1. INTRODUCTION

Sediment discharge causes various problems in river basins, such as flooding due to river bed aggradation and a reduction in sediment transport capacity, reduced water storage capacity due to sedimentation in reservoirs, scouring of the foundation bottom due to riverbed degradation, and acceleration of coastal erosion due to reduced sediment transport to the mouth of the river. To resolve these problems, it is necessary to consider the entire area of sediment movement from the mountain to the littoral drift area as a single sediment transport system and take comprehensive sediment control measures over the entire basin (Subcommittee for Comprehensive Sediment Control, River Council, 1998). As a first step, temporal changes in moving sediment volumes and particle size distributions during flood events should be understood.

Sediment discharges at the Tenryu and Hime rivers have been measured by collecting samples using a sampler placed at the overflow section of a check dam for collecting the suspended load and bed load at various depths, or using a sampler inserted into the flowing water from a backhoe for collecting the bed load (Nakano et al. 2001). Similar observations have been conducted at various positions along the Abe River basin, from the sediment source to the mouth of the river. (Matsuki, Hashinoki et al. 2005, Mizuno et al. 2005, Imaizumi et al. 2003, Kondo et al. 2005).

Both the suspended load and bed load are usually mixed at all depths when they are transported in flood flow. Therefore, the sampling position should be sufficiently flexible to trap sediment moving at all depths.

Here, based on a previously reported system (Nakano et al. 2001), we developed a sediment discharge trapping system (hereafter referred to as “Total Load Trapping Equipment”) capable of trapping all sediment passing through a unit width (1.0 m) of a flood flow passing through the overflow section. Using this system, we conducted field measurements to investigate sediment discharge in a mountainous river.

2. TARGET AREA AND THE TOTAL LOAD TRAPPING EQUIPMENT

2.1 TARGET DRAINAGE AREA

The Oshima check dam area is shown in Fig. 1; observations were conducted at the confluence of the Oya River and the Yomogi River, both upstream tributaries of the Abe River, which flows through Shizuoka city. The total drainage area of these rivers above the Oshima check dam is 7.8 km². The Yomogi River originates from Mt. Yanbushi (2,014 m) and has a drainage area of 3.8 km², a channel length of 4.0 km, and an average gradient of 1/3.6 up to this check dam. The Oya River originates from Mt. Oya (2,000 m) and has a drainage area of 4.0 km², a channel length of 3.2...
km, and an average gradient of 1/2.9 up to the dam. A mountainside that collapsed during a severe earthquake in 1707, the "Oya Kuzure", is located on the headwater area of the Oya river. The horizontal area of the "Oya Kuzure" is estimated to be 1.8 km$^2$; with a total height of 800 m, it provides nearly 120 million cubic meters of sediment to the river, (Shizuoka River Work Office of the Ministry of Construction (MOC), 1988) and is, thus, the primary sediment source to the Abe River basin. The geology in the upstream area above this dam belongs to the Setogawa formation group of the Palaeogene Period and mainly consists of sandstone, shale, and alternations of these rocks. Due to the Itoigawa-Shizuoka tectonic line to the east and the Sasayama tectonic line to the west, the geology in this upstream area of the Abe River is prone to collapse, because the bedrock is fractured due to tectonic movement.

The Oshima check dam, constructed in 1977, is 22-m-high and has a sediment trapping capacity of 410,000 m$^3$ (Shizuoka River Work Office, MOC, 1988). However, it is now almost full due to large-scale floods in 1982 caused by Typhoons No. 10 and No. 18. The present sedimentation gradient is about 1/15. An open-type check dam is installed 500-m upstream of the Yomogi River and a series of groundseis are located 500-m upstream of the Oya River.

2.2 TOTAL LOAD TRAPPING EQUIPMENT

Total Load Trapping Equipment was developed with the following four design objectives (Kakimoto, Yasuda et al. 2003):

- To sample both flowing water and sediment at all depths from the riverbed to the water surface.
- To sample water and sediment without disturbing water flow as much as possible.
- To sample flowing water along the stream center line, considered to be representative of total flow.
- To measure changes in sediment volumes and particle sizes over time.

To satisfy these objectives, we designed the system to collect flowing water and sediment along the center line of the stream with a trapping bucket at the front of the overflow section.

