Characteristics of Step-Pool Morphology in the Mountain Streams of Japan

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Abstract

In this study, the relationship between channel geometry and step-pool morphology are discussed. The channel geometry, i.e., the channel gradient, channel width, the step-pool dimensions, size and number of step particle, etc., were surveyed at 35 study reaches of eight small basins in Japan. The results show that the channel gradient, channel width, and particle size have various implications for the step-pool geometry. With regard to the longitudinal profile of a step, the relationship between the channel geometry, step wavelength and step-step drop differs from that reported by previous studies at high-gradient reaches (> 0.15 gradient). The channel width and particle size are important variables affecting the step wavelength and step-step drop. Step width, which is the transverse profile of a step, is about 6 times the mean size of the rocks that form the step, and it is probably controlled by the particle size and channel width. The pool geometry is likely to be related to the channel gradient, discharge, and particle size. The characteristics of the distribution and the geometry of the step-pool can be explained by three parameters (particle size, discharge, and channel gradient).

Keywords: channel morphology; mountain streams; step-pool; Niigata; Mie

Introduction

Coarse grained mountain streams are often characterized by alternating steps and pools. Step pools are commonly formed in mountain streams with gradients exceeding 2%. The step pools are composed of not only cobbles and boulders but also bedrock and logs. Therefore, the materials of the step and the scale of the step pool vary in different streams.

Step pools provide the organisms in mountain streams with habitats of various scales; therefore, they are an important physical component of the riparian ecosystem. Step-pool bed forms play an important role in the sediment transport phenomena through their formation and destruction processes, and the erosion and deposition processes of sediment in pools. In recent times, the field of erosion control engineering has been witnessing an increase in the public demand for synthetic sediment management in rivers and the consideration for the environment in Sabo works. Therefore, it is considered necessary to clarify the riparian ecosystem and the sediment transport phenomena. Thereafter, the knowledge of step pools, which is associated with both of them, is considered important.

Because step pools are generally formed under high-magnitude, low-frequency flows that are difficult to observe, most of the previous studies on the step-pool morphology were carried out in the laboratory (Ashida et al., 1984; Abrahams et al., 1995; Fujita and Ikeda, 1996). Ashida et al. also reported shear stress distribution and friction law of flow over step pools (Ashida et al., 1986b) and the flow conditions that are necessary for the formation and disruption of step pools (Ashida et al., 1986a; Ashida et al., 1987) supported by data from flume experiments. Ashida et al. (1985) have reported the applicability of their theoretical study to the experimental results obtained from field work. Recent studies have also provided insights into the origin (Abrahams et al., 1995; Chartrand and Whiting, 2000; Chin, 1999b), step-pool stability (Chin, 1998; Fujita and Michiue, 1996), and morphological relationships (Chartrand and Whiting, 2000; Chin, 1999a; Fujita and Michiue, 1995) of natural step-pool streams.

There exist step pools of various scales in the mountain streams. Previous studies reported that the scale of a step pool is controlled by the discharge, bed materials, sediment discharge, particle size distribution of the sediment, stream geometry, etc. in the formation process of step-pool sequences. However, a complete

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Table 1. Characteristics of study reaches

	Reach	Drainage area (km^2)	Mean gradient (m/m)	Mean channel width (m)	Mean particle size (cm)	Surveyed channel length (m)	Numver of step-pool units
R.Furu		3.16	0.046	3.31	62.4	94	8
		2.81	0.050	2.95	83.7	98	6
		2.62	0.071	3.18	90.6	114	5
		0.86	0.088	1.70	67.5	92	5
		0.59	0.080	1.84	62.4	113	7
	F	0.12	0.202	0.85	41.3	109	8
R.Otoshirisawa	A	0.57	0.113	1.39	43.8	92	29
	B	0.50	0.117	1.25	47.7	112	38
	C	0.43	0.139	1.67	59.4	97	27
	D	0.32	0.123	1.33	52.5	85	31
	E	0.27	0.196	0.65	54.5	102	26
R.Ikaura	A	4.23	0.047		57.4	205	24
	B	3.56	0.061		68.0	84	15
	C	3.22	0.054		76.1	129	20
	D	2.80	0.090		126.8	103	15
	E	2.21	0.080		87.8	87	11
	F	1.87	0.096		95.5	77	17
	G	1.32	0.097		53.7	68	18
R.Osawa	A	2.89	0.045		69.8	152	34
	B	2.28	0.038		66.8	195	28
	C	1.20	0.080		88.2	166	34
	D	0.70	0.091		69.0	160	33
R.Okura	A	2.71	0.059	3.77	33.5	153	24
	B	2.31	0.113	3.06	57.0	94	27
	C	1.42	0.317	2.32	75.0	98	25
	D	1.33	0.155	2.70	58.3	117	43
R.Itayama	A	5.70	0.016	4.62	69.3	103	9
	B	4.27	0.041	4.99	88.7	67	14
	C	2.84	0.084	4.95	96.8	120	21
	D	1.15	0.084	3.17	74.1	75	23
R.Toumyousawa	A	3.33	0.051	4.30	65.9	127	19
	B	3.06	0.147	3.58	106.0	118	20
	C	1.94	0.098	3.54	72.5	217	48
	D	1.65	0.163	3.39	97.9	105	21
R.Nhishimatatani	A	1.24	0.144	2.01	78.2	390	85

explanation of the step-pool system has not yet been obtained. Furthermore, although a large number of studies have been conducted on the longitudinal profile of the step, little is known about the transverse profile of the step and pool geometry (Buffington et al., 2002; Fujita and Michiue, 1995). Therefore, it is necessary to accumulate knowledge on step-pool systems.

