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Studies of sediment production on mountain slopes

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ABSTRACT Accurate estimation of the volume of sediment production on mountain slopes is required for erosion control and forestry conservation. In order to produce such estimates, penetration tests using a Doken-type penetration testing machine, and morphologic analysis of topographical maps have been undertaken. Interpretation and analysis of the results have revealed: (a) sediment production on mountain slopes is mainly due to sliding of the surface soil, and information on the depth of the surface soil is needed; (b) the results of the penetration tests have shown that the depth of $N_{10}=10$ roughly corresponds to the depth of the surface soil layer, and a "surface soil layer calculation formula" has been developed; (c) the results of morphologic analysis have indicated that the most important topographical factor influencing sediment production is the area/height distribution; and (d) the estimate of sediment volume based on the above results is 27 030 m^3 km^{-2}.

Recherches sur la production de sédiments sur les pentes des montagnes

RESUME Il convient d'estimer exactement le volume de sédiments produit sur les pentes des montagnes pour contrôler l'érosion et la conservation de la forêt. Pour faire des estimations sur le volume, des essais de pénétration ont eu lieu sur la pente de la montagne en utilisant l'appareil de pénétration du type Doken. L'analyse morphologique sur les cartes topographiques a été éxécutée. Les conclusions sont les suivantes: (a) la production de sédiments sur la pente de la montagne est due principalement au glissement de la couche superficielle, par conséquent il est nécessaire de faire une hypothèse sur l'épaisseur de la couche superficielle du sol; (b) d'après l'analyse des résultats de l'essai de pénétration, on a confirmé que l'épaisseur de $N_{10}=10$ correspond approximativement à celle de la couche du sol superficielle et une "formule mathématique de la couche superficielle du sol" a été obtenue; (c) d'après les résultats de l'analyse morphologique, le facteur topographique le plus puissant concernant la production de sédiments est la courbe de distribution des hauteurs en fonction de la surface; et (d) l'estimation du volume de sédiments calculé d'après la formule donnée ci-dessus est de 27 030 m^3 km^{-2}

INTRODUCTION

Control of erosion and floods is a major contribution toward the solution of one of Japan's most critical land use problems. Seventy per cent of Japan is mountainous, and the population and industries are mostly concentrated in the narrow area between the mountains and the sea. Fatalities by floods are decreasing year by year but those by mud flow or landslides are increasing (Table 1). Since the end of the World War II, population and industries have been concentrated in the urban areas, but because of the shortage of land, dangerous slope areas are now being developed. Therefore the effect of the soil transported downstream by mud flows or landslides cannot be disregarded. At present disaster prevention plans and their construction are the responsibility of the Ministry of Agriculture, Forestry and Fishery and the Ministry of Construction Works respectively. The purpose of these measures is:

(a) to prevent loss of human lives, and damage to houses, farms and rivers downstream from mud flows and landslides;

(b) to conserve the mountainous regions by protecting or controlling the production and transportation of sediment on mountain slopes;

(c) to protect and improve life in the cities;

(d) to conserve resources.

Table 1 Numbers of fatalities due to floods, mud flows and landslides

Year	Floods	Mud flows	Landslides
1967	593	207	158
1968	307	154	5
1969	203	32	82
1970	168	22	27
1971	478	53	171
1972	592	194	239

Protection works are usually installed in upstream regions and their effects have been estimated justly. The actual mechanisms of sediment production and transportation in mountainous regions are too complicated to analyse here and field and laboratory research is being done by specialists in many fields. In this study the authors consider that rainfall is the dominant factor in causing sediment related disasters and in this paper they estimate the sediment volume produced by rainfall.

DISASTERS CAUSED BY SURFACE SLIDES IN THE UPPER KIZU RIVER BASIN

In 1959, in the upstream region of the Kizu River (Fig. 1), typhoon "Ise" (typhoon no. 15-1959) caused a sediment-laden torrent which resulted in the loss of 16 lives and 43 houses destroyed and buried. The same region has been repeatedly stricken by heavy rains from typhoons or frontal storms and each time human life and property have been endangered by mud flows or

