Original Article

Fingerprinting Suspended Sediment Sources in the Nukabira River, Northern Japan

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Geological setting is crucial to the occurrence of slope failure and landslides, resulting in prolonged suspended sediment runoff; in this sense, local geology can affect the magnitude of suspended sediment yield. To clarify the suspended sediment sources in a watershed with various geological units, hydrological monitoring and fingerprinting techniques using natural radionuclides were conducted during a heavy rainfall event in August 2010 in the Nukabira River watershed, a tributary of the Saru River, in northern Japan. A GIS analysis for slope failure and landslide areas was also conducted to investigate the distribution of potential suspended sediment sources. During the rainfall event, the dominant sources of suspended sediment were found to be areas consisting of metamorphic rock (31%), sedimentary rock (30%), and accretionary sedimentary rock (24%). The highest sediment yield was found in metamorphic rock, which is consistent with the dense distribution of slope failure and landslides identified by the GIS analysis. Active landslides can introduce a significant amount of sediment from the hillslope to the stream channel, providing a source of fine sediment. In the area of the accretionary basalt block, there was an inconsistency between the sediment yield and the density of slope failure and landslides, perhaps attributable to the lack of a fine particle fraction in the sediment deposited on the bare slope along the stream channel and riverbed due to the resistance of bed rock to slaking and weathering. These results indicate that natural radionuclides can be used in order to elucidate the suspended sediment sources and sediment yield of various geological units within a watershed.

Key words: fingerprinting, suspended sediment, natural radionuclide, geology, GIS

1. INTRODUCTION

Mass wasting like landslides, gully, debris flow, and riparian bank erosion, triggered by episodic storm events, often generates a large amount of sediment, frequently resulting in on-site sediment disasters in residential and agricultural areas. Although some of the sediment produced by mass wasting is carried from the hillslopes to the river channel, a fair percentage of the sediment is usually deposited on the hillslopes, foot slopes, and riverbeds and is transported downstream in subsequent rainfall events. This leads to a prolonged discharge of suspended sediment [Page *et al.*, 1999; Koi *et al.*, 2008]. At the outlet of the catchment, most of the sediment is transported as suspended sediment, the importance of which is recognized in

the transport of nutrients and contaminants such as phosphorus (P), pesticides, polychlorinated biphenyls (PCBs), heavy metals, and pathogens through fluvial systems [Walling, 2005]. Therefore, while erosion control is primarily concerned with controlling on-site sediment disasters in mountainous regions, sediment control programs are more concerned with downstream problems and must consider a wider range of potential sources [Walling, 2005].

The suspended sediment load transported by a river or stream will commonly contain a mixture of sediments delivered from different locations and from different source types within the contributing catchment [Collins *et al.*, 1998; Yieger *et al.*, 2002; Mizugaki *et al.*, 2008]. In the case of a catchment that has experienced extensive landslides and gully, mass wasting scarring could represent the

primary source [Page *et al.*, 1999; Koi *et al.*, 2008]. Since the occurrence of mass movement such as landslides, slope failure, and gullying is well known to depend on the underlying geology [Aipassa *et al.*, 1990; Dai and Lee, 2002; Murakami *et al.*, 2006], numerous researchers have reported that the differences in the amount of sediment at the outlet of the catchment (i.e., deposited sediment in dam reservoirs) depend on the dominant underlying geology in the catchment [Tanaka and Ishigai, 1951; Ezaki, 1966; Marutani *et al.*, 2000; Mizutani, 2004; Okano *et al.*, 2004; Hasegawa *et al.*, 2005]. These literatures are based on comparisons of sediment yield among catchments, by assuming a uniform geology in each catchment; however, these studies have not dealt with the spatial variation in sediment sources within a catchment.

