SEDIMENT RUNOFF FROM MOUNTAINOUS AREAS IN KYUSHU, JAPAN

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Abstract

Sediment control over a whole river basin becomes important from the viewpoint of river environment and flood disaster. The sediment control needs an estimation of long-term and short-term runoff of sediment from a river basin. The purpose of the present study is to estimate a long-term sediment runoff from a river basin. Sediment runoff from a river basin occurs through several processes of sediment production caused by natural weathering and slope failure, and sediment erosion, transport and deposition caused by river and overland flow. Therefore, sediment runoff is governed by many factors, such as precipitation, geology, topography, land use, flow condition and so on. In the present study, reservoir sedimentation data is used for the analysis of sediment runoff. First, the relationship between specific sediment deposition and river basin area is discussed as parameters of prefecture region and geological condition. Second, a hydraulic consideration of the bed-load transport equation yields a linear relationship between annual sediment discharge and annual river flow discharge. Finally a simple formula is proposed to estimate annual runoff of sediments from a river basin.
Key Words: Sediment runoff, Reservoir sedimentation, Specific sediment deposition,

1. INTRODUCTION

There are many dam reservoirs in river basins of Japan. As a result, the reservoirs have serious problems of sedimentation in their upstream reach and bed degradation in their downstream reach. Therefore, sediment control over the whole river basins becomes important.

Sediment control over a whole river basin needs the knowledge of amount of sediment runoff from the river basin. However, there are less accurate measurement data and less exact prediction methods of sediment runoff. Reservoir sedimentation records, such as annual sediment deposition volume in reservoirs, are taken. Furthermore, hourly inflow discharge is measured. These are useful for estimation of sediment runoff.

There are several works on estimation of sediment runoff from a river basin (e.g. [1], [3-12]).
They are divided into two problems; one is on the estimation of long-term sediment runoff, and the other is on the estimation of short-term sediment runoff. The former is based on sediment deposition measurements every year at each dam reservoir and the latter is based on the hydraulic analysis of sediment runoff during one flood or debris flow event due to a heavy rainfall.

For the former problem, the concepts of specific sediment yield, specific sediment deposition and specific sediment runoff have been introduced, and then their relationship with precipitation, topography, geological condition and river basin area has been discussed (e.g. [1], [9], [12]). However, the relationship produces a fair degree of scatter in the data and a problem of accuracy of the estimation. The dependence of specific sediment runoff on river basin area significantly varies with regional characteristics, such as geology, topography, precipitation, land use and so on. For the latter problem, a river basin is divided into mountain slopes and river reaches. Runoff analysis of sediment and water is made on mountain slopes with kinematic wave method and in river reaches with a dynamic wave method ([5-8], [10], [11]). However, there occurs difficulty in an estimate of sediment runoff from the mountain slopes.

The present study deals with the former problem and develops an exact estimation method of long-term sediment runoff from a river basin. Hashimoto et al. [3] and Hashimoto and Nagano [4] have attempted to estimate long-term sediment runoff in dam reservoirs from the viewpoint of sediment transport hydraulics. The present study is an extension of these previous works [3-4].

First, sedimentation records of dam reservoirs are obtained from Kyushu Electric Power Co., Prefecture Government, Japan Water Agency, and Ministry of Land, Infrastructure, Transport and Tourism. Second, relationship between specific sediment deposition and the factors, such as river basin areas and geological condition, is examined. Relationship between annual sediment and water discharge is also investigated from hydraulic point of view. Finally, a semiempirical equation for an estimate of annual sediment runoff from a river basin is proposed.

2. SEDIMENTATION OF THE DAM RESERVOIR IN KYUSHU, JAPAN

Sediment deposition in dam reservoirs varies significantly for several years after dam construction. However, sediment deposition becomes relatively stable in 15 to 20 years after dam construction.

Therefore, we have selected 48 dam reservoirs which are more than 20 years old; their capacity is larger than 0.33 million cubic meters. We have obtained the data of measurements of annual sediment deposition volume and hourly inflow discharge for each reservoir. We have also obtained geological information of river basin at each dam site.

Geological condition of river basins at the selected reservoirs can be divided into 10 kinds: sandstone, slate, granite, andesite, basalt, phyllite, crystalline schist, gneiss, tuff and the other volcanic deposits termed 'Shirasu'.

