THE EXAMINATION OF SEDIMENT PRODUCTION ESTIMATION BY THE USLE METHOD IN MOUNTAINOUS BASINS OF JAPAN

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The steep-slope topographic condition makes Japan to face the problems of high sediment production and yield in many areas. The problems are much severe in comparison with the other part of the world, but slightly less than the East and Southeast Asia and South American areas. However, with many reservoirs which relatively small in size, the sediment depositions in the catchments create very serious problems.

In order to understand the sediment production and yields in the catchments scale, the USLE, the most widely used of Sediment Estimation Model, was applied in the catchments of Arakawa, Daimon, and Hirose reservoirs in the Fuji River Basin.

The result indicated that if parameters are properly selected to reflect the regional conditions, the USLE is adequately applicable for estimating long-term mean annual sediment production in the area. The results could be useful to understand the spatial variation in sediment production that is required for erosion and sediment yield reduction management on the basin. While for the short-term or annual sediment deposition calculation, some problems were encountered where the methodology could not explain the observed accumulated sediment in the reservoirs.

***Key Words**: sediment production, sediment yields, sediment depositions, USLE.*

1. INTRODUCTION

Sediment deposition causes a major problem in water resource management by decreasing the useful life of reservoirs. Uncontrolled sediment deposition is the key factor of nonsustainable component of reservoirs. Sedimented reservoirs cannot indefinitely be replaced by new dams at new site, and many of today's reservoirs are irreplaceable because of unique site characteristics [1)].

There are no accurate data on the rates of reservoir sedimentation worldwide. According to Meybeck [2)], 2 - 5 billion tonnes of sediments are trapped behind dams each year as of 13 billion tonnes of the world average annual sediment discharge to the sea (Milliman and Meade) [2)]. By assuming that 1.2 tonnes of sediment occupy 1 m^3, it means that the total losses of the world reservoirs volume are 1.7 - 4.2 billion m^3 per year, same as 0.03 – 0.07 percent per year of the 6000 km^3 of estimated world reservoir storage. This average world annual sediment rate seems to be too small to make a significant problem in the near future. However, since sediment yields differ greatly region-by-region, some areas are affected more severely than the others. For instance in East and South East Asia where about two thirds of world sediment load is discharged to the sea, there are many reservoirs filled in a much sorter time [2)]. Moreover, sedimentation in small reservoirs are much more serious than in large reservoirs.

(1) The Observation of Accumulated Sediments Depositions in a Reservoir

Sediment accumulation rate in reservoirs are usually observed by repeated reservoir capacity surveys that determine the total volume occupied by sediment. The survey method can be classified as either contour surveys or cross section surveys. Contour surveys are the most accurate technique for determining volume and also provide the most complete information on sediment distribution that use more complete topographic information to prepare a contour map of a reservoir. The cross section method uses a series of cross-section lines across the reservoir, which are resurveyed at intervals and used to compute the inter survey volume change in each reach. Cross section surveys are faster and more economical to perform than contour surveys because field data requirements are greatly reduced compared to contour surveys.

Sedimentation rate is computed as the difference between volume measurements from two surveys. The interval of survey should be based on individual site characteristics. At reservoirs losing capacity very slowly, a survey interval on the order of 20 years or even longer may be adequate. In contrast, at important sites which are losing capacity rapidly, or where the impact of sediment management is being evaluated, as short as 2 - 3 years or an annual survey interval might be required[1].

In Japan, where reservoirs are relatively small in size with high sediment deposition rates, reservoir volumes are generally measured annually by cross section survey with sounding method.

(2) Sediments Production and Yields Estimation

Reservoir volume surveys only measure the effect of sedimentation in diminishing of the reservoir capacity and lifetime. However, successful reduction of sediment yields and depositions require comprehensive understanding of the erosion process and transport process that is responsible for sediment delivery to the reservoirs. Moreover, knowledge of the spatial variation in sediment production and yields is required to focus erosion and yield reduction efforts on the landscape units that deliver most sediment to the reservoir.

