Watershed Management System: A model of rainfall-runoff, sediment production, and discharge processes

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ABSTRACT

A model able to predict rainfall-runoff, sediment production and sediment discharge is needed to plan structural and nonstructural countermeasures to control sediment related problems. Sediment production processes include shallow landslides, debris flows, torrent/river bed erosion, bank erosion and deep-seated landslides. As this model is intended to apply to ordinary watershed management activities, and less than 100-year frequency events, we exclude deep-seated landslides, which are rare. Rainfall amounts, soil infiltration rates, change in the water table, and soil mantle instability have all been used to predict landslides. However, it remains difficult to forecast shallow landslides with any accuracy. Predictions often overestimate the number of landslides, and miscalculate the occurrence time and how much of the soil from the slide is mixed into river water. The amount of soil entrained has to be estimated empirically. This study developed a model, the watershed management system (WMS), which predicts rainfall-runoff, sediment production and sediment discharge processes. To avoid the ambiguity of the rate of entrainment following shallow landslides, we determined zero-order basins where shallow landslides occur as torrents. Debris flow in the zero-order basins is judged according to the flow condition, calculated by a rainfall-runoff sub-model. Then, a sedimentation sub-model computes the discharge rate. We classify shallow landslides as debris flow. Measurements are used to parameterize the model. The model was applied to the Sumiyoshi River in the Rokko Mountains, Japan to estimate runoff and sediment discharge, and to evaluate Sabo, an erosion and sediment control project. The results demonstrate the effectiveness of the model.

Keywords: Watershed Management System, rainfall-runoff, sediment production and discharge, simulation model, sabo (erosion and sediment control)

Water Management System: A model of rainfall-runoff, sediment production and discharge processes

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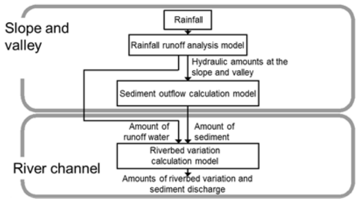
(1)Establishment of the "Basin Management System" using Sediment Discharge Observation Data



A similar system (CASFPS: Computer-aided Sabo Facilities Planning System) was established in 1998. However, it was a system primarily focused on calculating riverbed variation without including a rainfall runoff analysis model. In that system, sediment yield and sediment outflow parameters were arbitrarily given at the upstream end of a tributary.

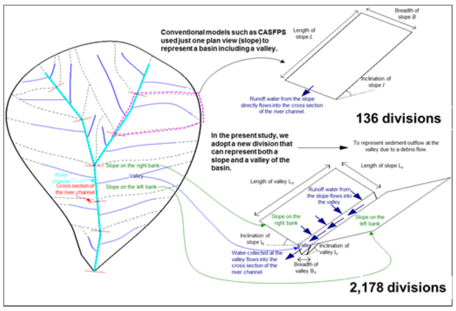


Figure 1: Division of the Basin Topography
The basin topography is divided into a slope and a valley by taking into account a zero-order valley so that occurrence or non-occurrence of a debris flow can be represented.

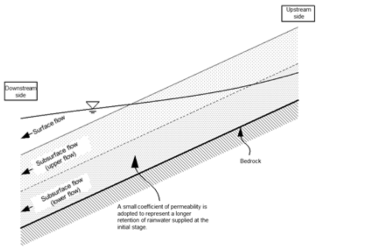
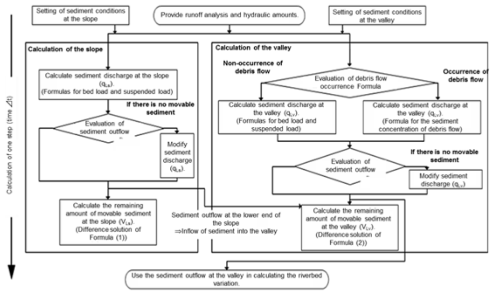


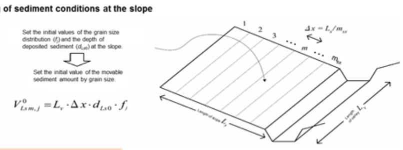
Figure 2: The subsurface flow of the rainfall runoff analysis model is divided into upper and lower flows.
By doing so, this model can include all rainfalls in the analysis, unlike a conventional model that analyzes only the effective rainfall by subtracting the loss of rainfall.

(2) Preparation of the sediment outflow calculation model

Composition of the sediment outflow calculation model



Setting of sediment conditions at the slope

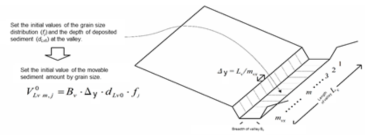


Calculation of the slope

1) Calculation of sediment discharge at the slope
   Sediment produced by erosion moves in two forms — bed load and suspended load.
   Calculate the sediment discharge by grain size using the following formulas:
   The Ashida-Takahashi-Mizuyama formula for bed load (ATM formula)
   The Ashida-Michiue formula for suspended load (AMS formula)
2) Calculate the critical tractive force using the modified Egiazaroff formula.
3) Calculate the settling velocity using Rubey's formula.

