Characteristics of sediments in a newly constructed reservoir in Japan

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Abstract The sediment formation mechanisms of a newly constructed reservoir in Ehime, Japan were evaluated by characterizing the soil particles (SP) and particulate phosphorus (PP) in the runoff and reservoir sediments. The SP and PP loads from the runoffs of the main river in the watershed considerably increased, when the specific discharge rates were over 300 l/s/km^2 (high flow conditions). When the specific discharge rates exceeded over 300 l/s/km^2, 19% of the watershed generated over 80% of the SP and PP loads. When the specific discharge rates were under 300 l/s/km^2 (low flow conditions), the contributions of the previously mentioned 19% area to the SP and PP loads were smaller. Significant amounts of smectite were found in the sediments in the reservoir and in the soil samples obtained at the forest exposed area in this 19% area while it was negligible in citrus orchards and paddy fields that constituted the remaining land surfaces. The forest area exposed by recent landslides was significant for the SP and PP in the reservoir. Judging from the outcomes, land use information alone may not be sufficient to detect critical sources of SP and PP in the runoffs and reservoirs. To identify and confirm crucial areas for the SP and PP in the runoffs, the investigations should be conducted under high flow conditions and the composition of clay minerals in the sediments should be checked against the clay mineral distributions of soils in the watershed.

Keywords Newly constructed reservoir; phosphorus; prevention of eutrophication; runoff characteristics; sediment; soil particle

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Introduction

Protecting reservoirs from eutrophication is essential to maintain the suitability of water for irrigation and recreational uses (Ryding and Walter, 1989). It is widely recognized that nutrient releases from the sediments are the primary causes accelerating the progression of the eutrophication processes in reservoirs (Correll, 1998). In existing reservoirs, sediments gradually accumulated overtime and the sediment layer had already formed (Bennett *et al.*, 2005). The origin of the existing sediments, the relative contribution of sediment and nutrient loads from sub units of the catchment basin, and the sediment deposition patterns in the reservoirs are not fully known. Therefore, it is imperative to understand the sediment formation and deposition processes when the reservoirs are first constructed. In this manner, protective measures and management strategies may be formulated to prevent the subsequent nutrient enrichment in the water body.

When a new reservoir for irrigation in Ehime, Japan was completed and began filling in 2001, it was an opportunity to investigate the water quality changes, chemical and physical condition of the reservoir sediments and relative contributions of sediment and nutrient loads of sub units of the catchment basin. It was established through initial investigations that the phosphorus release from the sediments would be the most important factor in eutrophication in the new reservoir. To devise suitable measures to minimize the generation of sediments and release of phosphorus, it is essential to understand the mechanisms of sediment formation in the catchment basin.

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This study examined the sediment formation mechanisms and the runoff characteristics of soil particles (SP) and particulate phosphorus (PP) and identified the critical sources of SP and PP in the watershed of a newly constructed reservoir in Japan.

Methods

Study site

The study site, a newly completed reservoir and its catchment basin, is located in the Ehime Prefecture of southern Japan (Figure 1).

The reservoir (designated as S-reservoir hereafter) has 1,100,000 m^3 of storage volume, and had been filled since January of 2001. The high water level of the reservoir is at 25.1 m, and the low water level is at 9.2 m. The surface area of the watershed surrounding S-reservoir is 4.05 km^2, consisting of claystone and shale formations with partly tuff. The catchment basin is 93% forest, 2.0% paddy field, and 1.6% upland field and the catchment has only eight households. The vegetation in the forest consists primarily of Japanese redwood and Japanese cypress. Almost all of upland fields are citrus orchards. The major river and its tributaries (designated as S-river hereafter), which has a catchment basin of 2.70 km^2, supplied the majority of the inflows to the reservoir. The watershed outside of the S-river catchment basin is covered entirely by forest and is uninhabited.

Sampling and analytical methods

Investigations were conducted in three parts.