Accordingly, in this study sediment production and yields in the mountainous topographic condition of Japan at the reservoirs catchments scale were examined. In this case, the USLE [3], SDR method [4] and Ackers and White's equation [5], and Brune method [1] were used for the calculation of the spatial variations in sediment production, sediment yields, and reservoir sediment deposition respectively.

2. THE ESTIMATION OF SEDIMENT ACCUMULATION IN THE FUJI RIVER BASIN BASED ON USLE

(1) About the USLE

The Universal Soil Loss Equation (USLE) is the method most widely used around the world to estimate average annual soil erosion rate. The USLE was first developed by Wischmeier and Smith in 1956, quantifies soil erosion as the product of five factors representing rainfall-runoff erosivity, soil erodibility, slope length and steepness, land cover-management practices, and support conservation practices, given by:

$$A = RKLsCP \qquad (1)$$

Where A is the soil erosion mass (ton/ha/year), R is rainfall-runoff erosivity, K is soil erodibility (ton/ha/year), Ls is slope parameter, C is land cover and management, and P is conservation practices factor [3].

a) Rain Erosivity Factor

In the original USLE procedure[3], rainfall erosivity factor R is calculated based on storm-based precipitation data. R factor is defined as a sum of erosivity of each evaluated storm in the period of calculation (monthly or annually). The erosivity of a storm itself is defined as product of a total kinetic energy of the storm and the maximum 30 minutes rainfall intensity. Kinetic energy of rainfall expressed in metric ton-meters per hectares per centimeter of rain is computed by the equation,

$$E = 210 + 89 * \log I \qquad (2a)$$

where I is the intensity at which the rainfall occurred that can be calculated from recorded rainfall data.

Using 10 minutes interval of rainfall data, the R factor can be mathematically defined as,

$$R = \sum_{s=1}^{m} 0.001 * \left[\sum_{t=1}^{n} E_t * \Delta V_t \right]_s * (I_{30})_s \qquad (2b)$$

where I_{30} is the maximum 30 minutes rainfall intensity in cm/hour, s is index of number of storms in a calculation period (monthly or annually), m is number of storm in the period, ΔV_t is rainfall volume at a time interval t in cm, and n is total time of the storm divided by the time interval t, in this case is 10 minutes. E_t is a kinetic energy at a particular interval time t in tonnes-meters/ hectare-cm, that calculated using the equation (2a) as a function of I_t. And I_t is rainfall intensity for a particular interval time t that can be expressed by

$$I_t = \frac{\Delta V_t}{t} \quad . \qquad (2c)$$

b) Slope Length-Steepness Factor *Ls*

Ls Factor is calculated by the following formula,

$$Ls = \left(\frac{\lambda}{22.1285} \right)^m \left(65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065 \right) \qquad (3)$$

where λ is slope length in meter, θ is angle of slope in degree, and m is constant that value is 0.5 if the percent slope is 5 or more, 0.4 on slopes of 3.5 to 5 percent, 0.3 on slopes of 1 to 3.5 percent, and 0.2 on slopes less than 1 percent.

(2) Domain and Data

The research takes place in 3 reservoirs in the Fuji River Basin, in the catchments of Arakawa (72.4 km^2), Daimon (51.7 km^2), and Hirose (76.64 km^2), (Figure 1.).

Data used in the calculation is 50 m x 50 m grid size of DEM (Digital Elevation Model) for topographical information, Land use map for land use information, and Geological Map as source for soil type classification.

Rainfall data used in the calculation is daily rainfall data from the gauges in the watersheds. There are 3 rain gauges in each catchment of Arakawa and Daimon, while only one rain gauge in the catchments of Hirose. Reservoir inflow data that observed daily is used as river flow data.