Recently, sediment fingerprinting studies have been focused on elucidating the suspended sediment sources within a catchment, using the quantitative interpretation of multivariate properties and property ratios, encompassing various mineralogic [Ohishi *et al.*, 2010], magnetic [Foster and Lees, 1999], radiometric [Olley *et al.*, 1993; Collins *et al.*, 1998; Walling *et al.*, 1999; Yeager *et al.*, 2002; Kato *et al.*, 2005; Mizugaki *et al.*, 2008; Uchida *et al.*, 2009; Fukuyama *et al.*, 2010], and chemical [Ishida *et al.*, 2010] parameters. The level of radiation on the earth's surface has been reported to differ depending on the underlying bed rock [Wollenberg and Smith, 1990; Furukawa, 1993; Matsuda and Minato, 1999]; therefore, researchers have used the activities of radionuclides as parameters by which to fingerprint the suspended sediment sources in a multivariate sediment mixing model [Collins *et al.*, 1998; Walling *et al.*, 1999; Yeager *et al.*, 2002].

The identification of suspended sediment sources is a key precursor to the design of effective sediment management and control strategies [Walling, 2005]. Recent advances in geographic information systems (GIS) and databases aid in the identification of scars of landslides and slope failure as primary sources of suspended sediment [Murakami *et al.*, 2006] and topographic features as potential controlling factors of suspended sediment yield [Okano *et al.*, 2004; Hasegawa *et al.*, 2005; Murakami *et al.*, 2006]. In addition, the suspended sediment sources causing prolonged sediment runoff can be identified by a fingerprinting technique. The objectives of this study are to examine this fingerprinting technique using radionuclides and to elucidate the suspended sediment sources in a catchment that has undergone landslides and slope failure. To achieve these objectives, a field survey and fingerprinting were conducted in the Saru River and Mu River

watersheds, in northern Japan, where a heavy storm event in August 2003 caused extensive landslides and slope failures.

2. MATERIAL AND METHODS

2.1 Study site

The study site encompassed two adjacent watersheds—the Saru River and Mu River watersheds—draining from the Hidaka mountain range in central Hokkaido, northern Japan, to the Pacific Ocean (**Fig. 1**). At the river mouth, the catchment areas of the Mu River and Saru River are 1,270 km² and 1,350 km², respectively. In the Saru River watershed, annual precipitation ranges from 975 mm in downstream areas (Hidaka-Monbetsu) to 1,353 mm in upstream areas (Hidaka). Eighty-five percent of both watersheds is covered by forest; agricultural land (5.5%) and residential areas (9.4%) lie along the river channel in the downstream area. The dominant geology of the study area consists of plutonic rock in the upstream area, cretaceous sedimentary rock and an accretionary complex from the upstream to midstream areas, and neocene sedimentary rock in the downstream area. Basalt block in the accretionary complex and metamorphic rock consisting of sedimentary rock and serpentinite are found in the midstream area.

From August 8–9, 2003, an extreme storm event in the form of typhoon 1003 (Etau) resulted in the highest discharge and sediment yield seen in the previous several decades, especially in the Saru River watershed. In the Nukabira River watershed, which is the subwatershed of the Saru River, the total rainfall during the event was over 400 mm, and the maximum rainfall intensity observed by radar was over 80 mm h⁻¹, resulting in approximately

Fig.1 Location of study site. Blue area denotes the Nukabira River watershed, where is the study site for fingerprinting suspended sediment sources.

4,000 slope failures and landslides [Murakami and Nakatsugawa, 2004]. Suspended sediment load during the event was estimated to be 1,267,000 t at the Nukibetsu gauging station of the Hokkaido Development Bureau (HDB), for which the watershed area is 384 km², including the Nukibetsu River watershed [Murakami and Nakatsugawa, 2004]. This amount was equivalent to only 8.9% of the sediment deposited on the hillslope by landslides and slope failure during the event [Murakami and Watanabe, 2007]. The residue, left at the foot slope and river bed across the watershed, may have been transported by subsequent storm events.

