basin-scale dynamics of sediment during torrential rains, by improving the model to be able to identify the grain size of sediment movement due to each of the slope failure and the deposition of river bed. The developed model is applied to the Tokai heavy rains in Yahagi Dam (504.5 km^2), in Chubu, Japan. The model represents the physical process of sediment movement from the sediment yield area to the dam reservoir during a torrential rainfall.

INTRODUCTION

As time passed, Dam reservoirs have to face functional deterioration due to sediment deposition without continuous sedimentation management. In particular, it is said that a number of occurrences of the local downpours due to global warming are increasing recent years. Therefore, predicting the large-scale reservoir sedimentation due to torrential rainfall is one of the most important issues not only for managing the risk of short-term loss of reservoir capacity and for efficiently maintaining sediment disaster prevention facilities but also for the integrated water resources management.

Against the above background, physically-based simulation models have recently been developed for studying the process of sediment runoff in the basin (e.g. works of Egashira et al. 2000, Sayama et al. 2003, Nakagawa et al 2007, Apip et al. 2008). These models focus on the sediment transport phenomenon caused by riverbed sediments but give no consideration to the sediment production process caused by slope failure.

The authors, in an attempt to compensate for the defect, developed a rainfall and sediment runoff model that enables the consideration of the slope failure process (surface failure) during torrential rains, based on a distributed rainfall and sediment runoff model

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developed by Sayama et al. (2003). The developed model is applied to the Tokai heavy rains in September 2000 at the Yahagi Dam (504.5 km^2), in Chubu, Japan. However, being strongly dependent on the initial conditions of river sediments, the model needs to understand the dynamics of sediment origin (Nagatani et al. 2009).

In this study, in an attempt to solve the above problems, a model was developed that considered the non-equilibrium property of suspended load, and identified the sediment runoff caused by initial channel sedimentation and by slope failure. The developed model was used to estimate the basin-scale sediment dynamics during heavy rains.

OUTLINE OF PREVIOUS STUDY MODEL

The runoff model is based on a cell based distributed runoff model developed by Kojima et al. (1998). The sediment runoff model and slope failure model described below are applied to the aforementioned model to calculate runoff consecutively from the upstream slope to downstream slope according to the basin topography.

Rainfall runoff model

A model developed by Tachikawa et al. (2004) is used that considers unsaturated flow, saturated subsurface flow and surface flow. The concept can be expressed as shown in Figure 1. The basic flow equation is given below.

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r(t)=f\cdot R(t), \tag{1}$$

$$q=\begin{cases} v_c d_c (h/d_c)^{k_a/k_c} & , (0\le h\le d_c), \\ v_c d_c + v_a (h-d_c) & , (d_c < h \le d_s), \\ v_c d_c + v_a (h-d_c) + \sqrt{i/N}(h-d_s)^m & , (d_s < h), \end{cases} \tag{2}$$

where, h is the water depth, q is the discharge per unit width, $r(t)$ is the effective rainfall intensity, f is the runoff coefficient, $R(t)$ is the measured rainfall amount, and v_c , v_a and d_s , d_c are mean velocities and the depth of layer of unsaturated and saturated flows, i is slope gradient, N is roughness coefficient of slope surface, m=5/3 (const.).

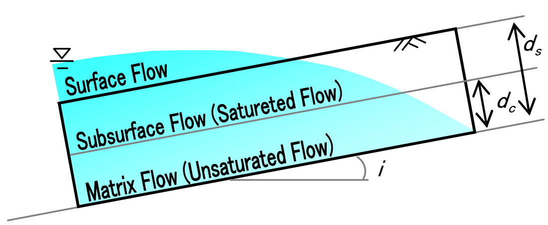

Figure 1. Modeling of Soil Structure.

Sediment runoff model

Calculation of bed material load. For calculating the bed load discharge, a sediment load calculation equation of Ashida and Michiue (1972) was adopted. According to the results of an existing observation experiment (NILIM, Japan, 2005), sediment load increased discontinuously where the value of non-dimensional tractive force was around 1.0. Then, bed load discharge was calculated as shown below.