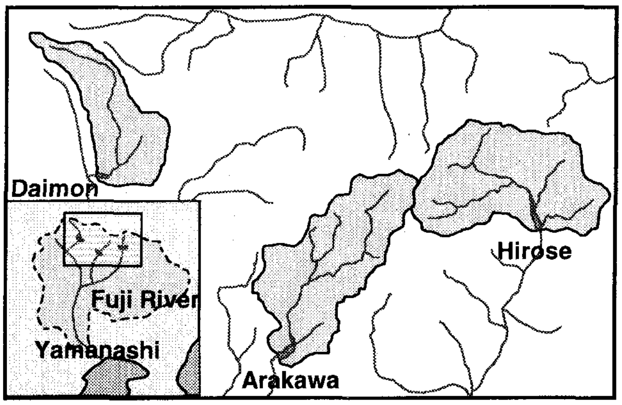

Fig.1. The Catchments of Daimon, Arakawa, and Hirose in the Fuji River Basin

(3) Methodology

The calculation of sediment production is taken based on grid size 50m x 50m. Spatial distribution of Slope and the Length-Steepness Factor Map of the catchments is calculated based on 50 m grid based of Digital Elevation Model (DEM).

The rainfall erosivity (R) Factor Map of the catchments is produced based on Thiesen method. In the USLE procedure, the rainfall erosivity (R Factor) is calculated as a summary of erosivity of each evaluated storm in the period of calculation (monthly or annually). However, since the data necessary for the evaluation is a storm based data, which is not available in the reservoir catchments area, the equation 2a, 2b, and 2c cannot be applied. In order to overcome this problem, two other equations were used to calculate R factor based on the available data. One of the equations was introduced by Bols [6] that calculates R factor based on monthly rainfall volume, rainy days in the month, and maximum daily rainfall in the month (equation 4a and 4b). The other one is proposed by the author that directly calculates R factor using daily rainfall data (equation 5) based on general approach used to estimate R factor values [7].

Adjusted Bols Formula:

$$R = \sum_{i=1}^{12} (EI_{30})_i \qquad (4a)$$

$$EI_{30} = 1.85 * R_m^{\ 1.21} * N^{-0.47} * R_{max}^{\ 0.53} \qquad (4b)$$

where EI_{30} is monthly rainfall erosivity, R_m is rainfall volume in a month in cm, N is the number of rainy days, and R_{max} is the maximum daily rainfall volume in cm.

Daily method:

$$R = \sum_{d=1}^{m} 0.0193 * P_d^{\ 1.753} \qquad (5)$$

where P_d is rainfall volume in a day in mm, d is index of the number of rainy days in a period of calculation (monthly or yearly), and m is the number of rainy days in the period, where a rainy day is defined as any day with precipitation.

The performance of equation (4a, 4b) and (5) is investigated by using 10 minutes interval AMeDAS data for Kofu in 1997. The result of R factors calculated by the original USLE formula, adjusted Bols formula, and the proposed daily-based equation are shown in the following figure 2.

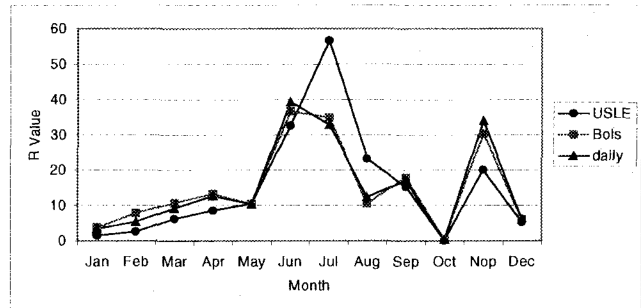

Fig.2. The Comparison of Rainfall erosivity factor calculated by original USLE formula, Bols method, and Dailv formula for Kofu 1997

Figure 2 shows that in July and August, R factors calculated both by adjusted Bols method and Daily method are smaller than the factors calculated by the original USLE formula, in contrast to the other months. It is because rainfall intensity of each storm in July and August are relatively higher than in the other months. In the present study, R factor is calculated using the equation 5.