2.2 Field sampling and observation

Detailed source material sampling was undertaken within each of the major geological systems constituting the study basin in order to examine the provenance of bulk suspended sediment samples collected at the basin outlet in terms of geological subareas. First, for sampling potential source materials, 13 sub-catchments were selected to encompass the major geological categories constituting the study area based on the geological map [Geological Survey of Japan, AIST, 2009] (Fig. 1). The geology of each sub-catchment is shown in Table 1. Second, in each sub-catchment, 5–8 bare slopes adjacent to the stream channel were selected as sampling points, from which 5 samples were collected from top soil likely to be eroded (i.e., 0–5 cm depth) and combined into a single sample. A total of 72 samples were obtained for the study area.

To observe the discharge and sediment runoff in the Nukabira River watershed, a water level gauge (OYO, S&DL mini; Tokyo, Japan) and turbidity meter (JFE Advantec, Infinity Turbi; Nishinomiya, Japan) were installed at the Nukibetsu Bridge, situated at the downstream end of the Nukabira River. The water level and turbidity were continuously recorded at 10-min intervals. The discharge and suspended sediment concentration were calculated by regression functions between water level and discharge and between turbidity and suspended sediment concentration, respectively [Abe et al., in this issue]. Suspended sediment discharge during the observation period was calculated using the following equation:

$$L = \sum_{i=1}^n C_{(t)} Q_{(t)} dt \quad (1)$$

where L is the total discharge of suspended sediment during the event (ton), $C_{(t)}$ is the suspended sediment concentration at time t (mg/L), and $Q_{(t)}$ is the runoff discharge at time t (m³/s).

To collect the suspended sediment during the

storm event, a time-integrated suspended sediment sampler [Phillips et al., 2000] was installed at Nukibetsu Bridge (Fig. 1). The suspended sediment accumulated in the sampler from August 11 to September 1, 2010, was collected in order to fingerprint the suspended sediment source. Surface water was also collected from the stream channel at Nukibetsu Bridge at the highest water level during the event.

2.3 Sample processing and analysis

Gamma-ray spectrometry was conducted in order to fingerprint the suspended sediment source. The collected soil and suspended sediment samples were dried for over 48 h at 105°C, sieved using a 0.5-mm open sieve, and packed in a 5-ml polyethylene bottle (Kartell, 737; Milano, Italy). These samples were sealed for more than five times the half-life of ²²²Rn, that is, 21 d, before the analysis began, in order to allow equilibrium to develop between ²²⁶Ra and ²²²Rn [Joshi, 1987; Murray et al., 1987]. High-resolution gamma-ray spectrometry was employed to resolve 13 radionuclides, i.e., ²¹⁰Pb (46.5 keV), ²³⁴Th (63.3 keV), ²³¹Th (84.2 keV), ²²⁶Ra (186 keV), ²¹²Pb (238 keV), ²¹⁴Pb (352 keV), ²⁰⁸Tl (583 keV), ²¹⁴Bi (609 keV), ¹³⁷Cs (662 keV), ²¹²Bi (727 keV), ²²⁸Ac (911 keV), ⁴⁰K (1461 keV), and lead-210 excess (²¹⁰Pb_{ex}) as the difference between the photo peaks of ²¹⁰Pb and ²¹⁴Pb [Joshi, 1987; Murray et al., 1987], by using a well-type HPGe gamma detector (ORTEC GWL-120-15; Oak Ridge, U.S.A.) coupled with a multichannel analyzer (SEIKO EG&G MCA7600; Tokyo, Japan) at our laboratory in the Civil Engineering Research Institute for Cold Region, PWRI. The energy and efficiency calibrations for this detector were performed using a standard sample including 11 radionuclides (Eckert & Ziegler; MODEL7603): ²¹⁰Pb (46.5 keV), ²⁴¹Am (59.5 keV), ¹⁰⁹Cd (88.0 keV), ⁵⁷Co (122 keV), ¹³⁹Ce (166 keV), ²⁰³Hg (279 keV), ¹¹³Sn (392 keV), ⁸⁵Sr (514 keV), ¹³⁷Cs (662 keV), ⁶⁰Co (1173 keV, 1333 keV), and ⁸⁸Y (898 keV, 1836 keV). For the analysis of radionuclide activity, each sample was measured for over 28,800 s. All the detected radionuclides were quantified according to the activity (Bq g⁻¹) from the reference samples.