$$Q_{bj}(x_i) = 17B\sqrt{sgd_j^{\,3}}\, p_j \tau_{*j}^{3/2}\left(1-\frac{\tau_{*cj}}{\tau_{*j}}\right)\left(1-\frac{u_{*cj}}{u_*}\right) \qquad (\tau_{*j} \le 1.0), \tag{3}$$

$$Q_{bj}(x_i) = 17B\sqrt{sgd_j^{\,3}}\, p_j \tau_{*ej}^{3/2}\left(1-\frac{\tau_{*cj}}{\tau_{*j}}\right)\left(1-\frac{u_{*cj}}{u_*}\right) \qquad (\tau_{*j} > 1.0), \tag{3'}$$

where, $Q_{bj}(x_i)$ is the bed load discharge by grain size, B is the river breadth, s is underwater specific gravity of sediment, g is the gravity acceleration, d_j is the grain size, p_j is the content of d_j-diameter grains, u_* is the friction velocity, u_{*cj} is the critical friction velocity of d_j -diameter particle, τ_{*j} is the non-dimensional tractive force of particle with grain size d_j, τ_{*ej} is the effective non-dimensional tractive force of particle with grain size d_j and τ_{*cj} is the non-dimensional critical tractive force of particle with grain size d_j.

Calculation of suspended load. The following equation was applied to calculate the suspended load by grain size on the assumption of equilibrium.

$$Q_{sj}(x_i) = \int_a^h c(z)u(z)\mathrm{dz}, \tag{4}$$

where, $Q_{sj}(x_i)$ is the suspended load by grain size, a is the elevation of reference level, z is the height, $c(z)$ is the concentration distribution, and $u(z)$ is the velocity distribution.

Rouse's suspended load distribution was applied for the distribution of concentration, and the logarithmic distribution law was applied for velocity distribution. The formula of Garcia and Parker (1991) was applied to the concentration at the reference level.

Slope failure model

The slope failure risk during the rain is determined not only by the topographic conditions but also by the total amount of rainfall and rainfall intensity. A model of slope failure process was developed based on the two conditions, (i) physically-based slope stability (the infinite slope stability model) and (ii) rainfall index as shown below.

$$R' = R_{fw0} - R_{fw}, \tag{5}$$
$$R_{fw} = \sqrt{(R_1 - R_w)^2 + a^2 (r_1 - r_w)^2},$$
$$R_w = \sum \alpha \times R,\ \alpha = 0.5^{t/T_1},\ r_w = \sum \beta \times r,\ \beta = 0.5^{t/T_2},$$

where, R_w is the long term effective rainfall, r_w is the short term effective rainfall, R_1 is 450mm, r_1 is 150mm, a is weight coefficient (=5), α, β are reduction coefficient, R is the amount of rainfall, r is rainfall intensity, T_1, t_1 are the half-life of long term and short term effective rainfall (=72h, 1.5h).

The model will determine that the slope failure occurs when the safety factor of hill slope stability F_s is less than the criteria F_{sc}, and the rainfall index R' exceeds the criteria R'_c (see Figure 2.).

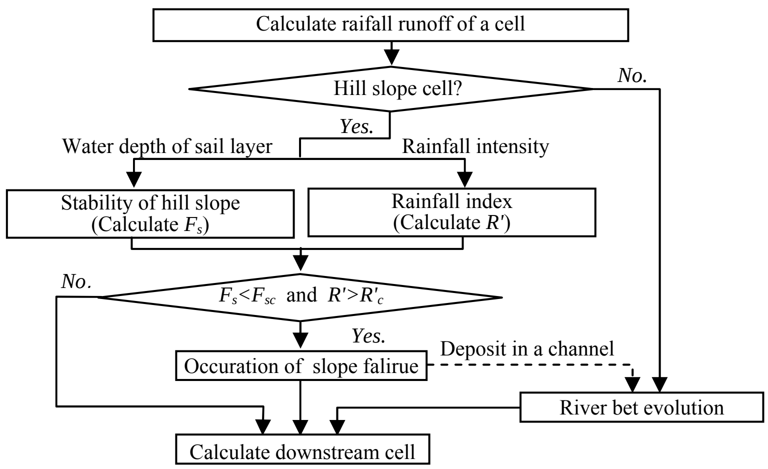

Figure 2. Calculation Flow of Slope Failure Model.