The Total Load Trapping Equipment system, installed in October 2004, is shown in Figs. 2 and 3. Because the primary objective was to measure the state of sediment discharge during flooding, the possible target floods ranged from small and medium floods that occur in normal years to large-scale floods that occur once every 10 years or more. However, if a large-scale flood is targeted, large equipment would be needed and the safety and operability may be impaired.

![Fig. 1 Outline of the Abe River drainage area.](image1)

![Fig. 2 Overview of Total Load Trapping Equipment](image2)
Therefore, a rainfall with a return period of about 20 years was selected as the target rainfall for the Total Load Trapping Equipment. The peak flow rate of this rainfall and the water depth at peak time were 38 m$^3$/s and 0.6 m, respectively.

The individual components of the system were designed to the target discharge, as follows:

**Trapping bucket:**
- The depth of the trapping bucket was 2.5 m, which is larger than water displacement in the target flow, as shown on the right side of Fig. 2. Hence, all flowing water from the riverbed to the water surface can be collected. The width of the bucket was 1 m.

**Water conveyance pipe:**
- Sediment and water were sent to the sampling tank from the trapping bucket through a water conveyance pipe, as shown in the center of Fig. 2. The conveyance pipe inside diameter was 0.8 m to prevent flow obstruction by pressure under a peak flow rate.

**Sampling tank:**
- The capacity of the sampling tank was 6.5 m$^3$ (outside diameter: 2.0 m; height: 2.5 m) to collect the target flowing water and sediment volumes without overflowing after a short time. Seven sampling tanks were used to measure sediment discharge at different flow rates.

- Sampling tanks were placed at the sampling position by a crane and changed after each sampling period to measure the total quantity of sediment and water in the tanks, as shown on the left side of Fig. 2.

### 2.3 MEASUREMENT METHODOLOGY

#### Flow rate:
- The flow rate at the overflow section of the Oshima check dam was measured via sampling. The velocity was obtained using a float. The water depth was measured using a supersonic wave-type water gauge, as shown in Fig. 4. The river width was assessed visually.

#### Sampling tank:
- It is necessary to separate the sediment and water to measure actual sediment discharge; however, it was not practical to separate sediment from all sampled water because the equipment system was too large. To estimate sampled sediment volumes, the sampling tank contents were divided into turbid water components (upper part) and subsidence components (lower part), as shown in Fig. 5, and each component was measured separately.
- The sediment concentration of the upper part was estimated by measuring 1.5 L of turbid waters dipped immediately after sampling. The weight and particle size of the lower part was measured directly after drainage of the upper part using a siphon. The total load was calculated as the sum of upper and lower parts.

- Particles smaller than 0.1 mm were considered to be washload, which is almost never exchanged with bed materials under natural conditions and does not usually remain on the riverbed (Ashida et al. 1985). These particles in the lower part were considered to have sunk during drainage and were, hence, excluded from subsidence component samples when the total load was calculated, such that there was no overlap with turbid waters.

### 2.3 OBSERVATIONS

Observations were conducted on 11 occasions between 2003 and 2007. During Typhoons No. 18 and No. 22 in 2004, Typhoon No. 11 in 2005, and
Typhoon No. 9 in 2007, large-scale discharge occurred, and sediments were sampled during the peak flow. These four observations were used for further analysis; the results are shown in Table 1.

In these observations, it was rare that flows from the Oya River passed through the entire width of the overflow section; thus, the discharge captured by the equipment was mostly from the Yomogi River. However, for evaluation purposes, it was assumed that flow conditions at the overflow section of the Oshima check dam were identical to those of the water flowing into the unit width of the equipment. For volume concentration calculations, the density of soil grains was assumed to be 2.75 (g/cm$^3$) from past soil test results (Kondo et al, 2004).

Total rainfall was obtained from measurements at the Umegashima Rainfall Gauging Station of the Japan Meteorological Agency (JMA). The return period was calculated from 33 years of data (1976-2008) at the same gauging station using the Iwai method (Iwai, 1946). The daily rainfall during the observation period was mostly in the range of a return period of 1-2 years. Accordingly, the measured flood was inferred to be within the normal range that occurs in ordinary years. The maximum daily rainfall that occurred on September 6, 2007 had a return period of 19.6 years; this observation was considered to target large-scale flooding.

In these four floods, the maximum values of flow rate, sediment discharge, sediment concentration, and particle size were obtained at 19:00 during Typhoon No. 9 in 2007. The maximum sediment concentration and the maximum particle size were 2.0% and 300 mm, respectively.