The particle size distribution was measured for all the potential source materials and suspended sediment by means of sieving and laser beam diffraction. Sieving was conducted for coarser fractions over 0.075 mm in diameter, and laser beam diffraction (Shimadzu SALD-3000S and SALD-2000J; Shimadzu Corp., Kyoto, Japan) was used for finer fractions less than 0.5 mm in diameter after hydrogen peroxide pretreatment.

Table 1 Geological unit of sub-catchment for sampling potential source materials

Sub-catchment	Era	Period	Bed rock	Geology
M4	Unknown	Unknown	Metamorphic	Ultramafic
M5	Methozoic	Late Cretaceous	Sedimentary	Marine sedimentary rock
M6	Methozoic	Jurassic-Early Cretaceous	Metamorphic	Kamuikotan metamorphic rock
M7	Methozoic	Late Jurassic-Early Cretaceous	Accr. Volcanic	Mafic volcanic rock
M8	Methozoic	Jurassic-Early Cretaceous	Metamorphic	Kamuikotan metamorphic rock
M10	Methozoic	Early-Late Cretaceous	Accretionary complex (Sedimentary)	Mainly sedimentary rock
S2	Methozoic	Late Cretaceous	Sedimentary	Marine sedimentary rock
S3	Pale-Methozoic	Permian-Late Jurassic	Accr. Basalt	Exotic basalt block
S10	Cenozoic	Eocene-Oligocene	Sedimentary	Marine or non-marine sedimentary rock
S11	Methozoic	Late Jurassic-Early Cretaceous	Accretionary complex (Sedimentary)	Mainly sedimentary rock
S12	Methozoic	Late Cretaceous	Sedimentary	Marine sedimentary rock
S14	Cenozoic	Early-Middle Eocene	Plutonic	Mafic plutonic rock
S15	Cenozoic	Early Miocene	Plutonic	Felsic plutonic rock

2.4 Statistical and numerical methods

The geology of the sampling points for the source material was determined and categorized into source groups on the basis of three geological categories: era, bedrock, and rock type. A two-stage statistical procedure was used to identify optimum sets of source material and sediment properties for use as composite fingerprints [cf. *Collins et al.*, 1997, 1998; *Walling et al.*, 1999]. First, the Kruskal-Wallis H-test was used to establish which properties exhibited significant differences between individual source groups within a particular category of sources. Second, multivariate discriminant function analysis was applied to the properties selected in the first stage in order to identify the set of properties, or composite fingerprint, that afforded optimum discrimination between source groups. A stepwise selection algorithm based on the minimization of Wilks' lambda or *U*-statistic was used in this analysis. These statistical analyses were performed using the JMP 7 software (SAS institute Inc., USA, 2007).

If most of the suspended sediment originates from a particular source group, the tracer properties associated with that sediment will be similar to those associated with that source group. Since the similarity (definable as the inverse of the difference) in tracer properties between suspended sediment and source area can represent the contribution of the source area to the suspended sediment [*Ishida et al.*, 2010], we assumed that the contribution of a source group to the suspended sediment can be calculated as follows:

$$p_i = \frac{\frac{1}{d_i}}{\sum_{i=1}^n \frac{1}{d_i}}, \quad \sum_{i=1}^n p_i = 1 \quad (2)$$

where p_i is the contribution of source group i to the suspended sediment, and d_i is the difference in tracer properties between source group i and the suspended sediment. In this study, the Mahalanobis distance in tracer properties between source groups and suspended sediment was employed because it accounts for the deviation in tracer properties associated with source materials from each source group in d_i .