We introduce the concept of specific sediment deposition. Here, specific sediment deposition can be defined as cumulative sediment deposition volume in each dam reservoir divided by its upper river basin area and by its elapsed years after the dam construction. Specific sediment deposition indicates average annual sediment deposition per unit basin area. Although all the fine component of sediments carried from the upper river basin was not trapped in reservoirs, the other components are assumed to be deposited in reservoirs. Therefore, sediment deposition represents approximately sediment runoff in reservoirs. The concept of specific sediment deposition is central to the understanding of most problems in sediment production and runoff in a river basin.

Fig. 1 shows the distribution of specific sediment deposition at the dam sites in Kyushu. This is useful to know the actual regional characteristics of sediment deposition. The regions with specific sediment deposition larger than 500 m^3/km^2/year are located at the boundary area between Fukuoka and Saga Prefecture, the middle area of Miyazaki Prefecture, and the south-east area of Kagoshima Prefecture. Geology of these regions is granite, sandstone and 'Shirasu'. Granite and sandstone are easy to be weathered by climate, and 'Shirasu' is easy to be eroded by rain water flow. Therefore, these can be sources of active sediment production.

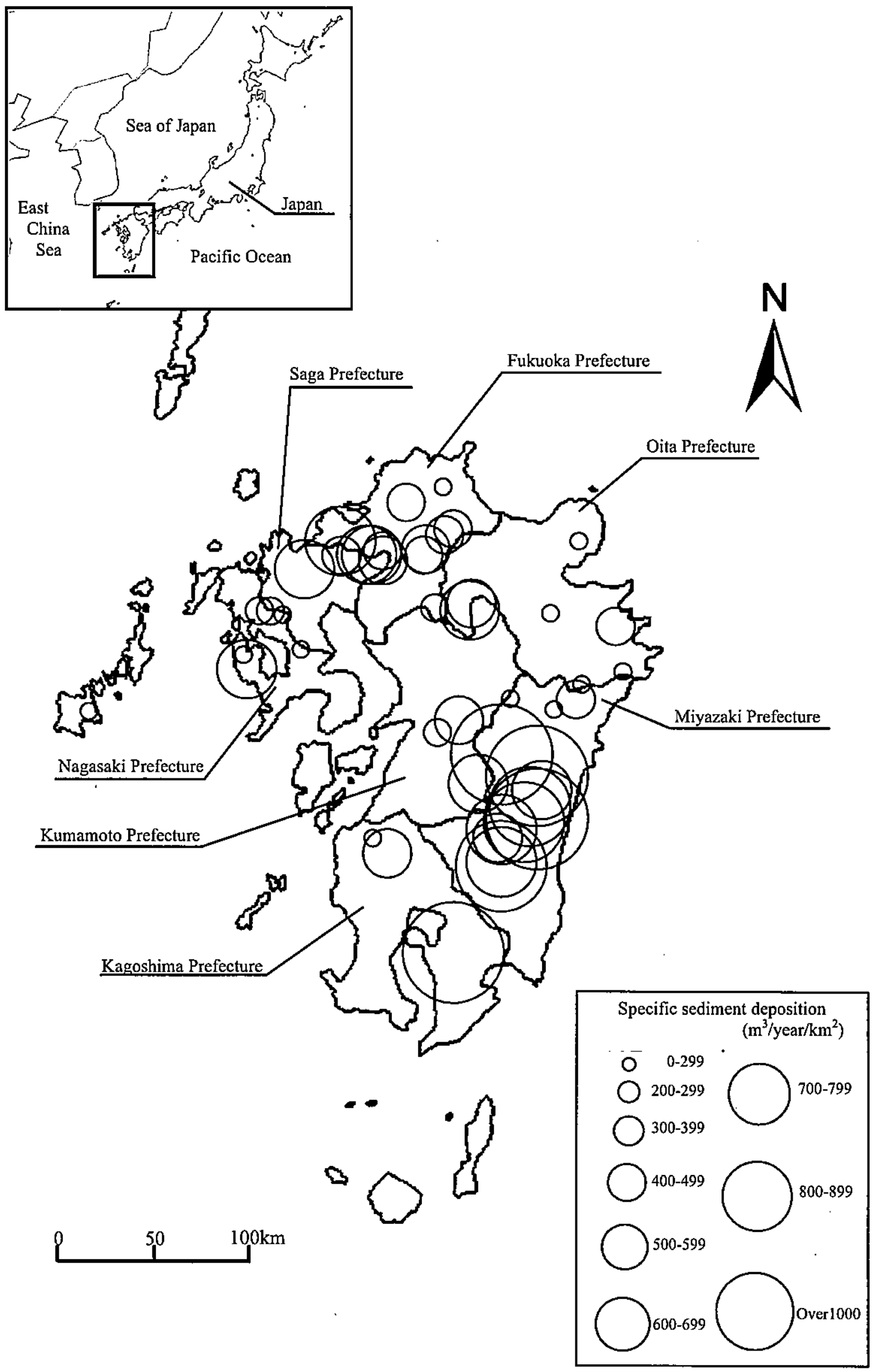

Fig.1 Distribution of specific sediment deposition in Kyushu, Japan

3. RELATIONSHIP BETWEEN SPECIFIC SEDIMENT RUNOFF AND RIVER BASINS

Ashida and Okumura [1] proposed a relationship between specific sediment deposition q_s (m^3/year/km^2) in reservoirs and their river basin area A (km^2) in the following form:

$$q_s = \alpha A^{-0.7} \tag{1}$$

where α : coefficient representing regional characteristics. This coefficient indicates different values for five groups of regions of characteristic sediment yield in Japan.