### 2.4 CLASSIFICATION OF SAMPLES BY SEDIMENT DISCHARGE TYPE

The observation results obtained from the Total Load Trapping Equipment were not directly usable for evaluation of sediment movement type, because the sediment was kept in a tank together with water. To compare the results of observations with past results from other areas or calculated values, sediment movement type was defined and classified according to particle size. It was assumed that subsidence with a fall velocity faster than the friction velocity flows as bed load, and that other subsidence components and the turbid water component flows as suspended load and washload. The friction velocity was calculated as follows:

$$u_f = \sqrt{ghi}$$  \hspace{1cm} (1)

where $u_f$ is the friction velocity (m/s), $g$ is the gravitational acceleration (9.8 m/s$^2$), $h$ is the water depth (m), and i is the bed slope gradient.

The water depth was measured using a supersonic wave-type water gauge, and the bed slope was defined as 1/15 from past observations. The fall velocity was calculated using Rubey's formula (Rubey, 1933):

$$\frac{w_0}{\sqrt{s+\Delta}} = \sqrt{\frac{2}{3} \left[ \frac{36\nu^2}{s+\Delta} \right]^\frac{3}{2} \left[ \frac{36\nu^2}{s+\Delta} \right]^\frac{1}{2}}$$  \hspace{1cm} (2)

where $w_0$ is the fall velocity (m/s), $s$ is the submerged unit weight (t/m$^3$), $\Delta$ is the particle size (m), and $\nu$ is the coefficient of viscosity (0.01 cm$^2$/s at 25°C).

Under the observational conditions, the particle size division between the bed load and suspended load ranged from 2.0 to 9.5 mm.

### 3. RESULTS

#### 3.1 RELATIONSHIP BETWEEN FLOW RATE AND SEDIMENT DISCHARGE (TOTAL LOAD)

Figure 6 shows the relationship between flow rate...
and sediment discharge obtained from the four observations. The sediment discharge ranged from $10^{-6}$ to $100 \text{ m}^3/\text{s}$ and the flow rate from $10^{-1}$ to $10^2 \text{ m}^3/\text{s}$, indicating an increase in sediment discharge of three orders for a one-order increase in flow rate.

3.2 RELATIONSHIP BETWEEN BED LOAD AND SUSPENDED LOAD AND WASHLOAD

Figure 7 shows the relationship between flow rate and sediment discharge for the four observations, specified by movement type. The sediment discharge through the bed load ranged from $10^{-7}$ to $10^0 \text{ m}^3/\text{s}$ for flow rates ranging from $10^0$ to $10^2 \text{ m}^3/\text{s}$. The sediment discharge through the suspended load plus washload ranged from $10^{-6}$ to $10^0 \text{ m}^3/\text{s}$ for flow rates ranging from $10^{-1}$ to $10^1 \text{ m}^3/\text{s}$. This indicates that the bed load is more sensitive to changes in flow rate compared with the suspended load plus washload.

The relationship between flow rate and suspended load plus washload for the four observations was approximated as follows:

$$Q_s = 2.8 \times 10^{-4} \times Q^2$$

where $Q_s$ is the suspended load plus washload (m$^3$/s) and $Q$ is the flow rate (m$^3$/s).

Figure 8 shows the relationship between flow rate and the ratio of suspended load plus washload to total load. It can be seen that the ratio of suspended load plus washload to total load is over 50% in most cases. A number of results are over 80%, and several values close to 100% were observed. This suggests that, in the case of floods expected to occur in normal years, suspended load plus washload accounts for a large proportion of the total load for a mountainous river, compared with the bed load.

3.3 TRANSITION OF FLOW RATE AND SEDIMENT DISCHARGE

Figure 9 shows the transition between flow rates and sediment discharge obtained from the four observations. The amount of suspended load plus washload was larger than the amount of bed load in most cases; however, when the bed load increased, the quantity of bed load approached or exceeded the amount of suspended load plus washload (e.g., in Typhoon No. 18 at 16:00; in Typhoon No. 22 at 15:00, in 2004). This indicates the discontinuous movement of the bed load.