1. To define the runoff characteristics of SP and PP of the S-river watershed, the water was sampled and the corresponding flows were measured simultaneously at the point where the S-river is emptied into the S-reservoir (Station A in Figure 1). The water sampling and the flow rate measurement were made for 20 rainfall events during the 2001 to 2003 period. The water samples were filtered by Whatman GF/B glass fiber filters with 1 μm pore size, and the spent filters were heated at 600°C for 30 min to obtain the non-volatile solids content. The non-volatile solids were regarded as the soil particles, SP in the water. Total phosphorus (TP) and dissolved total phosphorus (DTP) of the water were analyzed by the molybdenum-blue method after the aliquots of filtered and non-filtered water were digested with potassium peroxodisulfate according to procedures outlined by the Japanese Industrial Standards Committee (1993), and the particulate phosphorus, PP, was obtained from the difference between TP and

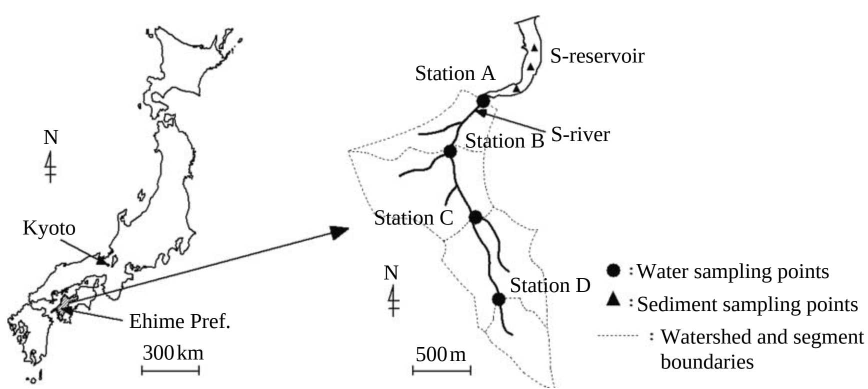

Figure 1 Maps showing the location of the S-reservoir and sites of water and sediment sampling

DTP. Flow rates were calculated from measurements of water depth, stream cross sectional area and flow velocity.

2. To delineate the origins of SP and PP in the catchment basin, water sampling and flow rate measurement were simultaneously made at the mid point of three rainfall events in which 19, 23, and 55 mm of rain had fallan, respectively at the four sites along the S-river, namely Stations A through D in the map in Figure 1. Table 1 shows the land use patterns of the entire watershed of S-river and the sub-catchments covered by each gauging station. Water sampling was collected at 0.5 to 1 hour before the peak of rains.
3. To identify the critical sources of SP and PP in the watershed, the clay minerals in the reservoir sediments and in the soils representing land uses of the watershed were analyzed by the X-ray diffraction method. In the reservoir, the sediment samples (surface 1 cm of the reservoir bottom) were taken at the three sites as shown in Figure 1 in the autumn of 2001. In the watershed, samples of surface soils (the 0 to 1 cm layer) were taken at a paddy field, an orchard, and an exposed area of the forest that had experienced recent land slides adjacent to the S-river.

Results and discussion

Sediment and phosphorus loads and runoff characteristics

Figure 2 shows the effects of specific discharge rates on the specific loads of SP and PP at Station A, runoff entry point to the S-reservoir.

The SP and PP loads of the reservoir inflows during the rainfall events (measured as mass of particulates and mass of phosphorus per second per km^2) changed dynamically with the changes of the specific discharge rates. Both of the SP and PP loads from the S-river increased considerably, when the specific discharge rates exceeded 300 l/s/km^2. For example, the SP and PP specific loads reached 310 g/s/km^2 and 190 mg/s/km^2, respectively at the specific discharge rate of 1,100 l/s/km^2. In contrast, when the specific discharge rates were under 300 l/s/km^2, the SP and PP specific loads were less than 10 g/s/km^2 and 15 mg/s/km^2, respectively.