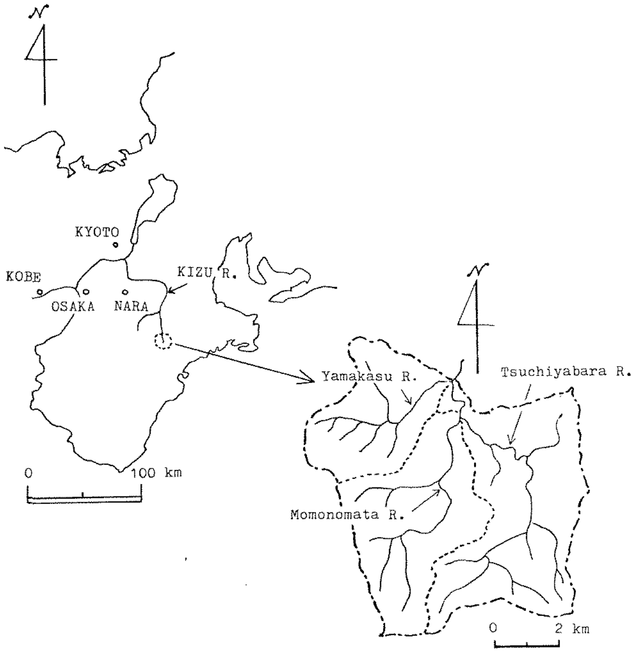

Fig. 1 The Upper Kizu River study area.

Table 2 Data on landslides in area devastated by typhoon Ise in 1959 (from the Upper Kizu River Works Office, Ministry of Construction)

	Tsuchiya basin	Momonomata basin	Yamakasu basin
Basin area (km^2)	18.14	14.03	9.58
Number of landslides			
on mountain slopes	1261	927	333
on river banks	342	246	14
Total	1603	1173	347
Area affected by landslides (km^2)	0.54	0.39	0.18
Density of landslides (number/km^2)	88.4	83.6	36.2
Ratio of landslide area to basin area	0.0296	0.0280	0.0018
Mean area of landslides (m^2)	334.9	335.0	531.8
Mean depth of landslides (m)	0.68	0.70	1.18

sediment-entrained flow containing sediment produced on the mountain slopes. Table 2 shows the results of research on landslides in the area devastated by typhoon Ise. It can be seen that (a) the number of landslides is high; (b) the area and the depth of each landslide are not so large (area = 323.4 m^2, depth = 0.85 m); (c) the sediment produced by landslides totalled 1090 m^3. This quantity is not particularly large, but it resulted in severe damage to life, houses, farms and forests. This type of landslide is often seen in the central-southwest part of Japan (Fig. 2), where the mountains are of deeply weathered granite. The main factor causing these landslides is heavy rain. The authors have called these landslides "surface slides" and have conducted a study to predict the scale of the slides caused by heavy rain and to estimate the sediment volume produced by these surface slides.

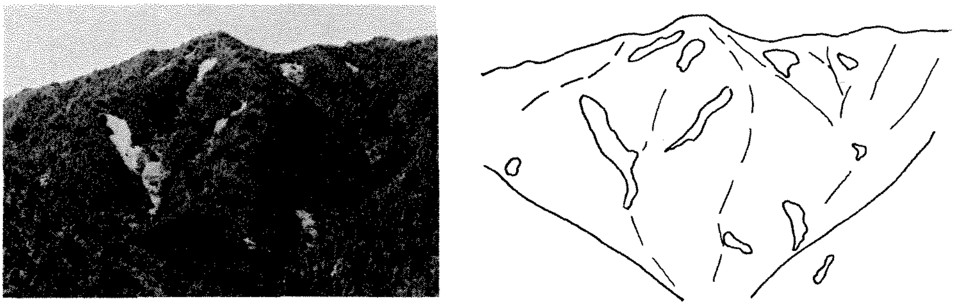

Fig. 2 Picture showing 11 landslides in an area 300 m wide.

PENETRATION TESTS

Figure 3 shows a histogram of the depth of surface slides, and three peaks at 0.5, 1.0, 0.3 m (in order of frequency) can be seen. This indicates that the slides on these slopes are mainly due to the sliding of a thin surface layer. These surface layers are generally looser than the layers beneath and are easily saturated by water, resulting in a decrease in their strength, and then collapse triggered by heavy rain. The boundary between the upper loose layer and consolidated layer beneath is not clear, but is usually gradual, and slides will probably occur somewhere in this "transition" zone.