The purpose of this study is to clarify the characteristics of step-pool morphology and the distribution of step pools in mountain steams. The authors investigated the physical conditions in the channel of eight small basins in Japan, i.e., the channel gradient, the channel width, the step-pool dimensions, size and number of step particles, etc. at 35 study reaches with different characteristics. We examine the relationship between the channel conditions — channel gradient, channel width, and particle size — and the step-pool morphology. We also present new data on the transverse profile of a step. Finally, we provide the basis for a conceptual model of the relationship between channel conditions and step-pool.

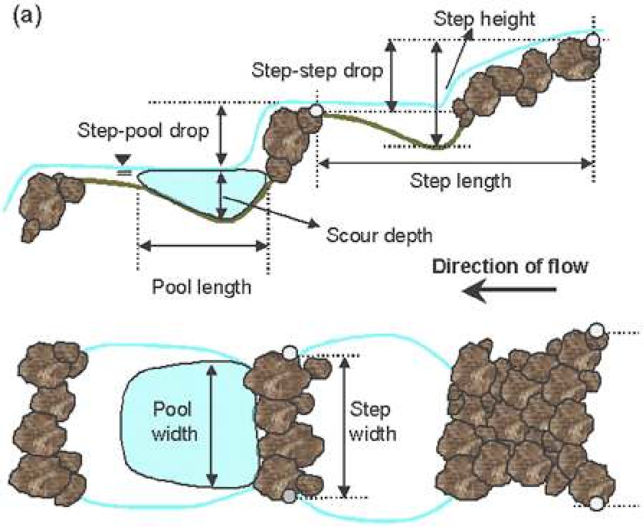

Fig. 1. Definitions of (a) geometric features of step pool and (b) number of front particles

Study Site and Methods

The study reaches are located in Niigata (R. Furu, R. Otoshirisawa, R. Ikaura, R. Osawa, R. Okura, R. Itayama, and R. Toumyousawa) and Mie (R. Nhishimatatani) in Japan; they have a complex geology and varied physical geography that includes cobble and boulder-bed channels with drainage areas ranging from 0.7 to 6.3 km^2. The elevation of headwater basins varies from approximately 210 m to about 910 m. The study reaches in Niigata have large amounts of snow in winter and moderate rainfall in summer. The mean annual temperature is 10 °C, and the mean annual precipitation ranges from approximately 1600 to 3200 mm. On the other hand, the study reach in Mie is characterized by warm rainy summers and mild dry winters with about 50% of the rainfall occurring between July and September. The mean annual temperature is 12.3 °C, and the mean annual precipitation is 2481 mm. Overall, 35 study-reaches, which are alphabetized from downstream to upstream at each river, were surveyed during the period from 2000 to 2005. The study-reaches ranged from 67 to 390 m in length and 0.016 to 0.202 m/m in gradient during (Table 1). Longitudinal profiles were measured using a compass and tape along the centerline of the channels. Channel bed elevation was measured at each step crest and at each pool. The channel width under low-flow conditions was measured with a tape as the distance between the banks in the direction perpendicular to the direction of the flow at each step at all reaches except at R. Ikaura and R. Osawa. For the measurement of the particle size, the three largest rocks were selected at each step; the a, b, and c axes were measured, and the geometric mean of a–c was used in the analysis to represent the step particle size. In addition, the "number of front particles" was counted. The term "number of front particles" refers to "the number of rocks that form each step on the downstream side that can be observed from downstream" (Fig.1b).

The step-pool geometry can be defined by several morphometric features (Fig.1a) that have been measured using stadia rod and tape. For step geometry, the step-step drop, step wavelength and step width were measured; however, step wavelength was measured at all reaches except in R. Furu. The step-step drop is the vertical distance between successive step crests. The step wavelength is the downstream distance between successive step crests measured at the channel centerline. The step width is the distance across the channel over the step crest. For pool geometry, the scour depth, length, and width of the scouring part due to the water flow and step-pool drop were measured. The step-pool drop is the difference in the elevation between the water surface and the water on the surface immediately downstream of the step.

Results from the measurements of the step-pool geometry are given in Table 2. Each reach contained at least nine step-pool units. The average values of the step-pool geometry measurements for each reach are reported. With regard to R. Ikaura and R. Osawa, we used step-width data instead of the channel-width data for analysis.