Table 1 Land use of the S-river watershed

Catchment	Catchment area (km^2)	Orchard (%)	Paddy field (%)	Upland field* (%)	Forest (%)	Others (%)
S-river	2.70	2.1	3.0	0.2	83.2	11.5
> Station D	0.39	0.0	1.4	0.0	87.4	11.2
Station C-D	0.44	0.4	7.2	0.9	73.4	18.0
Station B-C	1.37	2.3	2.9	0.0	91.7	3.1
Station A-B	0.50	4.7	0.8	0.2	65.2	29.1

*Except for orchard

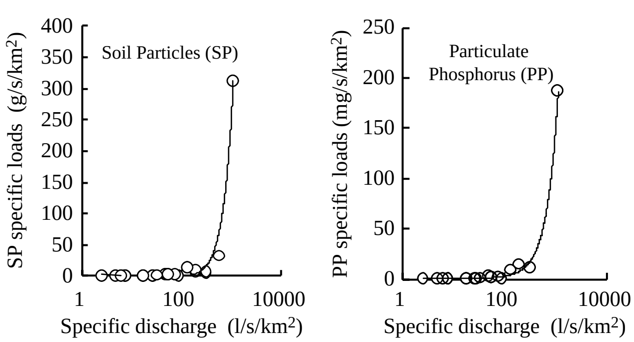

Figure 2 Relationship of specific discharge rates and specific loads of SP and PP

The sediment loads of the S-river were associated primarily with rains that generated discharges exceeding 300 l/s/km^2. Therefore, the sources contributing to the SP and PP loads must be identified with specific discharge rates that are greater than 300 l/s/km^2.

Contribution of sub-catchments

Figure 3 shows the SP and PP loads of the sub-catchments defined by the four gauging stations along the S-river. Under 55 mm of rainfall, the specific discharge rate was 1,100 l/s/km^2. Following 23 mm and 19 mm of rainfall, the specific discharge rates were 55 l/s/km^2 and 33 l/s/km^2, respectively.

Data plotted in Figure 3 demonstrated that the contribution of each sub-catchment of the watershed to the SP and PP loads of the reservoir varied with the antecedent rain conditions and the specific discharge rates. Had the scale not been expanded by 25 times, the SP and PP loads of the 19 and 23 mm rainfalls would not be distinguishable from the x-axis. Under the rainfall event of 55 mm, the SP loads at Station B were only 15% of the SP loads at Station A, and the PP loads at Station B were only 16% of the PP loads at Station A.

In contrast, the SP loads at Station B were over 40% of the SP loads at Station A, and the PP loads at Station B were over 35% of the PP loads at Station A when the rain was 23 mm. When the rain was 19 mm, the SP loads at Station B were over 50% of the SP loads at Station A, and PP loads at Station B were over 45% of the PP loads at Station A.

The sub-catchments of gauging Station A covered 19% of the watershed, yet the contributions to the SP and PP loads to S-reservoir varied considerably with the increase of discharge rates. When the specific discharge rates were over 300 l/s/km^2, the contribution of the sub-catchment from Station B to Station A were several orders of magnitude greater than those from all of the upstream sub-catchments added together. When the specific discharges were less than 300 l/s/km^2, the relative contribution of the sub-catchment defined by Station A was considerably lower. These results indicate that the critical sources of SP and PP were present in the sub-catchment from Station B to Station A.

Nishimura *et al.* (2002) showed that the citrus production areas were significant generators of the non-point source pollutant loads of the downstream water bodies. The sub-catchment from Station B to Station A contained slightly larger citrus production area than other sub-catchments (Table 1). Therefore, the results shown in Figure 3 appeared to imply that the citrus orchard could be a significant source of SP and PP.

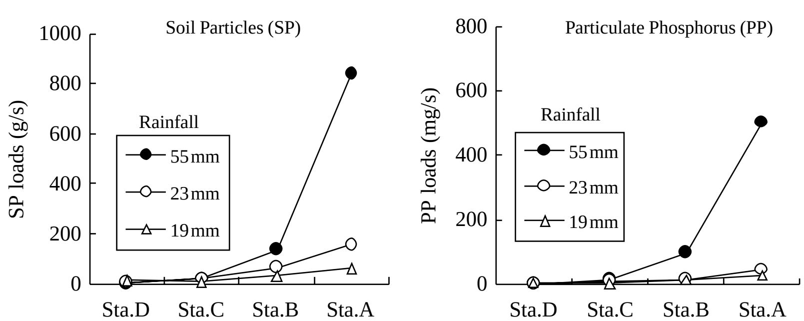

Figure 3 SP and PP loads in S-River following 19, 23 and 55 mm of rainfall (the points indicating 19 and 23 mm rainfall are plotted 25x of their actual values)