DEVELOPMENT OF A MODEL FOR TRACING SEDIMENT BY SOURCE

Introduction of non-equilibrium of suspended load

Equation for calculating non-equilibrium suspended load. The equation for the transport of suspended load was defined as shown below based on an equation for the mean concentration of suspended load in the direction of depth.

$$\frac{\partial c_{sj} h}{\partial t} = \frac{1}{BL}\left(\sum_{in} c_{sj} Q - \sum_{out} c_{sj} Q\right) + E_{sj} - D_{sj}, \tag{6}$$

where, c_{sj} is the mean concentration in the direction of depth, and E_{sj} and D_{sj} are the rates of erosion and deposition of suspended load and expressed as shown below using sediment settling velocity W_{sj}, concentration at the base level c_{bej} and concentration at the bottom c_{bj}.

$$E_{sj} = w_{sj} c_{bej}\,, \quad D_{sj} = w_{sj} c_{bj}\,, \tag{7}$$

For the sediment settling velocity, Rubey's equation was applied. For the concentration at the base level c_{bej}, an equation of *Ashida* and *Michiue* (1970) was applied.

As a result of assumption of a logarithmic distribution as for the distribution of suspended load in the direction of depth, the relationship between mean concentration in the direction of depth c_{sj} and concentration at the bottom c_{bj} was expressed by

$$c_{sj} = \frac{c_{bj}}{\beta}(1 - e^{-\beta})\,, \tag{8}$$

where, eddy viscosity coefficient $\beta = ku_*h/6$ and Karman's constant k (= 0.4).

<u>Method for calculating river bed evolution.</u> For the process of river bed evolution, continuity Equation (9) was applied. For the grain size distribution in the sediment deposited layer, Equations (10) and (11) were used.

$$\frac{\partial Z_B}{\partial t} = \frac{1}{(1-\lambda)BL}\left(\sum_{in} Q_b - \sum_{out} Q_b\right) + D_s - E_s\,, \tag{9}$$

$$\frac{\partial p_{exj}}{\partial t} = \frac{1}{(1-\lambda)aBL}\left(\sum_{in} Q_{bj} - \sum_{out} Q_{bj}\right) + \frac{(D_{sj} - E_{sj})}{a} + \frac{\partial Z_B}{\partial t}\frac{p_{*j}}{a}\,, \tag{10}$$

$$P_{*j} = P_{exj} : \frac{\partial Z_b}{\partial t} > 0 \quad , \quad P_{*j} = P_{*0j} : \frac{\partial Z_b}{\partial t} \le 0\,, \tag{11}$$

where, Z_b is the bed elevation, λ is the void ratio, E_{sj} and D_{sj} are the rates of erosion and deposition of suspended load, respectively, Q_b is the bed load discharge, L is the channel length, P_{exj} is the percentage of grains with size d_j in the bed load layer, p_{*0j} is the percentage of grains with size d_j in lower levels of the bed load layer.

<u>Development of a model for tracing sediment inflow from different sources</u>

<u>Outline.</u> For discussing the plans for efficiently arranging and maintaining such facilities, it is important to identify whether the sediment inflow is caused by river bed deposition or slope failure for reflection in sediment control plans.

Then, the reservoir sedimentation during a flood event were divided into the (i) sediments that deposited on the river bed (bed sediments) and (ii) sediments newly generated by failure (failure-generated sediments). A model was developed that enables the tracing of the bed evolution process separately for (i) and (ii).

Sediment tracing methods by source. In the model, the amounts of (i) bed sediments and (ii) failure-generated sediments that are transported are evaluated by multiplying the total amount of sediment transport calculated by grain size in each cell by the percentage of each type of sediments (Figure 3).

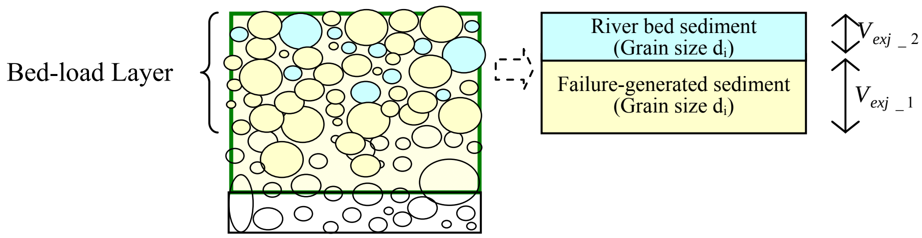

Figure 3. Modeling of Sediment Transport.

The amount of bed load Q_{bj_1} and Q_{bj_2} originating from bed sediments and failure-generated sediments with grain size d_j were expressed by Equation (12).