Table 2. Results from the measurement of step-pool geometry

	Reach	Mean step-step drop (m)	Mean interval of steps (m)	Mean step width (m)	Mean pool length (m)	Mean pool width (m)	Mean scour depth (m)	Mean step-pool drop (m)
R.Furu		0.32		3.32	2.30	1.93	0.38	0.21
		0.49		4.44	3.00	3.12	0.63	0.47
		0.95		5.77	2.63	1.46	0.51	0.72
		0.74		3.95	2.66	2.09	0.51	0.51
		0.74		2.96	2.30	1.88	0.43	0.43
	F	1.01		2.97	1.03	0.70	0.33	1.00
R.Otoshirisawa	A	0.30	2.79	2.22	1.43	1.36	0.25	0.26
	B	0.37	2.29	2.11	1.47	1.26	0.30	0.36
	C	0.50	2.78	2.63	1.74	1.76	0.33	0.54
	D	0.35	2.47	2.22	1.65	1.47	0.30	0.43
	E	0.63	3.02	2.30	1.23	1.19	0.21	0.63
R.Ikaura	A	0.55	5.48	3.83	2.19	1.96	0.42	0.32
	B	0.44	4.76	4.07	3.04	2.44	0.55	0.35
	C	0.63	6.56	4.29	2.27	2.00	0.49	0.35
	D	0.99	6.85	5.71	2.98	3.10	0.78	0.48
	E	0.70	6.98	3.81	3.91	2.91	0.74	0.57
	F	0.60	4.19	4.04	2.48	2.44	0.59	0.38
	G	0.60	4.10	3.46	1.90	2.02	0.45	0.41
R.Osawa	A	0.53	4.53	4.78	1.89	1.86	0.38	0.22
	B	0.72	6.99	4.46	2.26	2.24	0.47	0.28
	C	0.74	5.17	4.30	2.29	2.20	0.51	0.35
	D	0.77	4.94	3.58	1.64	1.68	0.44	0.34
R.Okura	A	0.38	3.78	3.83	1.34	1.42	0.40	0.28
	B	0.57	3.48	3.81	1.57	1.63	0.47	0.30
	C	1.34	3.94	3.69	1.45	1.63	0.57	0.91
	D	0.53	3.03	3.53	1.22	1.34	0.42	0.42
R.Itayama	A	0.43	8.40	5.16	3.31	1.88	0.51	0.17
	B	0.61	5.26	5.07	2.69	2.45	0.64	0.25
	C	0.74	5.37	5.12	2.75	2.26	0.59	0.40
	D	0.57	4.37	3.75	1.95	1.73	0.46	0.33
R.Toumyousawa	A	0.34	6.67	4.52	1.85	1.60	0.48	0.23
	B	0.67	5.35	4.38	1.95	1.43	0.56	0.60
	C	0.43	4.35	3.83	1.12	0.86	0.44	0.41
	D	0.60	4.75	4.24	1.38	1.14	0.45	0.53
R.Nhishimatatani	A	0.60	4.60	3.09	1.55	1.34	0.37	0.50

Results and Discussion

Physical conditions in the channel

The physical conditions in a river generally change with the distance (drainage area) downstream. In addition, the decrease in the gradient is generally accompanied by a decrease in the particle size and an increase in the discharge according to the distance downstream (Fig.2a). However, in some cases, these relationships are not applicable.

Fig.2b illustrates the relationship between the mean particle size of a step and the distance from the ridge line in the 35 study reaches of the streams in the Niigata and Mie. Although it may be considered intuitively that the largest rock size at each step increases with the distance from the ridge line, in fact, the particle size in Niigata and Mie rises to its peak in the range from about 1500 to 3000 m.

In Niigata and Mie, the channel width is shown to be positively correlated with the drainage area (Fig.3 $r^2 = 0.77$). In this discussion, for analysis, we use the channel width as an indicator of the discharge because it seems reasonable to suppose that the discharge increases with the drainage area downstream; the channel geometry generally increases concomitantly.

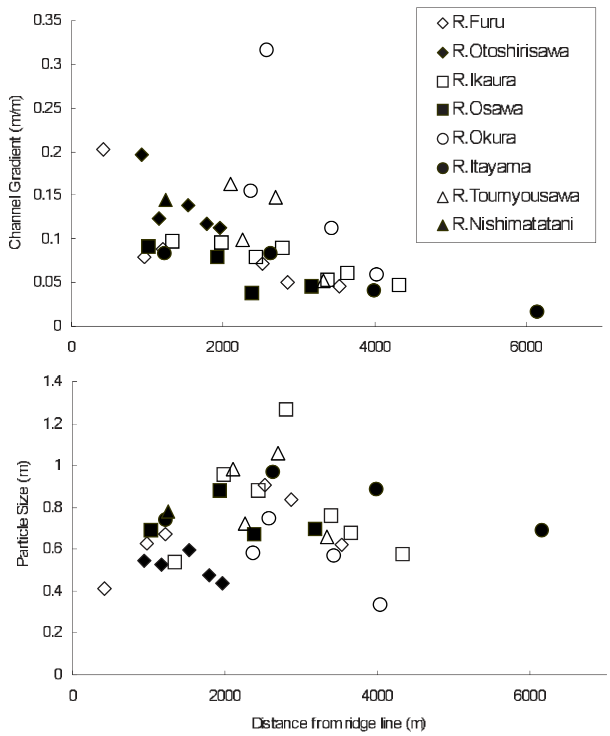

Fig. 2. Relationship with distance from ridge line. (a) channel gradient and (b) particle size of the step.