Another problem was in the calculation of soil erodibility (K) factor. In the Agricultural Handbook no 537, Soil erodibility (K) Factor is derived from the nomograph proposed by Wischmeier and Smith[3] given the percentage of sand, the percentage of silt and find sand, the percentage of organic matter, the soil structure, and the soil permeability. Since the soil data required for the calculating is not available, the method is not applicable in the area. To overcome this problem, the geological classifications of the catchments are derived based on the Geological Characteristic Map of Yamanashi Prefecture. The value of soil erodibility (K) Factors for each geological class in the catchments are firstly identified based on assumption of correlated soil classes, and then adjusted to meet the long-term sediment deposition rate in the reservoirs. Table 1 shows the result of soil erodibility factor values derived from Geological Feature of the areas.

Table 1. Geological Features for Soil Erodibility Value (K Factor)

Geological Features	Area Arakawa km²	Area Daimon km²	Area Hirose km²	Groups	Value
Granite	40.72		65.86	Granite, Quartz, Gravel	0.132
Quartz with green flash rock			1.86		
Clay slate, mudstone, gravel, granite			3.35		
Volcanic rock made of trash		36.52		Volcanic Rock (Erupted Material)	0.119
Volcanic rock made of ash		5.09			
Clayly sand, stone		2.57			
Sandy soil with gravel	4.57		2.41		
Volcanic rock, not compact	12.07	1.84		Volcanic Rock made of Lava/ tuff	0.191
Volcanic rock made of lava/ tuff		5.69			
Lava rock (not hard enough)	8.33				
Lava rock			1.53		
Rock made of clay/ sandy rock	5.02			Sedimentary Rock	0.066
Gravel, clay slate, hard rock	1.68		0.36		
Gravel, clay slate, lime stone			1.27		
TOTAL	72.40	51.70	76.64		

Land cover and management factor C was selected depending on the land use type based on the USLE procedure. While since it is assumed that there is no any conservation practice in the area, P factor value is 1. Table 2 shows the selected values for Land cover and management factor C used in the present study.

Table 2. Vegetation/ Land Cover Value (C Factor)

Vegetation/ Land Cover	Area Arakawa km²	Area Daimon km²	Area Hirose km²	Value
Small-needle leaves trees	38.07	24.08	39.63	0.002
Broad leaves trees	30.27	17.65	33.32	0.003
Woody/ mixed forest	0.46			0.008
Palm trees	0.31			0.008
Rice field		1.21		0.010
Bamboo		0.68		0.017
Creeping pine/ Grass land	1.45			0.020
Housing/ Street Area		3.58		0.150
Farms		2.80		0.240
Waste land with grass cover	1.85	1.70	3.69	0.450
TOTAL	72.40	51.70	76.64	

Wash Load is calculated as a product of Sediment Production and Sediment Delivery Ratio (SDR),

$$L_w = A * SDR \qquad (6)$$

where A is the sediment Production from USLE calculation and SDR is sediment delivery ratio.

Sediment Delivery Ratio SDR is calculated using the equation 7, which determine SDR as a function of area A in hectare, average slope S in percent, and average manning roughness for overland flow in the watershed n [4],

$$SDR = \left[\frac{S*\left(1-C_1*A^{C_2}\right)}{2*(S+50*n)}\right] + C_1 * A^{C_2} \qquad (7)$$

where C_1, C_2 is constants.

The Following figure 3 shows the methodology in calculation of sediment production and wash load.