2.5 GIS Analysis

To examine the validity of the estimated contribution of source areas to suspended sediment, GIS was used to investigate the topographic features and precipitation for each source area as indices of potential sediment yield (ESRI; ArcGIS 9.3.1, Spatial Analyst). Altitude and slope gradient were evaluated on the basis of a 10-m mesh digital elevation model (DEM) provided by the Geospatial Information Authority of Japan. For relief and profile curvature, the original DEM was re-sampled to a mesh size of 150 m and 30 m, respectively, to represent the indices of suspended sediment yield and transport [*Nishida et al.*, 1997]. The locations of slope failure and landslide scars caused by the extreme event in 2003 were also investigated for each source area. GIS databases of slope failure and landslides were employed from *Murakami and Nakatsugawa* [2004] and *Yamagishi* [1993], respectively. Precipitation during the event was investigated using precipitation in 5-min intervals in a mesh size of 1 km, observed by a weather radar

Fig.2 Turbid water during the rainfall event on August 12, 2010, at the Nukibetsu Bridge of Nukabira River

Fig.3 Precipitation, discharge and suspended sediment concentration during the event

belonging to the Japan Meteorological Agency. The total precipitation and maximum rainfall intensity for 1 h during the event were calculated for each source area.

3. RESULTS

3.1 Suspended sediment load

In the Nukabira River watershed, the rainfall event from August 11–12, 2010, resulted in precipitation of 199.6 mm in total and 22.7 mm/h in maximum intensity, as recorded by the weather radar. This resulted in a middle magnitude storm runoff event (**Fig. 2**). Runoff discharge at the outlet of the Nukabira River showed a quick response to rainfall, and discharge peaks were found 3 h after the rainfall peak (**Fig. 3**). Suspended sediment concentration had already reached over 1,000 mg/l with the first increase in discharge and was over 12,000 mg/l at its maximum value 2 h after the maximum discharge. Suspended sediment load and suspended sediment yield during this event were 293,377 t and 1,010 t/km², respectively.

Suspended sediment concentration in the recession stage of discharge was higher than that in the rising stage, suggesting a counter-clockwise hysteresis for discharge [Abe *et al.*, in this issue].

Further, a significant amount of suspended sediment was recorded during the recession stage [Williams, 1989]. The suspended sediment load and suspended sediment yield observed in this study were equivalent to 23% and 30.6%, respectively, of those observed downstream at the Nukibetsu gauging station of the HDB (**Fig. 1**) during the extreme event in August 2003 [Murakami and Nakatsugawa, 2004].

3.2 Appropriate combination of tracer properties and source areas of suspended sediment

The non-parametric Kruskal-Wallis H-test was performed for 13 radionuclides associated with source material samples, and a significant difference between source groups was found for 8–9 radionuclides (**Table 2**). For those radionuclides showing significant differences between source groups, multivariate discriminant analysis was

Table 2 The results of using the Kruskal-Wallis test to assess the ability of each tracer property to discriminate between surface (c. top 5 cm) soil from various source groups categorized by geological units such as period, geological types and bed rock.

Tracer property	Period (8)		Geology (10)		Bed rock (6)	
	Hvalue	Pvalue	Hvalue	Pvalue	Hvalue	Pvalue
Pb-210	18.26	0.011 *	23.44	0.005 *	11.46	0.043 *
Th-234	11.16	0.132	16.53	0.057	13.83	0.017 *
Th-231	7.52	0.377	12.87	0.169	7.96	0.159
Ra-226	12.35	0.090	13.74	0.132	9.27	0.099
Pb-212	41.33	0.000 *	46.98	0.000 *	43.49	0.000 *
Pb-214	22.65	0.002 *	33.35	0.000 *	29.46	0.000 *
Tl-208	31.05	0.000 *	38.47	0.000 *	32.79	0.000 *
Bi-214	12.22	0.094	17.29	0.044 *	13.41	0.020 *
Cs-137	9.59	0.213	11.57	0.239	10.21	0.070
Bi-212	17.97	0.012 *	15.64	0.075	13.63	0.018 *
Ac-228	36.64	0.000 *	42.23	0.000 *	39.67	0.000 *
K-40	23.83	0.001 *	41.49	0.000 *	39.57	0.000 *
Pbex	21.05	0.004 *	24.33	0.004 *	9.23	0.100

Number in parenthesis indicates the number of source group.