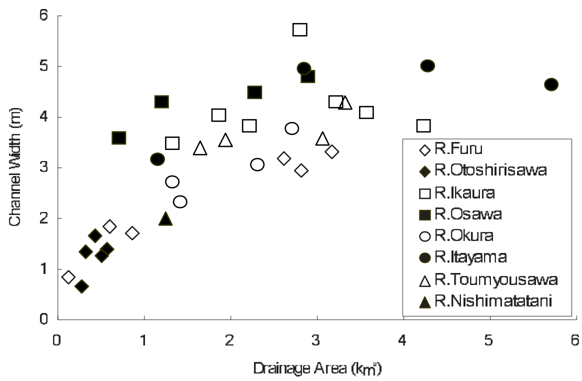

Fig. 3. Relationship between the channel width and drainage area.

Longitudinal profile of a step (step-step drop and step wavelength)

The longitudinal profile of a step is characterized by the following two features: first, the step-step drop in the streams in Niigata and Mie shows a positive association with the particle size, although some scatter exists in these data (Fig.4a). Previous studies have reported that the step-step drop is as large as the mean size of the rocks that form the step (Ashida et al., 1984; Ashida et al., 1985; Fujita and Michiue, 1995). In Niigata and Mie, the mean step-step drop ranges from about 0.5 to 1 times the particle diameters for all but two reaches (Fig.4a). The scatter in the step-step drop data is approximately twice the mean particle size in the two reaches (F reach in R. Furu and C reach in R. Okura, and the channel gradient of both of the reaches is greater than 0.2).

Fig.4b shows the relationship between the channel gradient and the step-step drop at each study reach. For channel gradients ranging from 0.03 to 0.15, the maximum step-step drop is steady at about 1.5 m, whereas the value is higher than 1.5 m for channel gradients greater than 0.15. The relationship between the mean step-step drop and the channel gradient is not clear.

In addition, Fig.5a shows a positive correlation ($r^2 = 0.62$) between the channel width and the step

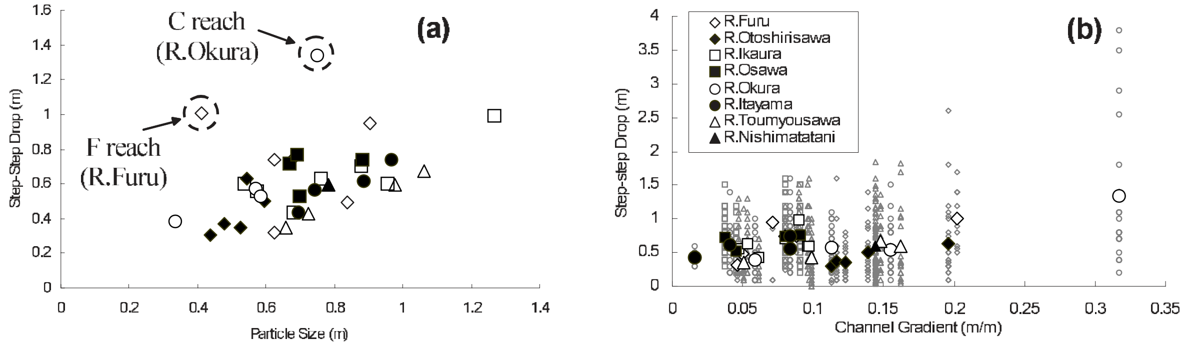

Fig. 4. Relationship between step-step drop and (a) particle size and (b) channel gradient. The smaller marker indicate the range of value at each study reach.

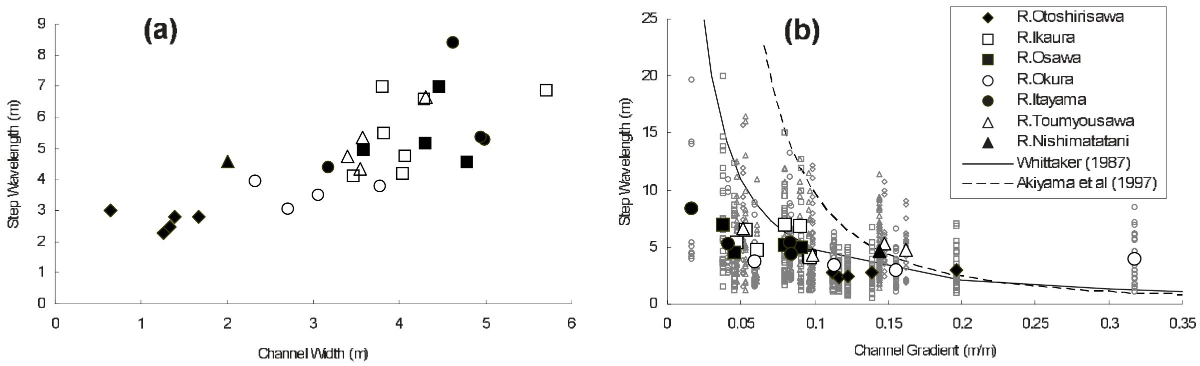

Fig. 5. Relationship between step wavelength and (a) channel width and (b) channel gradient. The smaller marker indicates the range of value at each study reach.