4) The precondition of "sediment outflow" is that sediment should not flow out more than the amount of movable sediment existing in each division.
5) Calculate the sediment amount remained in each division.
6) The sediment amount at the lower end of the slope is assumed to flow out to the valley.

Calculation of the valley



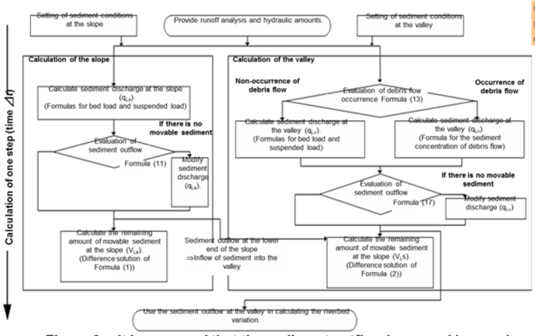
Calculation of the valley

1) Evaluation of occurrence or nonoccurrence of debris flow
   It is judged that a debris flow will occur if the following formula is satisfied based on the depth of surface flow at the valley which is obtained from the rainfall runoff analysis.

$$I_v \geqq \frac{C_*(\sigma-\rho)}{C_*(\sigma-\rho)+\rho(1+h_{v0}/d_m)}\tan\phi$$

I_v : inclination of valley, C_* : concentration of deposited sediment, σ: density of debris, ρ: density of water, h_{v0} : depth of surface flow at the valley, d_m : mean grain size at the valley, ϕ: angle of internal friction

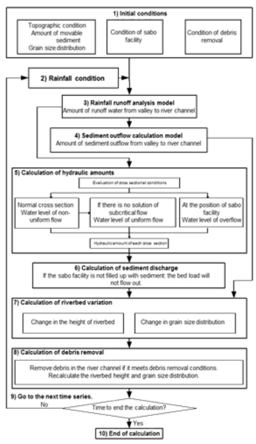
(3) Preparation of the riverbed variation calculation model



Composition of the riverbed variation calculation model

Figure 3: It is assumed that the sediment outflow is caused by erosion and debris flow. The sediment movement associated with the "movement of water" is represented.

Flow of calculation



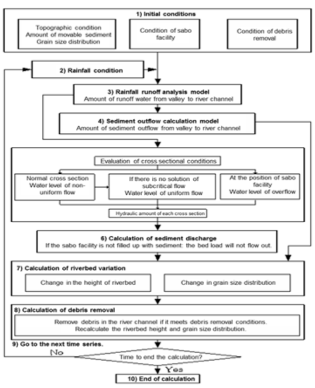
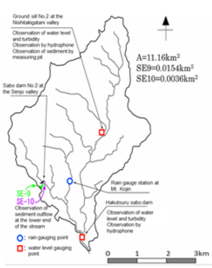


Figure 4: Establishment of the riverbed variation calculation model integrated with a rainfall runoff analysis model and a sediment outflow calculation model

(4) Verification calculation for the sediment outflow calculation model and the riverbed variation calculation model

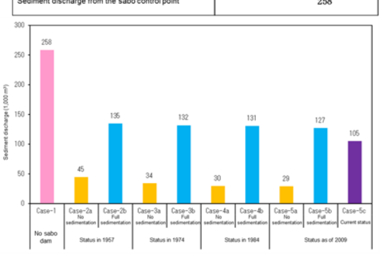
Observation points of the data for verification



Data for verification calculation
- Rainfall data
- Grain size distribution
- Coefficient of permeability
- Depth of subsurface flow
- Coefficient of roughness at the slope, valley, and river channel
- Amount of sediment outflow by observation
- Attributes of sabo dam

RESULTS OF CALCULATION

Item	Amount of sediment (1,000 m³)
Sediment outflow from the slope	1, 036
Variation of sediment retention at the valley	290
Sediment outflow from the valley	746
Riverbed variation in the channel upstream of the sabo control point	488
Sediment discharge from the sabo control point	258



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1. INTRODUCTION

To develop erosion and sediment control plans and appropriate sabo dam systems, it is first necessary to predict rainfall-runoff, sediment production, and sediment discharge processes under extreme rainfall events. Such management plan could include both structural and nonstructural countermeasures to prevent sediment related disasters due to the rainfall. However, it remains difficult to predict shallow landslides with any accuracy. We developed a new model called the Watershed Management System (WMS) to evaluate rainfall-runoff, sediment production, and sediment discharge processes in areas where debris flows, rather than shallow landslides, are the main sediment production process.