Figs. 2 and 3 show the variation of specific sediment deposition with river basin area at dam sites in Kyushu. The parameter in Fig. 2 is prefecture region and the parameter in Fig. 3 is regional geology. For comparison, the data in Mie and Nagano Prefecture in the regions different from Kyuhsu are also plotted. Solid lines in these figures indicate the calculations of Eq.(1) for the typical regions in Japan. Line (1) indicates those for the Kuroba and Tenryu River basin with most active sediment yield in Japan. Lines (2) and (3) indicate those for the Kiso and Yoshino River basin located along the geologically famous fault lines. Lines (4) and (5) indicate those for the river basin in Chugoku-chiho region, which is known as relatively stable area from the viewpoint of geomorphology.

The data obtained in the present study are scattered within the range between lines (2) and (5). The reservoir data in Fukuoka, Saga, Oita and Nagasaki Prefecture are plotted in the neighborhood of lines (4) and (5). The reservoir data in Kumamoto, Miyazaki and Kagoshima Prefecture, on the other hand, are plotted within the range between lines (3) and (4).

From the viewpoint of river geomorphology and geology (Figs. 2 and 3), we cannot avoid the scatter in the data of specific sediment deposition. Sediment deposition in reservoirs is approximately equal to sediment runoff. Therefore specific sediment deposition is useful index in macroscopic view of sediment runoff. However this estimation method is crude and the accuracy is not excellent. It is necessary to investigate factors governing sediment runoff from the viewpoint different from the concept of specific sediment deposition.

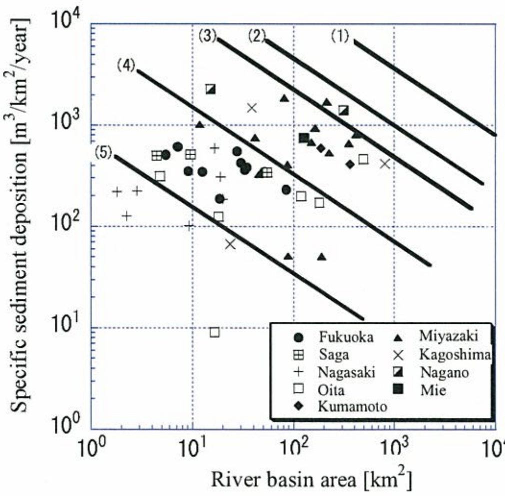

Fig.2 The relationship between specific sediment deposition and river basin area at dam sites for each prefecture.