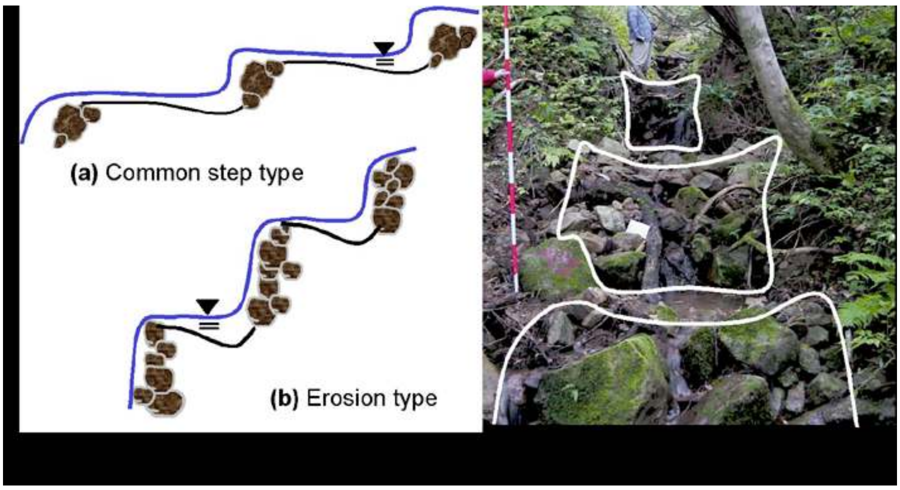

Fig. 6. The difference between (a) common step type and (b) erosion type

wavelength in Niigata and Mie. Chin (1989) and Chartrand and Whiting (2000) have suggested that the channel width can be used to estimate the step wavelength. Chin (1989) found that the steps in the Santa Monica Mountains exhibit a wavelength of approximately 1.9 times the channel width, and Chartrand and Whiting (2000) found that the steps in Idaho vary from about 0.6 to 1 times the channel width. The step wavelength in Niigata and Mie varies from about 0.9 to 1.9 times the channel width.

Previous studies have reported that the mean step wavelength is negatively correlated with the channel

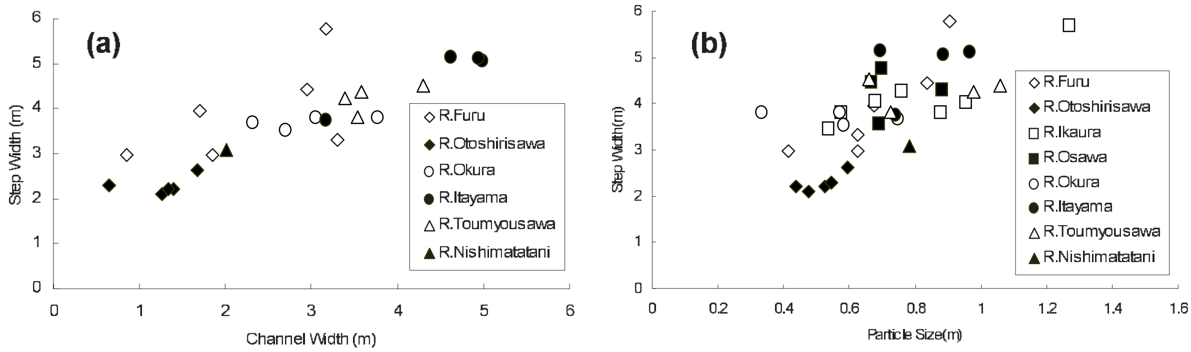

Fig. 7. Relationship between step width and (a) channel width and (b) particle size.

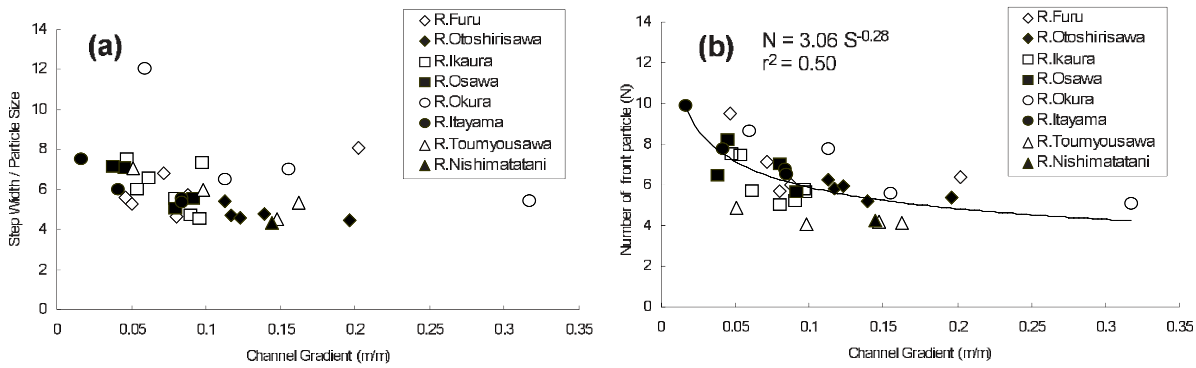

Fig. 8. Relationship with channel gradient. (a) step width scaled by particle size and (b) number of front particles.