Table 3 The results of using stepwise discriminant function analysis to identify which combination of tracer properties provides the best composite fingerprint for differentiating source materials on the basis of geology groups

Period (8)		Geology (10)		Rock (6)*	
Tracer property	Cum. % classified correctly	Tracer property	Cum. % classified correctly	Tracer property	Cum. % classified correctly
Pb-212	33.33	Pb-212	33.33	Pb-212	50.00
K-40	36.11	K-40	40.28	K-40	66.67
Bi-212	44.44	Ac-228	40.28	Ac-228	72.22
Ac-228	43.06	Pbex	45.83		
Pbex	43.06	Tl-208	51.39		
Tl-208	56.94	Bi-214	55.56		
Pb-214	61.11	Pb-214	58.33		
		Pb-210	61.11		

performed in each geological category to seek the best combination of radionuclides. The discriminant analysis showed that the highest number of correct classifications, 72.22%, was found when a combination of three radionuclides— ^{212}Pb , ^{40}K , and ^{228}Ac —was selected to discriminate the following 6 source groups by bed rock: sedimentary rock, accretionary sedimentary rock, accretionary basalt block, accretionary volcanic rock, plutonic rock, and metamorphic rock (Table 3). A geological map

Fig.4 Bed rock and scar of slope failure (Murakami and Nakatsugawa, 2004) and landslide (Yamagishi, 1993) in the Nukabira River watershed.

Fig.5 Bed rock composition in the Nukabira River watershed

Fig.6 Contribution to suspended sediment and sediment yield from various bed rock areas

shows that all six source groups of bed rock are found in the Nukabira River watershed (Fig. 4). Sedimentary rock covers the largest area and, together with accretionary basalt block and accretionary sedimentary rock, accounts for 87.5% of the entire area of the watershed (Fig. 5).

Using ^{212}Pb , ^{40}K , and ^{228}Ac as appropriate tracers, the contribution of source groups on the basis of bed rock to suspended sediment collected at peak discharge and during the event were calculated by equation 1. Little difference in the contribution of source groups to suspended sediment was found between the sediment samples collected at peak discharge and during the event (Fig. 6). For sediment during the event, the highest contributions were found for metamorphic rock at 31.2% and sedimentary rock at 30.0%, followed by accretionary sedimentary rock at 23.7%, resulting in over 80% of the suspended sediment originating from these three bed rocks. The contributions of accretionary basalt block, plutonic rock, and accretionary volcanic rock were significantly low, with contributions of 7.7%, 5.4%, and 1.7%, respectively.

However, a different tendency was found in suspended sediment yield for each bed rock, which was calculated by products of suspended sediment yield during the event and the contribution of each bed rock (Fig. 6). Significantly high sediment yield was found from metamorphic rock (4,662 t/km²), followed by plutonic rock (2,847 t/km²), showing significantly higher yields compared to those from sedimentary rock (794 t/km²), accretionary sedimentary rock (1,125 t/km²), and accretionary basalt block (263 t/km²), in spite of their large area in the watershed. The sediment yield found from accretionary basalt was the lowest, despite the fact that it accounted for the second largest area in the watershed.