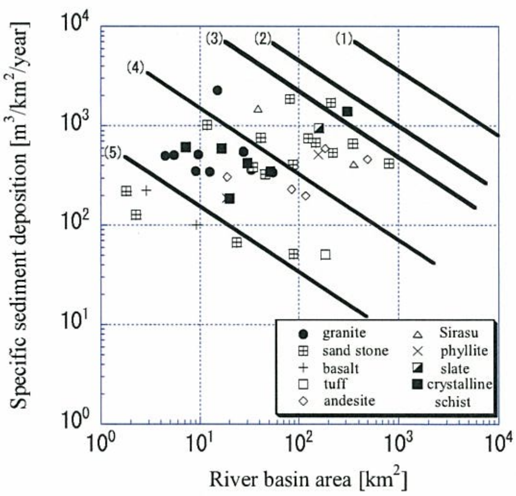

Fig.3 The relationship between specific sediment deposition and river basin area for the geological conditions.

4. HYDRAULIC CONSIDERATION ON SEDIMENT RUNOFF

Sediment runoff is the result of the following various processes: sediment production by slope failure and natural weathering, and sediment erosion, transport and deposition by river and overland flow. It is necessary to consider sediment runoff from the viewpoint of geology, geomorphology and hydraulics.

So far, there are many studies which have investigated the relationship between sediment production and parameters, such as precipitation, geology and geomorphology. On the other hand, there are few studies which have investigated the relationship between sediment runoff and river flow discharge.

Therefore, in this chapter, sediment runoff is discussed on the basis of sediment transport hydraulics; the relationship between annual sediment and river flow discharge is derived. Major type of sediment transport is assumed to be bed load.

Under the condition of active sediment transport, we can express a bed-load transport equation [2] for mountain rivers as

$$\frac{q_B}{\sqrt{sgd^3}} = K\left(\frac{u_*^2}{sgd}\right)^{1.5} \qquad (2)$$

where q_B: bed load per unit river width, s: specific weight of sediment grains in water, g: gravitational acceleration, d: sediment grain diameter, K: coefficient, and u_*: friction velocity. Denoting river flow discharge by Q and sediment discharge by Q_s, according to Tsubaki [13] we can rewrite Eq. (2) as

$$Q_s = \frac{QKI_e}{s\varphi} \qquad (3)$$

where $\varphi = v/u_*$: non-dimensional average velocity, v: average velocity, and I_e: hydraulic energy gradient. It should be noted that sediment discharge Q_s is proportional to flow discharge Q. Further indicating volumetric concentration of transported sediments by C, and using the relation $C= Q_s/Q$, we can obtain

$$C = \frac{KI_e}{s\varphi} \qquad (4)$$

Usually we have s=1.05 for natural sediments, $\varphi \approx 15$, $I_e \approx$ flow surface gradient of rivers near reservoirs, and K=a constant. Therefore we can expect almost constant value for volumetric concentration of inflow sediments at dam reservoirs in Japan.

5. RELATIONSHIP BETWEEN ANNUAL SEDIMENT AND WATER DISCHARGE

Integrating Eq. (3) with respect to time yields

$$\int_0^{1\,year} Q_S dt = \int_0^{1\,year} Q\frac{K}{s\varphi}I_e dt \approx \frac{K}{s\varphi}I_e\int_0^{1\,year} Qdt \qquad (5)$$

Therefore, we can find that annual sediment discharge is proportional to annual river water flow discharge. Annual sediment discharge is almost equal to annual sediment deposition volume in dam reservoir and annual river flow discharge is equal to inflow discharge in reservoirs; the former is measured every year and the latter is measured every hour. Therefore, plotting annual sediment deposition volume versus annual inflow discharge, we can examine the relationship of Eq.(5), as shown in Fig. 4. The regression relation of the plotted data results in

$$V_S = 0.81 \times 10^{-4.0} V_Q^{1.03} \tag{6}$$

(Dimension in m^3/year)

where $V_S = \int_0^{1\,year} Q_s dt$ and $V_Q = \int_0^{1\,year} Q dt$. Although the plotted data are scattered, we can see that annual sediment deposition varies in a linear fashion with annual inflow discharge. This result agrees with that of Hashimoto et al. [3]. Precipitation condition, sediment production, and river and overland flow situation are different every year in a same river basin. All the same annual inflow discharge does not have the same value of sediment deposition volume. Therefore, the scatter in the data is the natural result. The data scatter is also ascribed to the measurement error of annual sediment deposition in reservoirs.