A portable penetration testing machine (Fig. 4) improved at the National Institute of Civil Engineering, and with a hammering weight of 5 kg which is less heavy than that commonly used, was employed to measure the depth of the surface layer concerned with surface slides and thus sediment production. In general, penetration records were analysed by two methods. First, by plotting the penetration index (P.I.) against the total depth of penetration. But plotting the P.I. *vs*. penetration depth curve involves much work; the authors had already concluded that the depth is equivalent to P.I. = 2 which corresponds to the depth of the surficial layer on mountain slopes. Second, to plot the

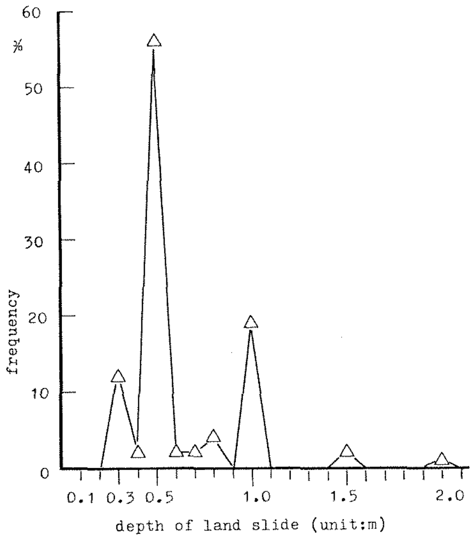

Fig. 3 Histogram of depth of surface slides.

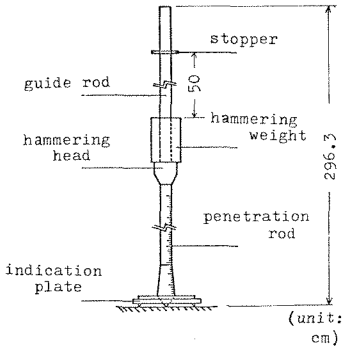

Fig. 4 The penetration testing machine.

number of hammerings necessary to penetrate to an arbitrary depth, taken as 30 cm (indicated by N_{30}) for the average thick soil layer on poor ground, but the surficial layers on mountain slopes are not so thick, and the value of N_{10} was chosen by trial and error. The number of hammerings necessary to penetrate the surface layer completely must be determined. Comparing the histogram of surveyed depths for N_{10} = 5, 10, 20 respectively (Fig. 5) with Fig. 3 the authors adopted the value of N_{10} = 10 (10 hammerings were necessary to penetrate 10 cm). Figure 6 shows the relation between N_{10} = 10 and P.I. = 2, and it is clear that these two factors correlate well with a correlation

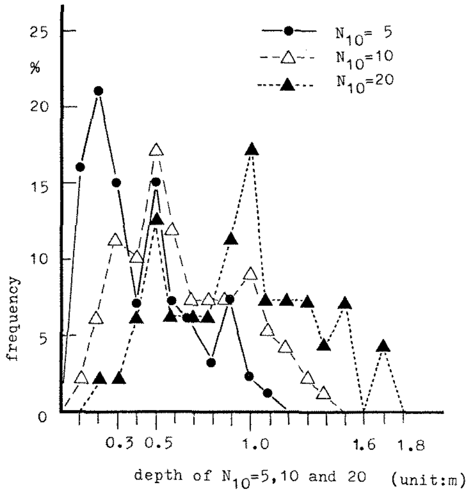

Fig. 5 Histograms for N_{10} = 5, 10 and 20.

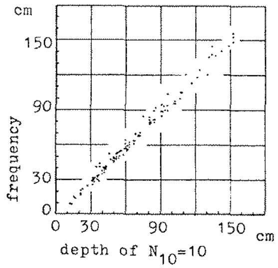

Fig. 6 Relationship between P.I. = 2 and N_{10} = 10.

of r = 0.99.

GEOMORPHIC FACTORS CONCERNED WITH SEDIMENT PRODUCTION

As shown in Fig. 2, surface slides are characteristic of the mountainous regions of granitic rocks and of relatively low relief, where the effects of weathering are strong and there is severe erosion. These areas were surveyed and the landslides and the results of our tests were plotted on topographical maps with scales of 1:2500 or 1:3000 obtained from the Ministry of Construction Works. In plotting the results of the penetration tests the positions of the points were described as non-dimensional relative heights shown in Fig. 7(a). From the maps the valleys were classified into first order, second order etc.