3.3 Spatial distribution of controlling factors in suspended sediment yield and transport

Topographic features such as altitude, slope gradient, relief, and profile curvature were investigated for each source group area in order to

Table 4 Topographic features of the Nukabira River watershed

		Sed.	Accretionary Sed.	Basalt	Volc.	Plut.	Meta.
Area	km ²	111.0	61.9	81.4	10.7	6.2	19.6
Altitude	m	447.1	613.6	630.1	788.6	1436.6	846.3
Slope	Deg.	22.8	27.7	30.9	35.9	33.6	21.7
Relief	m	98.6	125.2	156.4	181.5	203.8	110.8
Prof. curvature		0.036	0.019	0.021	0.035	0.017	0.003

Fig.7 Topographic features of bed rock categories in the Nukabira River watershed. a) Slope gradient, b) relief, and c) profile curvature.

compare the potential controlling factors of suspended sediment yield and transport among the source groups (Table 4). In the volcanic rock, the slope gradient was slightly steeper than those in the other source groups, while the metamorphic rock had predominantly gentler slopes of less than 25 degrees. The relief in all source groups ranged widely, but the metamorphic rock was represented by a predominant relief of 90 to 100 m (Fig. 7b). The plutonic rock showed the highest relief because it had the highest altitude, followed by the accretionary volcanic rock and accretionary basalt block (Fig. 7b, Table 4). In the sedimentary rock and accretionary sedimentary rock, the predominant relief was 70 to 80 m due to the lower altitude. Profile curvature was similar among the source groups and showed predominantly negative values (Fig. 7c); however, the average profile curvature showed positive values (Table 4). This result

Fig.8 Areas of a) slope failure and b) landslide in the Nukabira River watershed

Fig.9 Total precipitation and maximum rainfall intensity in various bed rock areas of the Nukabira River watershed

suggests that convex slopes are slightly dominant in all source areas.

The area of slope failure was highest in the accretionary basalt block, with a maximum density of 1.66%, attributed to the large amount of rainfall and its high intensity during the extreme event in 2003 [Murakami and Nakatsugawa, 2004] (Fig. 8a). In the sedimentary and accretionary sedimentary rocks, the area of slope failure was high because these types of rocks accounted for a larger area of the watershed; however, the density of slope failure was somewhat low in the sedimentary rock. With regard to the metamorphic and plutonic rocks, the density of slope failure was as high as 1.65% and 1.44%, respectively, despite the small area of slope failure. A large area of landslide scar was found in the metamorphic rock and accretionary basalt block,

Fig.10 Particle size distribution of potential source materials in each bed rock areas.

with an especially high density in the metamorphic rock at 28.6% (**Fig. 8b**). The density of landslide scars was lower in the sedimentary rock and accretionary sedimentary rock, and there were few landslides in the accretionary volcanic rock.

Precipitation during the event was very similar among the source groups, ranging from 193.8 mm to 224.8 mm (**Fig. 9**). However, maximum rainfall intensity was slightly different, showing a maximum at 35.6 mm/h for the accretionary sedimentary rock and a minimum at 18.4 mm/h for the plutonic rock.

The particle size distribution of the suspended sediment and source materials collected from each source group is shown in **Fig. 10**. D_{90} , which is the sediment size that 90% of the suspended sediment is finer than, was 0.2 mm and 1.0 mm, respectively, for sediment collected by surface water sampling and by the time-integrated suspended sediment sampler (SSS) at the outlet of the Nukabira River. All the potential source materials were significantly coarser than the suspended sediment, showing a difference in content of finer fractions of less than 0.2 mm among source groups.

4. DISCUSSION

The contribution of geological source areas seemed to be generally similar to the areal proportion of source groups defined by bedrock type within the Nukabira River watershed. However, disagreements were found in the accretionary basalt block and metamorphic rock areas, where the suspended sediment yields were the lowest and highest, respectively (**Figs. 5** and **6**). Compared to the distributions of slope failure and landslide scars, the highest sediment yield in the metamorphic rock may be attributable to the highest densities in slope failure and landslide scars (**Fig. 8**). In the accretionary basalt block, a high suspended sediment yield can be expected from the high densities in slope failure and landslide scars (**Fig. 8**), but it was the lowest among the source areas. In the

plutonic rock, with the second highest suspended sediment yield, the density of slope failure was high, but landslide scars were not observed. These results suggest that in the case of a watershed with complex geology, the suspended sediment may not be simply explained by the distribution of slope failure and landslides.