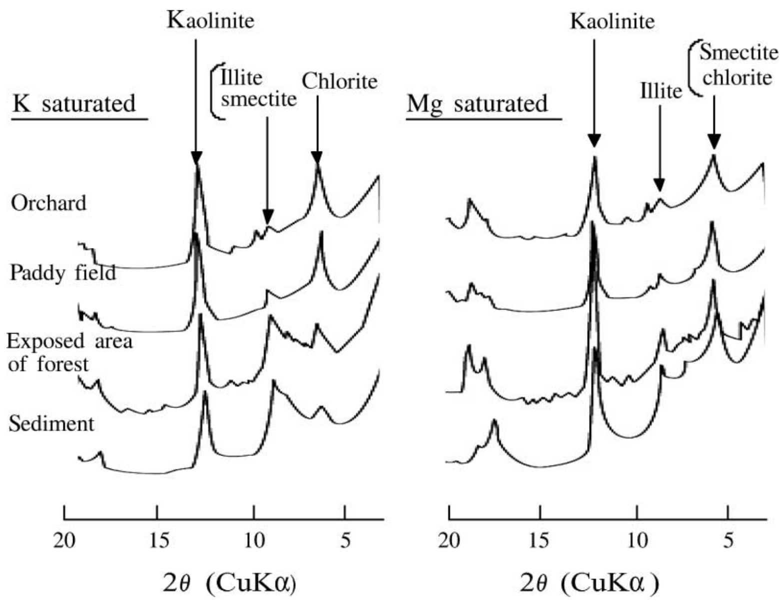

Figure 4 X-ray diffraction patterns for soils and sediments

Clay minerals in soils and sediment

The X-ray diffraction patterns showed that mineral compositions of three sediment samples were similar and only one tracing for the sediment was illustrated (Figure 4). It is difficult to separate the illite and smectite peak in the K saturated samples, but in the Mg saturated samples, illite and smectite peaks can be separated.

The shape of the X-ray diffraction patterns showed that mineral compositions of the sediment were very similar to that of soils obtained at the exposed area of the forest. Smectite in this case was detected in a large quantity relative to other clay minerals in the sediments. At the exposed area of the forest, smectite was also detected in a relatively large quantity. Conversely, in the paddy field and the orchard, the presence of smectite was considerably less prominent. In our survey, the sub-catchment from Station B to Station A contains a much more exposed area of forest. Kaolinite was detected in a large quantity in all samples. It is indicative that instead of the citrus orchards the exposed forest area in sub-catchment of Station A was the most significant source of sediments in S-reservoir. The mineralogical analysis of the clays accurately identified the source sediments in the S-reservoir.

Summary and conclusion

1. The soil particles (SP) and particulate phosphorus (PP) loads of the main river flowing into the newly constructed reservoir increased considerably, when the specific discharge rates exceeded 300 l/s/km^2. For example, the SP and PP specific loads reached 310 g/s/km^2 and 190 mg/s/km^2 respectively at the specific discharge rate of 1,100 l/s/km^2. These results indicate that the SP and PP loads, when the specific discharge rates were over 300 l/s/km^2, had significant effects on the generation of sediments and the sediment phosphorus in the reservoir.
2. When the specific discharge rates were over 300 l/s/km^2, 19% of the catchment basin generated over 80% of the SP and PP loads to the reservoir. The remainder of the watershed had great contributions to the SP and PP loads of the reservoir only under

the low rainfall conditions. This indicates that the major source of the SP and PP loads was associated with releases from the 19% area.

3. The X-ray diffraction patterns of minerals in the sediments were near identical to that of the surface soil sample obtained at the exposed area of the forest. Significant amounts of smectite were detected in the sediments and the soil samples representing the exposed forest area. Conversely, smectite was less prominent in the soil samples obtained from paddy fields and the citrus orchards that constituted the remainder. The results indicate that the exposed area in the forest is the significant SP and PP source.

To assess the SP and PP loads to reservoirs, land use information alone may not be sufficient. The critical source areas of SP and PP in a watershed are best investigated under the high flow rate conditions during and following significant rainfall events. To identify and confirm the critical source origins, it may be essential to check the clay mineral distribution of the sediment in the reservoir against the clay mineral distributions of soils in the watersheds.

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