As for bed load, the rates of erosion of suspended load E_{sj_1} and E_{sj_2} originating from bed sediments and failure-generated sediments with grain size d_j were evaluated using the values obtained by Equation (13).

$$Q_{bj\_1} = Q_{bj} \times \frac{V_{exj\_1}}{V_{exj\_1} + V_{exj\_2}}, \quad Q_{bj\_2} = Q_{bj} \times \frac{V_{exj\_2}}{V_{exj\_1} + V_{exj\_2}}, \tag{12}$$

$$E_{sj\_1} = E_{sj} \times \frac{V_{exj\_1}}{V_{exj\_1} + V_{exj\_2}}, \quad E_{sj\_2} = E_{sj} \times \frac{V_{exj\_2}}{V_{exj\_1} + V_{exj\_2}}, \tag{13}$$

where, V_{exj_1} and V_{exj_2} are the amounts of bed sediments and failure-generated sediments with grain size d_j in the bed load layer.

The rate of deposition of suspended load was calculated using Equations (7) and (8) based on the mean concentrations of (i) bed sediment and (ii) failure-generated sediment.

APPLICATION TO YAHAGI DAM BASIN

The model developed in this study was applied to the Yahagi Dam basin and the dynamic behavior of failure-generated sediments during the Tokai heavy rains was estimated.

Setting of calculation conditions

Grain size distribution. For the grain size on the bed for modeling, the result of boring in the reservoir conducted in 1979, a few years after dam construction in 1970, which was considered to be equivalent to the grain size on the bed, was used. For the grain size of failure-generated sediments, the result of boring in the reservoir in 1998 after the lapse of certain time, which was assumed to have been affected by the sediments generated by failure, was used.

Initial bed condition. In this study, aiming at identifying the dynamic behavior of failure-generated sediments during the Tokai heavy rains, the initial bed was defined as the bed in a state where the amount of sediments that flowed into the dam reservoir was nearly the same as actual value, using the following method.

(i) A sediment depth of 2.0 m was applied uniformly throughout the channel.
(ii) Multiple small to medium floods were calculated in the channel.
(iii) The *Tokai* heavy rains were reproduced by calculation where the bed was in the state at the end of step (ii). The bed in the state where the sediment inflow into the reservoir was nearly the same as the actual value was defined as the initial bed.

c) Rainfall runoff parameters. For the parameters related to rainfall runoff, the values identified in an existing study (Nagatani et al. 2009) were used.

Results of the transportation process of failure-generated sediments

The depth of deposition of failure-generated sediments and the mean grain size in the channel during the Tokai heavy rains one and 24 hours after the failure occurred were plotted (Figure 4).