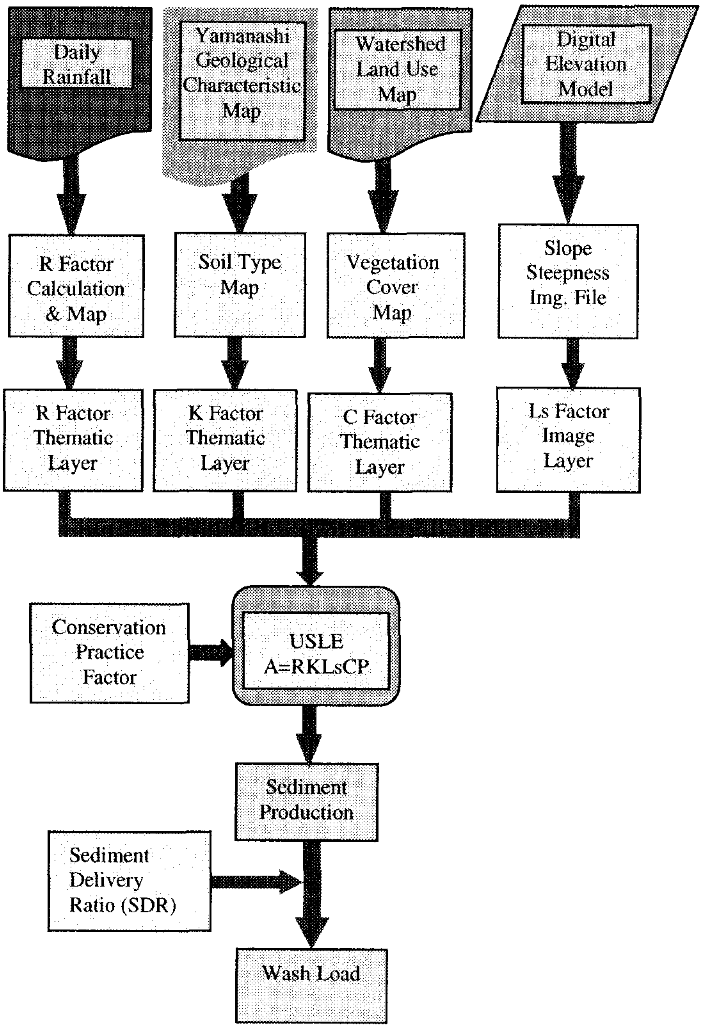

Fig. 3 Flow chart of Sediment Production and Wash Load Calculations

The total sediment yields entering the reservoir is calculated as the sum of Bed Material Load and Wash Load (figure 4). Bed Material Load is calculated based on daily discharge using sediment rating curve method, while Wash Load is determined as a part of sediment production reaches river mouth in the upstream of reservoir [5],

$$L_T = L_w + L_{BM} \qquad (8)$$

Where L_w is wash load and L_{bm} is bed material Load, that calculated by the following equation,

$$L_{BM} = \sum_{d=1}^{i} C_d Q_d \qquad (9)$$

where d is index of number of days in a calculation period (monthly or yearly), i is number of days in the period, Q_d is average discharge in a day m^3/sec, and C_d is sediment consentration for corelated discharge in kg/m^3. Sediment consentration C_d was obtained from the Sediment Rating Curve calculated using Ackers and White's Equation, which is the equation that has been used by many hydrologists in Europe and America [5].

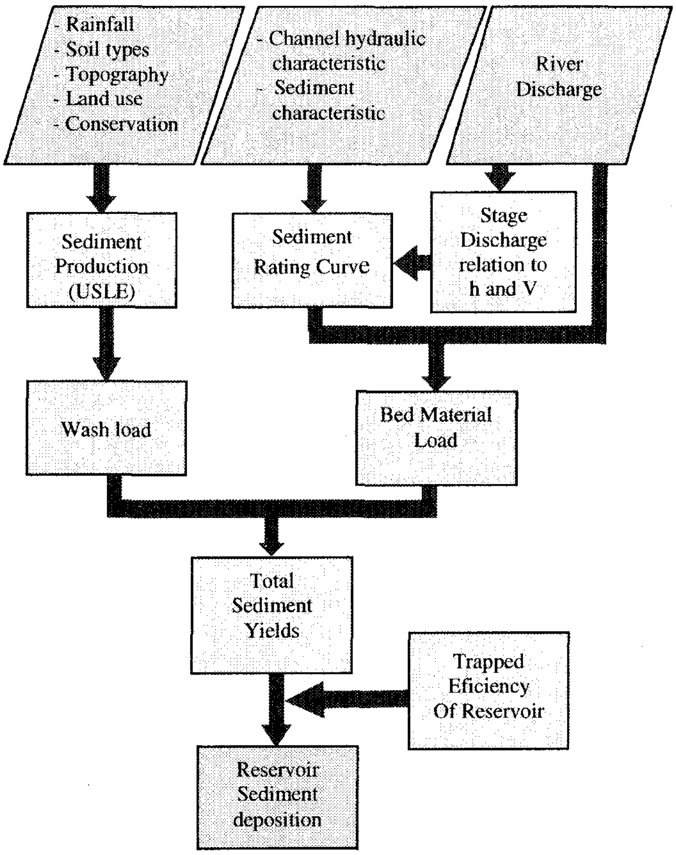

Fig.4 Flow Chart of Calculation of Sediment Yields and Reservoir Sediment deposition.