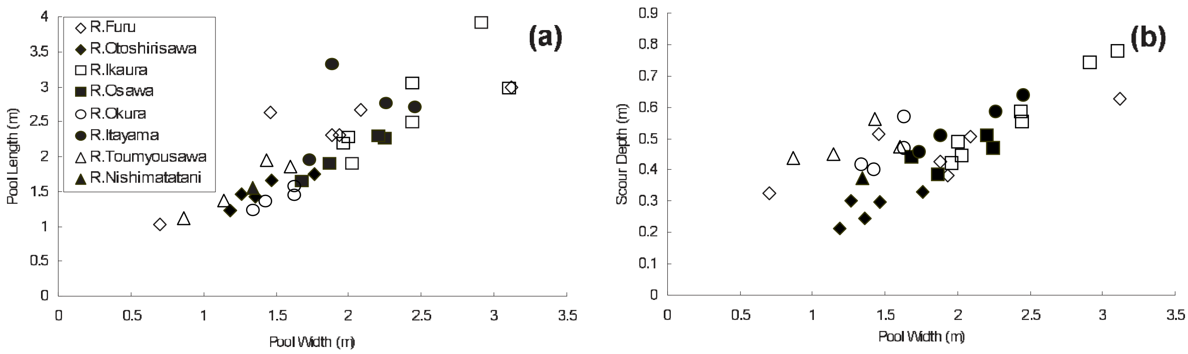

Fig. 9. Relationship with pool width. (a) pool length and (b) scour depth.

gradient (Judd, 1964; Whittaker, 1987; Chin, 1989; Akiyama and Maita, 1997; Chartrand and Whiting, 2000). Streams in Niigata and Mie exhibit an inverse power law relationship between the mean step wavelength and channel gradient (Fig.5b). Judd (1964), Whittaker (1987), Abrahams et al. (1995) developed the expression to relate the mean longitudinal step length to the channel gradient:

$$\lambda = \mathrm{H/aS^b} \tag{1}$$

where λ is the length between steps, S is the channel gradient, H is the representative bed element height, and a and z are constants. For 26 step-pool reaches in New Zealand, Whittaker (1987) obtained the relation:

$$\lambda = 0.311\mathrm{S}^{-1.188} \tag{2}$$

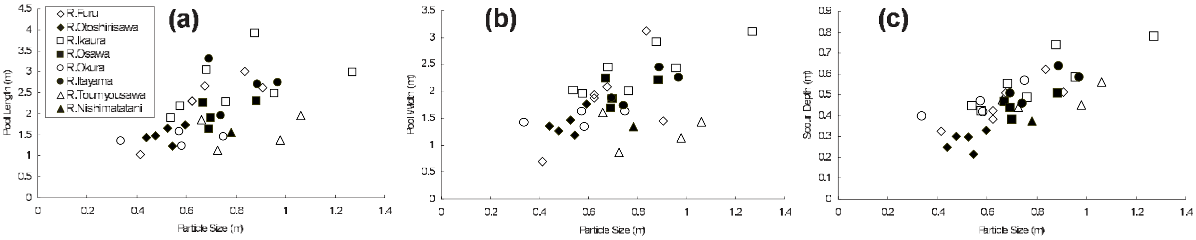

Fig. 10. Relationship with particle size. (a) pool length, (b) pool width, and (c) scour depth.

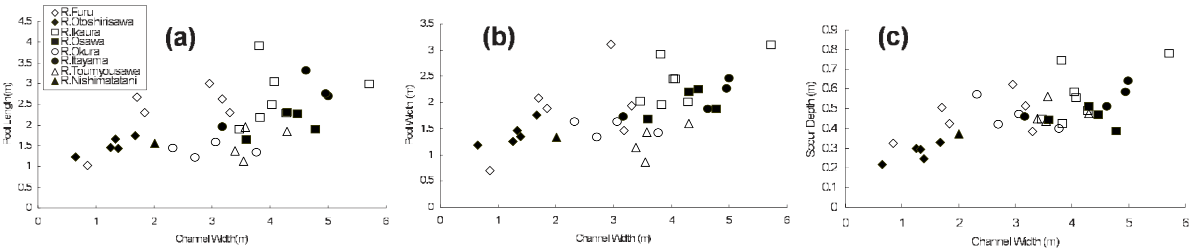

Fig. 11. Relationship with channel width. (a) pool length, (b) pool width, and (c) scour depth.

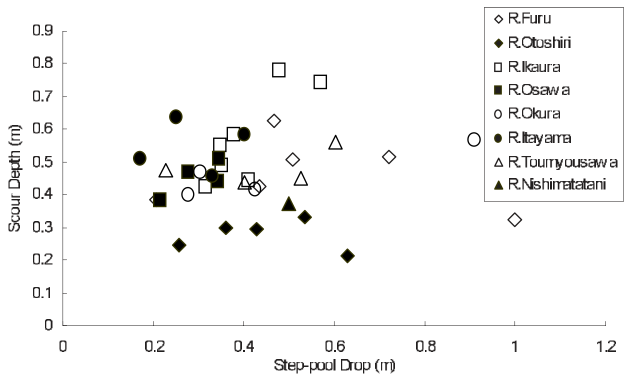

Fig. 12. Relationship between scour depth and step-pool drop.