Generally, suspended sediment provided from the hillslope to the channel, unlike sediment produced by slope failure, can be transported by surface erosion of the bare slope and bank erosion of the foot slope into the channel [Aipassa *et al.*, 1990; Araya and Kuroki, 2001]. Aipassa *et al.* [1991] observed soil creep from active landslides in the midstream of Saru River (the geology appears to be serpentinite, although the literature found it to be sedimentary rock) and reported that the foot slope of the landslide continued to slide 1–2 m downslope to the channel. They concluded that the landslide was a major source of suspended sediment. Araya and Kuroki [2001] reported that the amount of sediment provided by surface erosion from landslide scars to the channel was 2 to 3 times larger than that from slope failure scars. Therefore, the result of this study—that the suspended sediment yield in the metamorphic area was the highest—can be supported by the dense landslide distribution in that area.

On the other hand, in the case of the accretionary basalt block, the lowest suspended sediment yield can be explained by the slaking and weathering features of the debris. Murakami *et al.* [2008] conducted a slaking test for bed rock materials and elucidated that in case of Neocene sedimentary rock, 99.7% of the original particles were slaked into finer particles, while in the case of accretionary basalt block, only 9% of original particles were slaked. Due to the resistance of the bed rock to weathering, the sediment transported from the hillslope to the river channel may have been deposited on the river bed and footslope as relatively large particles [Murakami *et al.*, 2008], resulting in a low contribution to suspended sediment.

The second highest suspended sediment yield, shown by the plutonic rock, may be affected by the topographic features and particle size composition of the source material. The plutonic rock area was characterized by the fact that it had almost the highest altitude, slope gradient, and relief among the source groups (**Fig. 7**, **Table 4**). These steep topographic features can be expected to transport much more sediment [Tanaka and Ishigai, 1951; Ezaki, 1966; Mizutani, 1981; Marutani *et al.*, 2000; Okano *et al.*, 2004; Hasegawa *et al.*, 2005]. Furthermore, the source materials collected in this

study contain a high proportion of fine particles (**Fig. 10**), perhaps because granite, the dominant rock type of plutonic rock, is generally susceptible to weathering. These steep topographic features and fine particles available for transport most likely lead to a high sediment delivery ratio for the plutonic rock.

5. CONCLUSION

Suspended sediment sources estimated by a fingerprinting technique using natural radionuclides suggested differences in suspended sediment yield depending on the underlying bed rock type. The high suspended sediment yield in areas underlain by metamorphic rock can be attributed to dense landslides and slope failure scars, which are likely to continue to provide suspended sediment from the hillslope to the river channel by creeping soil during rainfall events. This result was supported by the hysteresis in suspended sediment concentration during the event [Abe *et al.*, in this issue; Williams, 1989], showing higher suspended sediment concentration in the recession stage than in the increasing stage of runoff discharge. In the area underlain by plutonic rock, which also had a high sediment yield, fine sediment produced by weathering may be transported easily to the stream channel from the hillslope and/or footslope due to the steep topography. These areas with high suspended sediment yield may be characterized by geological and topographical features, with parameters suggested by the literature, such as creep, weathering, and slope gradient. In the area of accretionary basalt block, however, the low suspended sediment yield could be explained by neither the spatial density of landslides nor slope failure, but by the resistance to rock weathering. These results indicate that a comprehensive technique of hydrological monitoring and fingerprinting can provide a qualitative evaluation of suspended sediment yield from individual sediment sources on the basis of bed rock type in a catchment, although the reliability of fingerprinting using only three natural radionuclides still remains uncertain. Further studies are needed to improve the robustness of the fingerprinting technique, for example, by using other tracers as mineralogical and/or geochemical parameters complementarily.

ACKNOWLEDGMENT: The authors are grateful for the data and suggestions provided by the Muroran Branch of Hokkaido Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism. The authors are also grateful for the field

assistance provided by FUKUDA Hydrologic Center Co. LTD and Hokkaisuiko Consultant Corporation.

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