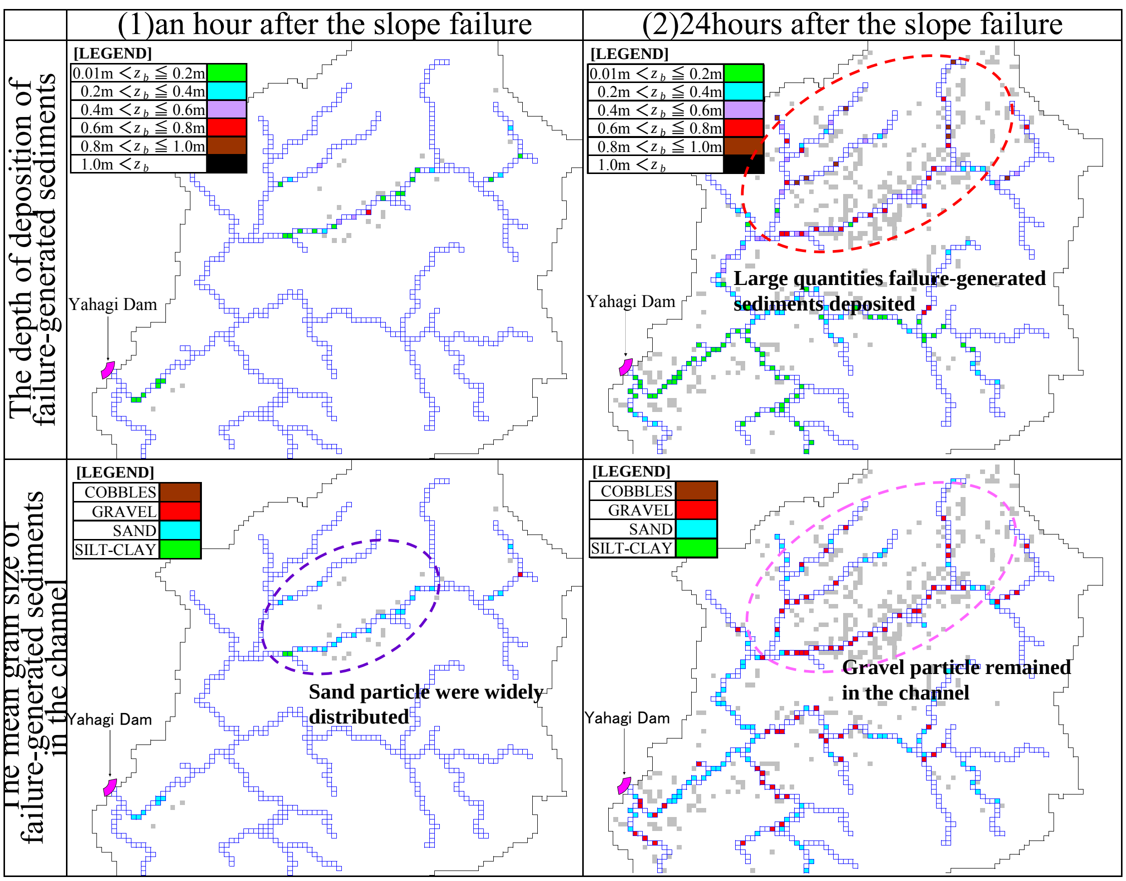

Figure 4. Distribution of failure-generated sediments (□:river channel, ■:failed slope).

Depth of deposition of failure-generated sediments. It was confirmed that the failure-generated sediments deposited in large quantities in the upper reaches of the basin where numerous failures occurred.

With the lapse of time, more areas in the lower reaches were affected by the failure-generated sediments. The depth of deposition of failure-generated sediments varied little in nearly one day after the failure and later. The sediments were supposed to have remained in the channel.

Mean grain size of failure-generated sediments. The mean grain size of failure-generated sediments that remained in the channel was examined. Sand particles were widely distributed right after the occurrence of the failure. Nearly one day after the failure, relatively large particles, mainly silt particles, constituted the sediment. It was therefore assumed that fine particles flowed out of the remaining sediments.

Results of estimation of sediment inflow

Sediment inflow hydrograph. The hydrographs of sediment inflow by source during the *Tokai* heavy rains are shown in Figure 5 ((i) river bed sediments shown at the top and (ii) failure-generated sediments at the bottom).

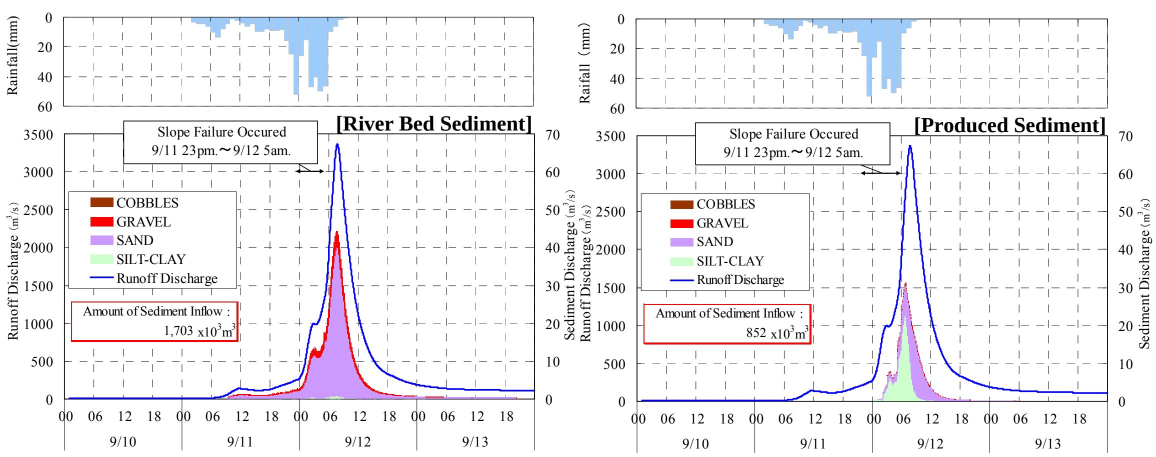

Figure 5. Calculated Hydrograph during Tokai heavy rains.
(Left figure: river bed sediment, Right figure: failure-generated sediment)

Most of the particles that constituted the failure-generated sediments that flowed into the dam reservoir were suspended load composed of clay and fine sand. Few coarse particles flowed into the reservoir but most remained in the channel.