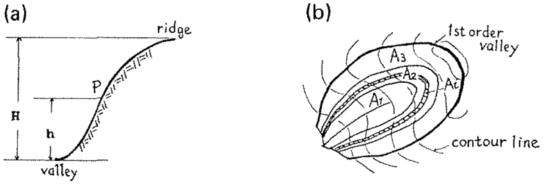

Fig. 7 Definition of (a) relative height (h/H) of a point on a slope, and (b) classification of valleys according to h/H.

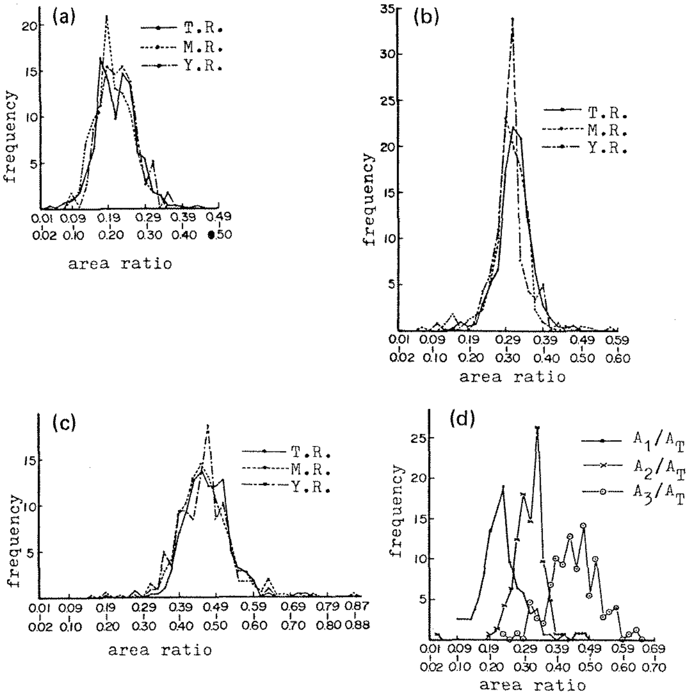

Fig. 8 Histograms of area ratios of valleys in the study area: (a)-(c) A_1/A_T, A_2/A_T and A_3/A_T for a first order valley; and (d) of A_1/A_T, A_2/A_T and A_3/A_T for valleys larger than second order valleys. T.R., Tsuchiyabara River; M.R., Momonomata River; Y.R., Yamakasu River.

valleys according to Horton's law of the development of streams. 658 points were surveyed.

SURFACE LAYER DEPTH ANALYSES

The depth of the surface layer described by N_{10} increases as the relative height (h/H) increases. The formula derived by the regression curve calculated by using the method of least squares considering the depth as a function of (h/H) is

$$D = -17.5(h/H)^2+51.9(h/H)+29.4 \qquad (cm) \qquad (1)$$

where D is the vertical depth, surface to penetration reach. To obtain the depth normal to the surface this must be multiplied by cos θ.

The total volume of surface sediment from all three basins surveyed was then calculated. On the topographical map each valley was divided as shown in Fig. 7(b), and the total surface sediment volume given by

$$V_t = \Sigma_{i=1}^{n} A_i D_i \qquad (2)$$

where A_i is the area which corresponds to relative height (h_i/H). As this summation involves much work, the authors divided the data on depth into three groups by matrix scattering analysis. And between the classes, the variation was highly significant. The depth surveyed data were classified by h/H:

$$(h/H) \lesssim 0.29, \qquad 0.30 \lesssim (h/H) \lesssim 0.59, \qquad (h/H) \gtrsim 0.60$$

The authors used another non-dimensional parameter in describing the area, the area ratios A_1/A_T, A_2/A_T, A_3/A_T, which correspond to the classes of h/H. Figure 8(a), (b) and (c) show the histograms of A_1/A_T, A_2/A_T and A_3/A_T of first order valleys and Fig. 8(d) shows the results for higher order valleys. Then in order to correlate these histograms with the longitudinal form of a mountain slope, the authors considered that if the slope were uniform $A_1/A_T : A_2/A_T : A_3/A_T = 1 : 1 : 1$, but when A_1/A_T becomes less than 1.0 and A_3/A_T exceeds 1.0 the slope is convex, and when A_1/A_T exceeds 1.0 and A_3/A_T becomes less than 1.0 the slope is concave. In all three basins, almost all the longitudinal profiles are considerably convex. This tendency is also recognized in the valleys of higher order. From the geomorphological point of view, it is considered that erosion production is active in these mountains. Area ratio A_i/A_T was found to be one of the most important factors indicating the extent of erosion and the calculated values of the depth of the surface layer are shown in Table 3.