In order to avoid the plotted data scatter, annual sediment deposition volume and annual inflow discharge are averaged over ten pieces of data pairs for ten-year measurements, and their relationship is examined, as shown in Fig. 5. For comparison, data in Mie and Nagano Prefecture in the other regions are also plotted. We find that Eq.(5) is verified.

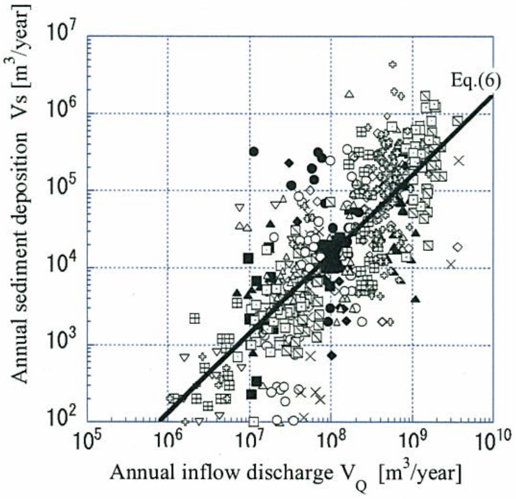

Fig.4 The relationship between annual sediment deposition and annual inflow discharge.

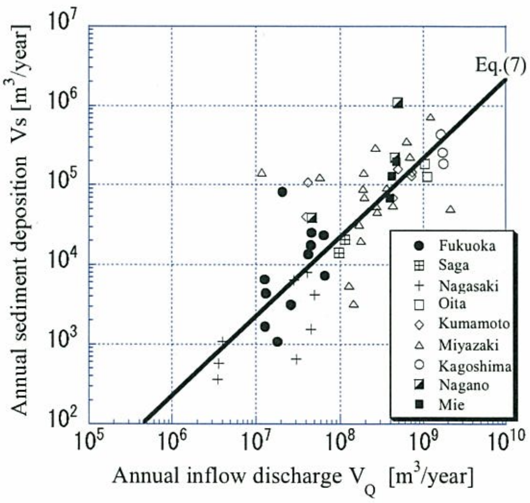

Fig.5 The relationship between averaged annual sediment deposition and annual inflow discharge.

From Eqs.(5) and (6), we can assume the following relation:

$$V_S = \beta V_Q \tag{7}$$

We determine the value of coefficient β such that Eq.(7) agrees with the plotted data in Fig.5. As a result, we can obtain volumetric concentration of sediments carried by flow.

$$C = \frac{V_S}{V_Q} = \beta = 2.1 \times 10^{-4.0} \tag{8}$$

This equation represents that river basins in Kyushu can carry sediments at the average concentration of $\beta = 2.1 \times 10^{-4.0}$ from the mountainous areas to the dam reservoirs. Eqs.(7) and (8) are valid for Kyushu and the other regions in Japan. If a region without sedimentation records needs an estimate of long-term sediment runoff, we can predict the sediment runoff by Eq. (7) or (8). Here V_Q can be estimated from runoff analysis of annual precipitation. Using the same average annual sediment deposition as in Fig.5 yields averaged specific sediment deposition. Although the specific sediment deposition shows significant scatter in the plotted data, plotting annual sediment deposition versus annual inflow discharge produces their clear linear relationship, as shown in Fig. 5. Therefore, Eqs.(7) and (8) are found more accurate than specific sediment deposition for the estimation of sediment runoff.

6. CONCLUSIONS

We have investigated amount of sediment deposition and flow discharge in reservoirs in Kyushu, Japan. Although all the fine component of sediments transported from the upper river basin was not trapped in reservoirs, the other components are assumed to be deposited in reservoirs. Therefore sediment runoff can be approximated by sediment deposition in reservoirs. Factors controlling annual sediment runoff were also investigated. Hydraulic approach to sediment transport yields linear relationship between annual sediment discharge and annual inflow discharge. Finally, we have proposed Eqs.(7) and (8) for estimating annual sediment runoff from a river basin. It must be emphasized that these equations are more accurate than specific sediment deposition for Kyushu and the other region in Japan.

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