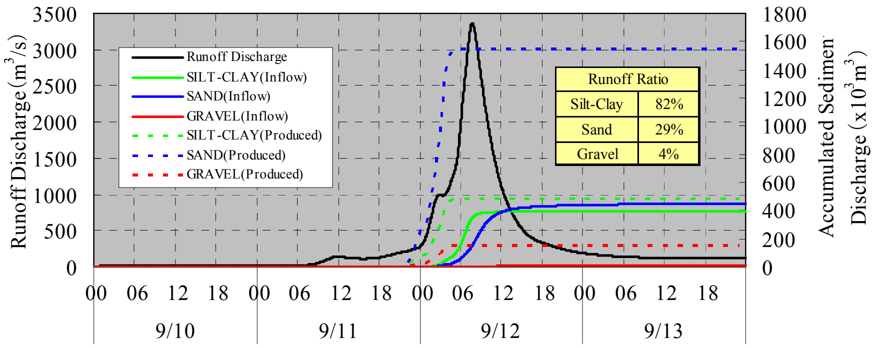

Figure 6. Accumulated Sediment Production and Inflow by Grain Size.

Figure 6 shows accumulated sediment production and inflow by grain size. It is confirmed that nearly all of the silt and clay contained in the failure-generated sediments flowed into the reservoir and that the failure-generated sediments started influencing sediment runoff at early stages.

For sand or larger particles, the ratio of inflow to production was lower. The tendency was more outstanding for larger particles.

Sediment budget. Figure 7 shows the sediment budget during the *Tokai* heavy rains estimated in this study. The failure produced approximately 2.15 million m^3 of sediments and caused approximately 850,000 m^3 of sediments to flow into the dam reservoir. In the model, it was assumed that nearly a half of the failure-generated sediments flowed into the reservoir and the other half remained in the channel.

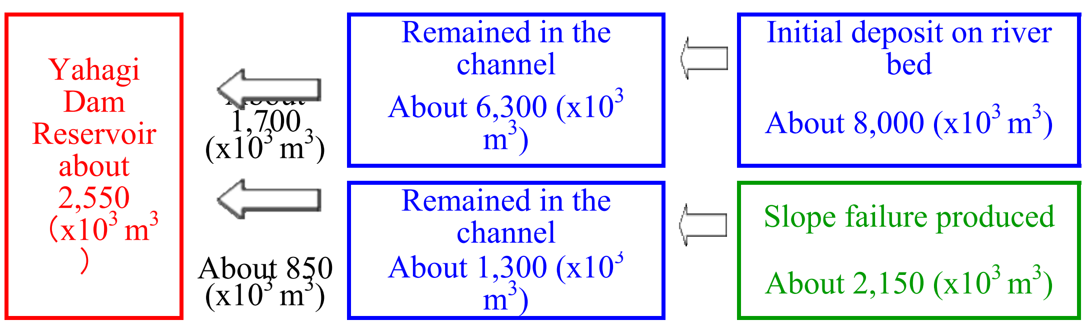

Figure 7. Sediment Budget During Tokai Heavy Rains.

Dynamic behavior of failure-generated sediments

The process of transport of failure-generated sediments and the hydrograph of sediment inflow suggest that fine particles quickly got out of the bed once the failure-generated sediments deposited on the bed. Coarse particles propagated downstream with time but most of them did not reach the dam reservoir during one flood and remained in the channel.

CONCLUSION

In this study, a distributed sediment runoff model that incorporated slope surface failure as a process of sediment production during heavy rains was improved to build a model that enables separate tracing of sediments from different sources, bed sediments and failure-generated sediments.

The model was used to estimate the dynamic behavior of sediments in the Yahagi Dam basin during the Tokai heavy rains that induced numerous slope failures. As a result, it was suggested that nearly a half of the failure-generated sediments flowed into the dam reservoir during a flood and the other half remained in the channel during the Tokai heavy rains.

It was shown that most of the failure-generated sediments that flowed into the reservoir were fine particles and most of the sediments that remained in the channel were coarse particles.

It was therefore found that nearly half of the sediments produced during the Tokai heavy rains remained in the channel in the Yahagi Dam basin and that large quantities of sediments were likely to flow into the reservoir during a next large-scale flood.

Thus, sediments can be controlled appropriately throughout the river system by properly evaluating not only short-term flood events but also the amount of sediments remaining in the channel in the basin.

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