ESTIMATION OF SEDIMENT VOLUME

As described hitherto, the volume of sediment can be calculated by formula (2). But the volume calculated would be equivalent to that resulting from the collapse of every slope all at

Table 3 Depth of surface layer (cm) in the different parts of a valley

Name of basin	D_1 foot slope	D_2 mid slope	D_3 upper slope
Tsuchiyabara	0.40	0.50	0.60
Momonomata	0.40	0.50	0.65
Yamakasu	0.40	0.50	0.60

Table 4 Landslides in granite mountain regions of Japan 1972 and 1974

Name of river	Max. precip. (mm h^{-1})	Area of basin A (km^2)	Area of landslide a(m^2)	Area ratio a/A
1972				
Gifu Pref.				
Fujitsuka R.	50	0.1	20 000	0.200
Todaisawa V.	50	0.3	18 000	0.060
Kamashita V.	50	0.3	12 000	0.040
Umenokihora	50	0.1	30 000	0.300
Gonzohora	50	0.1	20 000	0.200
Irigahora	50	0.12	23 000	0.192
Tochinoirihora	50	0.5	60 000	0.120
Takisaka R.	60	2.3	27 000	0.012
Saisaka V.	60	1.2	25 000	0.021
Shimo V.	60	0.35	24 000	0.069
Ichinotani V.	60	0.25	23 500	0.094
Ninotani V.	60	0.14	22 500	0.161
Miyanohora	60	0.32	23 500	0.073
Azuma V.	60	0.20	22 400	0.112
Marukusa R.	60	1.80	20 000	0.011
Aichi Pref.				
Kurayashiki R.	77	0.1	10 000	0.100
Matsune R.	77	1.0	100 000	0.100
Kitahora R.	77	0.6	30 000	0.050
Senarai R.	77	11.0	687 500	0.063
Higuchizawa	77	0.27	29 000	0.107
Tamotsuzawa	77	0.22	27 500	0.125
Nakahirazawa	77	0.31	35 000	0.113
Tarumata R.	42.5	0.27	31 000	0.115
Yamaguchi R.	77	0.43	8 130	0.019
Ikeshima R.	77	0.32	40 000	0.125
Nikake R.	77	1.25	150 000	0.120
Numasawa	68	0.25	30 000	0.120
Kangairisawa	68	0.12	25 000	0.208
Tentokusawa	68	0.11	30 000	0.273
Tanakazawa	68	0.02	3 000	0.150
Kamikawaguchihora	77	0.27	34 000	0.126
Yatsuhashirazawa	77	0.36	45 000	0.125
Tsukimizawa	77	0.40	50 000	0.125
Ookawara1zawa	68	0.13	16 000	0.123
Ookawara2zawa	68	0.20	35 000	0.175
Nishihagidaira R.	77	2.05	250 000	0.122
Kakuregasawa	68	0.09	10 000	0.111
Kisaizawa	77	0.02	5 000	0.250
Kihokuzawa	77	0.10	12 500	0.125
Kita R.	77	0.90	20 000	0.022
Isshikihora	42.5	0.30	20 000	0.067
Nakanehora	68	0.10	35 000	0.350
Inubuseichinosawa	68	0.10	35 000	0.350
Teradaira R.	77	0.11	14 000	0.127