The part of the total sediment load that is trapped and accumulates in the bottom of the reservoir is calculated by Brune's curve of sediment-trapped efficiency which determine the Trapped Efficiency of the reservoir as a function of ratio of reservoir capacity to the annual inflow (Brune) [1].

$$T_{eff} = S_{tr} / L_T \qquad (10)$$

and, $$T_{eff} = f(C / Q_a) \qquad (11)$$

where T_{eff} is reservoir-trapped efficiency, S_{tr} is sediment trapped in reservoir, C is reservoir capacity, and Q_a is annual inflow.

(4) Result and Analysis

Figure 5 shows the result of calculation for the annual sediment production in the catchments of Daimon basin. From the figure it can be seen that some areas are very productive with an annual erosion rate of more than 500 ton/ha. Hence, efforts in reducing the sediment accumulated in the reservoir should also focus in the reduction of the erosion rate in those areas.

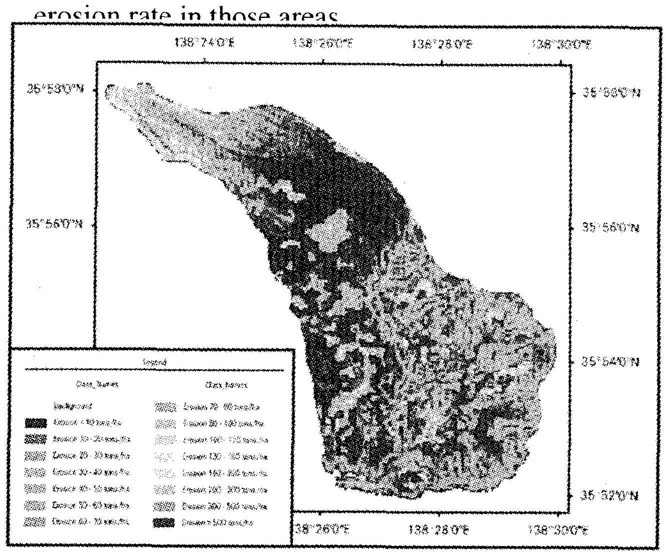

Fig. 5. Annual sediment production estimation in the catchments of Daimon

Table 3. Sediment Production, Yields, Deposition in the Reservoirs, and the Factors that influence

	Arakawa (72.4 km²)	Daimon (51.7 km²)	Hirose (76.64 km²)
Sediment Production (Tons/km²/ year)	869	769	3160
Sediment Yields (Tons/km²/ year)	377	306	1441
Sediment Deposition (M³/ha/ year)	239	154	689
Average Annual Rainfall Erosivity	280	311	375
Average Slope (%)	40.8	23.5	52.6
Major Land use / Vegetation Cover	Forest (96%) Idle land (2%)	Forest (81%) Idle land (3%)	Forest (92%) Idle land (5%)
Major Geological Feature	Granite (56%)	Volcanic rock (71%)	Granite (86%)

The results show that the average annual sediment production in the Arakawa is 869 tonnes/km^2, Daimon is 769 tonnes/km^2, and Hirose is 3160 tonnes/km^2, whereas the average of annual sediment yields entering the reservoirs of Arakawa, Daimon, and Hirose are 377 tonnes/km^2, 306 tonnes/km^2, and 1441 tonnes/km^2, respectively (Table 3). The results for Arakawa and Daimon are corresponding to the global pattern of suspended sediment yield according to Walling and Webb [8] that estimated 250 to 500 tonnes/km^2/year of suspended sediment yields in the East Japan. However for the Hirose reservoir the result is much higher than the work of Walling and Webb.