In addition, Akiyama and Maita (1997) developed the expression to relate the limited value of the step wavelength to the channel gradient:

$$\lambda_m = 0.096\mathrm{S}^{-2} \tag{3}$$

where λ_m is the maximum step wavelength. Fig.5b shows the relationship between the step wavelength and the channel gradient in this study; it is in close agreement with other reported equations in the range of channel gradients less than 0.15. Some reaches with channel gradients exceeding 0.15, however, have unusually higher values than the range estimated value by the predictive equation.

Thus, it seems reasonable to suppose that the step-step drop is directly controlled by the size of the rocks that form the step, whereas the step wavelength is scaled by channel width, in other words, discharge.

In addition, these results may suggest that the relationship between the longitudinal profile of a step and the physical conditions changes depending on the channel gradient. In other words, in the reaches with a gradient less than 0.15, the mean step-step drop is as large as the mean particle size; moreover, the maximum step wavelength is well fitted by the expression given by Akiyama and Maita. Overall, the longitudinal profile of a step in the reaches with a channel gradient less than 0.15 shows a trend similar to that published in reports. In contrast, in reaches with channel gradient greater than 0.15, the mean and maximum step-step drops are much higher than those of the reaches with a channel gradient less than 0.15. Similarly, there are maximum step wavelength data that are inconsistent with the expression given by Akiyama and Maita.

Incidentally, a different type of step — erosion type — was observed in the reaches with a channel

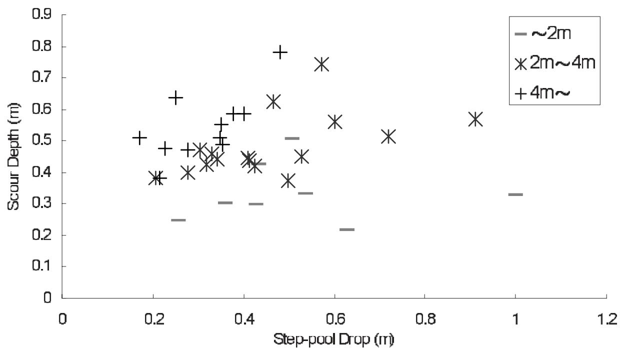

Fig. 13. Relationship between scour depth and step-pool drop. The data is classified by the channel width.

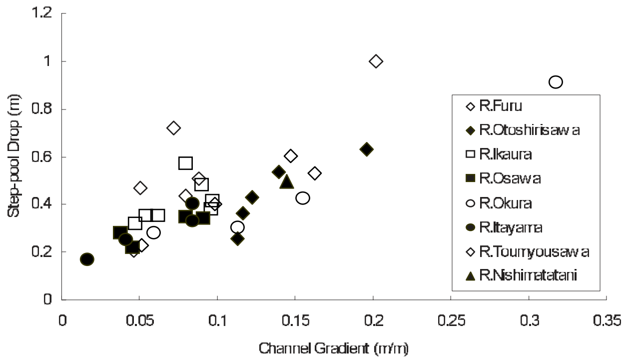

Fig. 14. Relationship between the step-pool drop and channel gradient.

gradient greater than 0.2 in Niigata. The structure of the step is different from that of the common step (Fig.6). The erosion type of step is formed by the vertical accumulation of cobbles.

Transverse profile of a step (step width)

Fig.7a illustrates the relationship between the mean step width and the channel width in the 25 study reaches of the streams in Niigata and Mie. The step width shows a generally positive correlation ($r^2 = 0.70$) with the channel width — the larger the channel width, the larger the step width.

The step width in Niigata and Mie is also moderately correlated ($r^2 = 0.48$) with the particle size (Fig.7b). The mean ratio of the step width to the particle size in each reach ranged from approximately 4.4 to 12 and is approximately 5.9 on an average. As shown in Fig.8a, the ratio of the step width to the particle size decreases with the channel gradient.

The mean value of the number of front particles in each reach ranged from 4.1 to 9.5; it is moderately correlated ($r^2 = 0.50$) with the channel gradient (Fig.8b). This is consistent with the data in Fig.8a, showing that the ratio of the step width to the particle size decreases when the channel gradient approaches a high value.

Thus, these data suggest that the step width, which is the transverse profile of a step, is probably controlled by both the particle size and the channel width or either of them. In addition, the number of front particles may be determined by the channel gradient.