Table 4 *(cont.)*

Name of river	Max. precip. (mm h^{-1})	Area of basin A (km^2)	Area of landslide a(m^2)	Area ratio a/A
Mie Pref.				
Ookami R.	75	0.75	2 000	0.003
Shimane Pref.				
Uenotani R.	47	3.2	7 000	0.002
Nakamadani R.	47	0.8	7 800	0.010
Shimokumidani R.	47	0.2	6 900	0.035
Shimonotani R.	47	1.0	5 000	0.005
Hinotani R.	47	1.5	6 000	0.040
Uehara R.	47	1.7	6 000	0.004
Yasumichidani R.	47	1.4	7 100	0.005
Hiroshima Pref.				
Kumasaki R.	18	0.2	800	0.004
Cho R. branch	38	0.15	6 000	0.004
Shinsho R.	26	0.35	10 000	0.029
Amaodani R.	26	0.06	900	0.015
Ehime Pref.				
Manganji R.	48	0.1	3 500	0.035
Doi R.	48	0.32	15 000	0.047
Kamikonomori R.	48	0.1	7 000	0.070
Huruodani R.	48	0.1	6 000	0.060
Hinoura R.	48	0.1	8 000	0.080
Naraki R.	48	0.35	15 000	0.043
Mizuide R.	48	0.1	8 000	0.080
Umakai R.	48	0.1	8 000	0.080
Taniyama R.	48	2.7	50 000	0.018
Takano R.	48	0.4	20 000	0.050
Miyanoshita R.	48	0.32	12 000	0.038
Hatakedera R.	48	0.15	12 000	0.080
Sai R.	48	0.8	10 000	0.013
Motokiri R.	48	0.92	15 000	0.016
Mizukake R.	48	0.1	7 000	0.070
Yamaguchi Pref.				
Goh R.	22	1.4	1 165	0.001
Yoshiya R.	24	0.9	270	0.000
Okutsudani R.	26	0.4	2 680	0.007
Kumamoto Pref.				
Hunatani R.	49	0.3	10 000	0.033
1974				
Gifu Pref.				
Nyusodo	59	6.0	40 000	0.007
Hizawa	59	0.6	10 000	0.017
Okute V.	59	1.24	18 000	0.015
Ooidozawa	59	0.24	8 000	0.033
Kamisawado	59	0.1	5 000	0.050
Kumiyaizawa	59	0.2	5 000	0.025
Yamaguro V.	59	0.5	6 000	0.012
Toseimon	59	0.12	1 500	0.013
Kagawa Pref.				
Katashiro R.	59	2.2	300 000	0.136
Yasudaohkawa R.	92	2.5	300 000	0.120
Moroguchi R.	90	0.9	20 000	0.022
Uchima R.	92	0.03	10 000	0.333
Sarubutai R.	92	0.1	30 000	0.300
Kamesaki R.	90	0.2	10 000	0.050
Tohama R.	90	0.1	20 000	0.050
Ootani R.	85	0.15	40 000	0.267
Chikatani R.	85	0.8	20 000	0.025

R., River; V., Valley.

the same time. Such a situation hardly ever occurs. Then the authors tried to estimate the volume of sediment from data on past landslides. Table 4 shows the data on landslides that occurred in 1972 and in 1974. As surface slides occur with heavy rain, data on the intensity of precipitation have been included, and the area ratio a/A of the surface slides is also indicated. In general a/A is inversely proportional to the area of the basin. It can be seen that the factors strongly affecting surface sliding are a/A and the intensity of rainfall, and a statistical analysis was performed to assess the effect of these factors. Area factors were divided into three classes: $A < 0.2$ km^2, $0.2 \lesssim A \lesssim 0.5$ km^2, and $A > 0.5$ km^2; and precipitation factors into two: $P \gtrsim 50$ mm, $P < 50$ mm (Ikeya, 1974). As a result, the area of a basin was found to be the most effective factor when $A < 0.2$ km^2, the precipitation intensity also affects the area ratio remarkably as when $P > 50$ mm h^{-1}, $a/A = 0.185 \pm 0.029$ and when $P < 50$ mm h^{-1}, $a/A = 0.108 \pm 0.029$, a difference of almost 1.7 times. When the area ratio exceeds 0.5 km^2, precipitation intensity has the least effect. The authors estimated the volume of soil that would be produced in the Takora Valley experimental basin. In the Upper Kizu River basins for $P > 50$ mm h^{-1}, $a/A = 0.051$, the area of the basin is 1.76 km^2 and from Table 3 $D_1 = 0.4$, $D_2 = 0.5$, $D_3 = 0.6$ m then

$$a = 89.760 \text{ m}^2$$
$$A_1 : A_2 : A_3 = 2 : 3 : 5$$
$$A_1 = 17.952, \quad A_2 = 26.928, \quad A_3 = 44.880 \text{ m}^2$$
$$V = 17.952 \times 0.4 + 26.928 \times 0.5 + 44.880 \times 0.6 = 47\ 572.8 \text{ m}^3$$

The volume of sediment per unit area of basin is 27 030 m^3 km^{-2}. The authors also evaluated the volume of sediment produced in one of the basins and found the value to be almost half that proposed by the Ministry of Construction Works, i.e. $V = 45\ 000 \sim 60\ 000$ m^3 km^{-2}, for disaster prevention planning according to data from real disasters in the past. However, if the safety factor 1.5 is considered, these evaluated volumes of sediment seem to be acceptable.

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