2. MODEL DEVELOPMENT

Sediment production includes such processes as shallow landslides, debris flows, torrent/riverbed erosion, bank erosion, and deep-seated landslides. Because the WMS is intended to be applied to ordinary watershed management activities and less than 100-year frequency events, we exclude deep-seated landslides, which are rare. To avoid the ambiguity of the rate of entrainment of shallow landslides, we consider zero-order basins where shallow landslides occur to be torrents. The occurrence of debris flow in the zero-order basins (torrents) is estimated according to the flow condition, calculated by a rainfall and runoff sub-model. Following debris flow estimation, a sedimentation sub-model computes the discharge rate. Here, we consider shallow landslide to be debris flow.

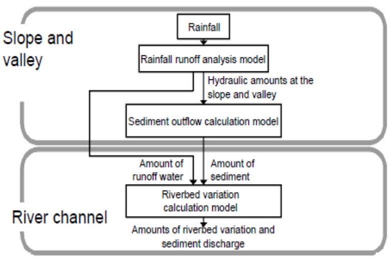

Fig. 1 The structure of the Watershed Management System (WMS)

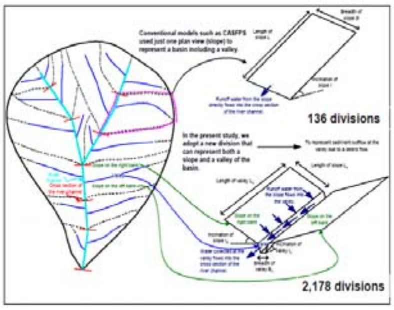

Fig. 2 Partition of a basin

3. MEASUREMENT

The study site was the Sumiyoshi River, located in the Rokko Mountains. Rainfall and runoff were measured at various locations in the basin, and sediment discharge was measured at various scales; including plots, slopes, and basins. Flow discharge data were used to determine the parameters of the two-layer intermediate flow model in the system. Loss of rainfall did not need to be given separately but was instead calculated automatically.

Bedload was measured using pipe hydrophones. The acoustic data were converted to the bedload transport rate using a pit bedload sampler calibration. Turbidity was measured to estimate the suspended load.

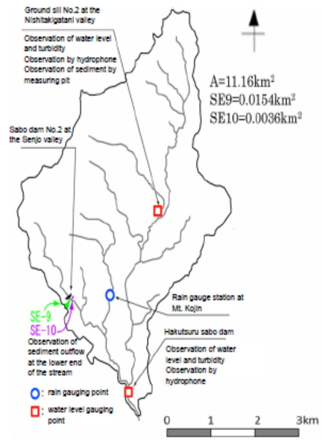

Fig.3 Observation locations for verification

Fig.4 Sediment measurement system

4.APPLICATION OF THE MODEL TO THE SUMIYOSHI RIVER

The WMS was applied to the Sumiyoshi River, and the effectiveness of sabo dams in controlling sediment flow was evaluated for both usual and extreme flood events. The drainage area of the Sumiyoshi River is 11.16 km^2. In our previous model, the Computer-Aided Sabo Facilities Planning System (CASFPS) the river basin was partitioned into 136 sub-basins, as the sediment supply was assumed to be equal to the sediment transport capacity at upstream ends. For the WMS, the Sumiyoshi River basin was partitioned into 2178 sub-basins to evaluate the surface erosion of slopes and debris flow in torrents.

5.RESULTS AND DISCUSSION

The WMS successfully modeled measured values of runoff and sediment discharge. The system was also applied to extreme events to predict the ability of sabo dams to control sediment discharge. The study area includes 63 sabo dams, and the results indicated that no sediment disasters would occur if the sediment-trap capacities of several downstream dams are maintained by excavation.

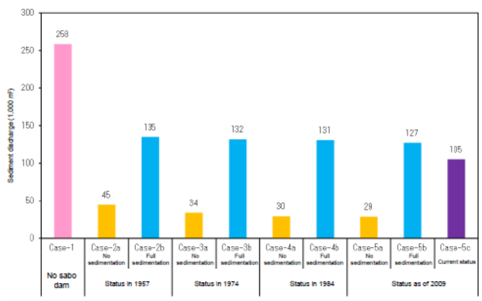

Fig.5 Computed sediment discharge from the mountain area; without sabo dams, no and full sedimentation of sabo dams in 1957, 1974, 1994, 2009 and current status.

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[1] Mizuyama, T., Y. Tomita, K. Ido, M. Fujita ; ComputerAided Sabo Facilities Planning System, Journal of Japan Society of Erosion Control Engineering, 50-6, 1998, pp.40-43 (in Japanese with English abstract)