Pool geometry

Pool length, pool width, and scour depth, which are components of pool geometry, show a positive relationship with each other. These results suggest that the average pool geometry is almost homothetic (Fig.9a, b). Fujita and Michiue (1995) found that the homothetic ratio of the scour depth to the pool length of the Sendai River in Japan is 0.1. For the streams in Niigata and Mie, the homothetic ratio of the pool length,

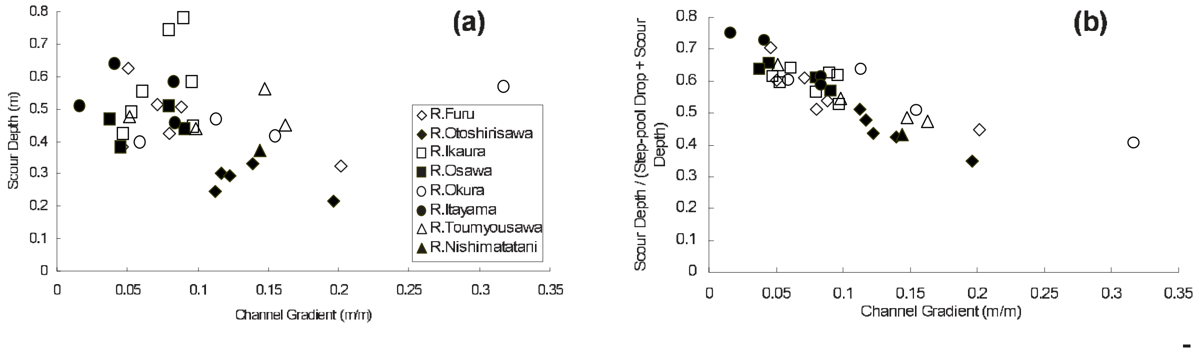

Fig. 15. Relationship with the channel gradient. (a) scour depth and (b) scour depth scaled by sum of the step-pool and scour depth.

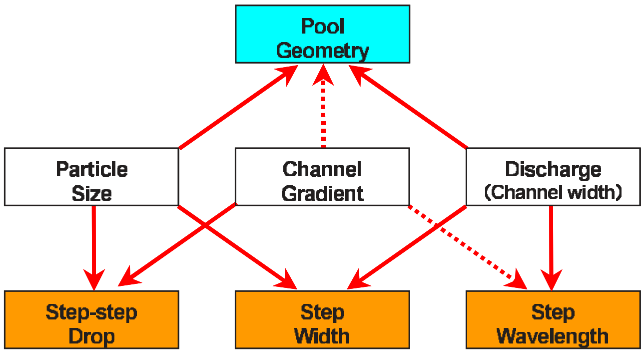

Fig. 16. The relationship of channel conditions and step-pool. The solid line and dotted line indicate the positive and negative relationship, respectively, between variables

pool width and scour depth is approximately 5:5:1. Therefore, their pool geometry is nearly homothetic not only in the longitudinal profile but also in the transverse profile.

The pool morphology shows a positive association with the particle size (Fig.10a–c) and channel width (Fig.11a–c). The pool length and pool width is approximately 3 times the particle size; the scour depth is approximately 0.7 times the particle size.

Ashida et al (1985) have reported that the scour depth deepens in proportion to the size of the step-pool drop immediately upstream of the pool. However, no relationship exists between the scour depth and step-pool drop throughout this study (Fig.12). Then, in view of the scale of the channel width at each reach, let us then consider the relationship between the scour depth and step-pool drop because it is possible that scour depth depends on the discharge (Fig.11c). They may be classified into reaches with a channel width less than 2 m, with a channel width between 2 m and 4 m, and with a channel width greater than 4 m. Fig.13 shows a positive relationship between the scour depth and step-pool drop in the reaches with channel width greater than 2 m. In addition, Fig.14 shows a generally positive association with the step-pool drop and channel gradient. Therefore, these data suggest that the pool morphology has a positive relationship with the step-pool drop and discharge — the higher the step-pool drop and discharge, larger the pool.

Scour depth, by itself (Fig.15a) and as scaled by the sum of the step-pool drop and scour depth (Fig.15b), decreases with the channel gradient. Although the relationship between the other pool geometry and the channel gradient cannot be represented here due to space constraints, the pool length and pool width also decrease with the channel gradient, similar to scour depth.

It is inferred from these data that the scale of the pool geometry is determined by the causal linkage between the particle size, channel width, and channel gradient. It is worthwhile to examine the subject more closely.

Summary and Conclusions

The analysis of 818 step pools in the streams in Niigata and Mie yielded several insights into the characteristics of step-pool morphology and distribution: (1) The relationship between the step-step drop, step wavelength, and channel gradient is different from the trend reported by previous studies at high-gradient reaches (> 0.15 gradient); (2) the mean step-step drop is as large as the mean size of the rocks that form the step for all but the erosion type of step, whereas the mean step wavelength is 1–2 times as large as the channel width for all types of steps; (3) the mean step width is 4–7 times as large as the mean size of the rocks that form the step. It is quite likely that the scale of the step width is determined by the channel width and particle size; (4) both the longitudinal profile and the transverse profile of the pool geometry are homothetic. The homothetic ratio of the pool length, pool width and scour depth is 5:5:1. It is quite likely that the scale of the pool geometry is controlled by the channel width, particle size, and channel gradient.

We can diagrammatically represent the relationship between the physical conditions in the channel and the step-pool morphology as shown in Fig.16. The positive and negative relationships are represented by solid line and dotted line, respectively; the arrows indicate the relationship between the channel conditions and step pools in this figure.

The step-pool morphology in real streams appears to have a complicated structure because many factors can influence step-pool dimensions and frequency, including channel geometry, and bed material size, etc. However, the characteristics of distribution and the geometry of the step pool can be explained by three parameters, viz., the particle size, discharge, and channel gradient.

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