3.4 COMPARISON WITH RESULTS FROM OTHER RIVERS

Figure 10 compares the relationship between flow

![Fig. 6 Relationship between flow rate and sediment discharge (total load).](image)

![Fig. 7 Relationship between bed load and suspended load plus washload.](image)

![Fig. 8 Relationship between flow rate and ratio of suspended load plus washload to total load.](image)
rate and suspended load obtained from the current observations with past observations from other rivers (Yoshida et al. 1983, Terada et al. 2002).

Outline results from past observations are given in Table 2.

It can be seen that the suspended load obtained from the current observations was one order larger than other results in the flow rate range of $10^{-1}$ to $10^{-3}$ m$^3$/s.

### Table 2. Outline results from past observations.

| Name of river       | Location of measurement                        | Drainage area (km$^2$) | Average gradient | Observation period |
|---------------------|------------------------------------------------|------------------------|------------------|-------------------|
| Abe River           | Oshina check dam (Oshina check dam)            | 8.8                    | 1.29, 1.6        | 2004-2007         |
| Abe River           | (Takamatu bridge)                              | 146                    |                  | 2000-2001         |
| Jinzu River         |                                                | 551                    |                  | 1979-1981         |
| Kawabe River        | Odoru river, tributary of the Kawabe River     | 15                     | 1.8              | 1979-1981         |
| Seto River          | average of twenty four points                  | 1-105                  | 1/6-1/78         | 1980-1981         |
| Tenryu River        | average of three points from two catchment area | 31.62                  |                  | 1975-1981         |

*Fig. 9 Transition of flow rate and sediment discharge.*

*Fig. 10 Suspended discharge plus washload at other rivers.*

**3.5 COMPARISON OF CALCULATED AND MEASURED BED LOAD**

Figure 11 shows the relationship between non-dimensional tractive force and non-dimensional sediment discharge by particle size, estimated from the current observation results using the Meyer-Peter-Muller formula (MPM) (Meyer et al. 1948), and the Ashida-Takahashi-Mizuyama (ATM) (Ashida et al. 1978) formulae. The critical tractive force at a single particle size was first calculated from the average...
particle size of the bed material using the Iwagaki formula (Iwagaki, 1956), and then the critical tractive force at each particle size was calculated using the modified Egiazaroff formula (Egiazaroff, 1965). The results are shown by particle size. The effective tractive force was used for the MPM formula. Particle size classes were established based on the particle size distribution test conducted in 2003, using sediment from the sedimentation site at the Oshima check dam (Kondo et al. 2004). It can be seen that the ATM formula results tended to be larger than the measurement results, and the MPM formula results were smaller than the measurement results.

Figure 12 shows a comparison of bed load amounts obtained by measurement, using the MPM and ATM formulas for the four observations. When the effective tractive force was lower than the critical tractive force, zero bed load was obtained using the MPM formula; these cases are not shown in Fig. 12. The bed load obtained by the ATM formula exceeded that from the measured results by three to five orders in most cases; however, when the sediment discharge increased, the difference between them was within one to two orders (Typhoon No. 22 - 13 : 00, 2004 and Typoon No 9 - 18 : 00, 2007). The bed load obtained from the MPM formula was smaller than the measurement results in most cases. However, when the sediment discharge increased, the difference between these was within one order, and sometimes the bed load obtained from the MPM formula exceeded the measured quantity (Typhoon No. 22 - 13 : 00, 2004 and Typoon No 9 - 16 : 00, 2007).

4. CONCLUSION

Sediment discharge at the Oshima check dam located upstream of the Abe River was measured using a newly developed Total Load Trapping Equipment system to investigate sediment movement in
mountainous rivers. Observations were conducted on 11 occasions. Using the results of observations conducted under flooding, the total load was classified into bed load and suspended load plus washload. The following conclusions were obtained:

- The ratio of suspended load plus washload to total load was nearly 80% or more and at times close to 100%. This suggests that, in the case of floods expected to occur in normal years, suspended load plus washload accounts for a larger proportion of the total load, as opposed to the bed load, in a mountainous river.

- In the flow rate range of $10^{-1}$-10 m/s obtained from the current observations, the amount of suspended load was larger than that of other rivers by one order.

- A comparison of bed load obtained from measurements with that obtained using two formulae showed that the amount derived from the ATM formula exceeded the actual amount by three to five orders in most cases, but remained within one to two orders at peak flow. The bed load derived from the MPM formula tended to be smaller than the actual amount, but remained within one order when the sediment discharge increased.

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