Considering factors that affect erosion, Hirose reservoir is located in the steepest-mountainous watersheds with the average slope of 52.6 %, followed by Arakawa and Daimon with the average slope of 40.8 % and 23.5 %, respectively. Rainfall erosivity of Hirose catchments area is also the highest, with an annual value of 375, followed by Daimon of 311, and Arakawa of 280. Most of land uses in the watersheds area of the reservoirs are forest. But there are 3.7 km^2 or 5% of the area of the Hirose watersheds is idle land, whereas only 3 % in the Arakawa and Daimon watersheds.

Moreover, in Hirose catchment in 1982 there was a typhoon that caused 255-mm of maximum daily rainfall and 123 m^3/sec of river discharge, which dramatically increased erosion rate and flushed the sediment into the reservoir. At the end of 1982, the survey result indicated that there was a remarkable increase of 986 000 m^3 of sediment trapped in the bottom of the reservoir that was same as an estimate about 26 950 tonnes/km^2 of sediment load entering the reservoir (figure 6).

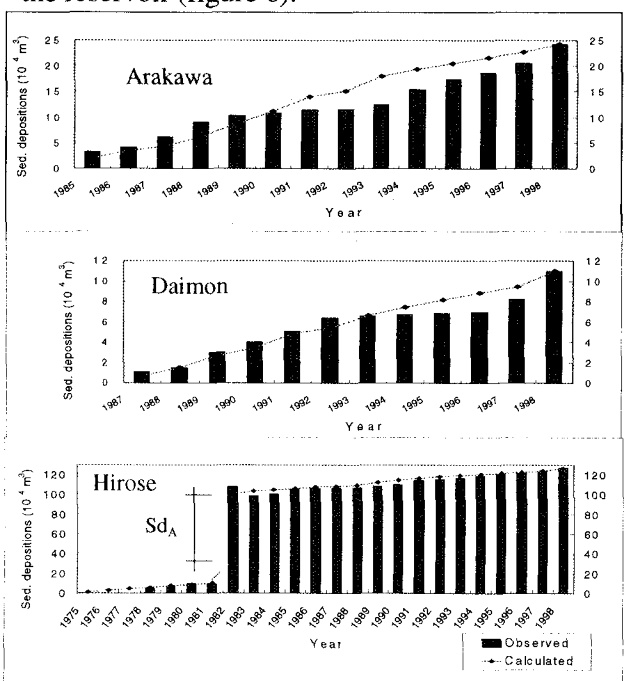

Fig. 6 Observed and Calculated Sediment Deposition in the Reservoir of Arakawa, Daimon, and Hirose

That phenomena of dramatic increase of sediment flushing into the reservoir cannot be accommodated adequately in the USLE and Ackers and white of Bed Material Load equations that result in the estimation of 6 950 tonnes/km^2 of sediment yield. In order to overcome the problem, in the present study, it is assumed that there was an additional sediment load of 20 000 tonnes/km^2 or 732 000 m^3 of sediment depositions in the reservoir (Sd$_A$) resulted by slope failure and mash washing caused by typhoon in the area in first August 1982.

3. CONCLUSION

The USLE can be adequately applied by identifying the parameters properly that reflects the regional conditions for estimating the long-term mean annual sediment production in Japan. The results could be useful in order to understand the spatial variation in sediment production that is required in erosion and sediment yields reduction efforts on the landscape units that deliver most sediment to the reservoir. However, in some cases because of the fragile-steep-slope topographic conditions of Japan and the strong wind-heavy rainfall caused by typhoons that frequently occur, more sediment yields are expected to be caused by slope failure and mash washing must be added to the USLE estimates.

Since the USLE is an empirical approach that only estimate erosion process that vary only with rainfall rate, using the USLE for short-term variation sediment yields and depositions estimations result in much different estimates in comparison with the observed. For proper sediment yields estimation at catchments scale, it is necessary to integrate physically based erosion and transportation process considering infiltration capacity of the soil and slope of the ground and hydraulic and mechanical properties of soil in the area.

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