Temporal change of step-pool morphology in a mountain stream after a debris flow event

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In this paper, the change in form, number, and structure of step-pools in the Okochi River in Sado Island, Niigata, Japan, during three year period from 2011 to 2013,after the debris flow event in December 2010 are discus. The channel geometry and step-pool morphology were surveyed 10 times at four study reaches in the Okochi River. Temporal changes in the structures of step-pools were detected using photographs taken at each step-pool morphological survey. The mean value of the channel and step-pool geometries over each study reach, and the total number of step-pools at each reach remained nearly constant for more than three years after the debris flow event. However, many step-pools were deformed, destructed, and reconstructed repeatedly during a three-year period. Temporal changes in step-pool structures were estimated by using hydrodynamic equations based on the dynamic conditions proposed by *Ashida et al.* (1984) under which step-pools are formed. Estimated temporal changes in step-pool structure generally coincided with detected change by using photographs, although the number of stable step-pools tended to be overestimated by the hydrodynamic equations. It was assumed that the overestimation of the number of stable step-pools occurred mainly because of errors in evaluating critical tractive force on each particle composing step.

Keywords: Step-pool, morphology, temporal change, debris flow event, Sado Island

1. INTRODUCTION

In mountain streams, step-pools are generally observed in stream beds. Step-pools are repeatedly deformed, destructed, and reformed with increasing discharge, and are dynamically maintained.

It is reported that step-pools play an important role in the sediment transport phenomena controlling discharge and particle-size distribution of sediment through their formation and destruction processes, in addition to the erosion and deposition processes of sediment in pools [*Ashida et al*., 1984, 1986a, 1986b].

In recent years, societal demand has increased for consistent synthetic river sediment management through Sabo projects in the field of river and erosion-control engineering. In order to realize synthetic river sediment management, it is important to grasp the quantity and the quality of sediment movement within mountain streams, which are the source areas of sediment [*Fujita et al*., 2004; *Tsutsumi et al*., 2008].

However, in mountain streams with steep slopes, the particle size distribution of stream bed material is wide ranging. Unique bed forms such as step-pools and armor coats, which do not exist in an alluvial river but rather in a mountain stream. Thus, the sediment transport process in a mountain stream is more complicated than in an alluvial river, and it is difficult to quantitatively evaluate the sediment discharge [*Ashida et al*., 1986b, 1987; *Tani et al*., 2012]. Therefore, in order to determine the sediment transport process in a mountain stream and to realize the quantitative evaluation of sediment discharge, it is critical to understand how step-pool bed forms are maintained dynamically through the formation, deformation, and destruction processes [*Ashida et al*., 1984; *Egashira et al*., 1985]. Although numerous studies focusing on step-pool dynamics have been conducted by using experimental channels in Japan, only a few field observations focusing on the morphological changes in step-pools have been conducted.

In this research, the morphological changes of step-pools, such as their formation, deformation, and destruction, were continuously investigated during a three-year period in a mountain stream where a debris flow event occurred at the end of December 2010.

The main reason the river was chosen as a study site after the debris flow event is that we expected the sediment transport phenomena would actively

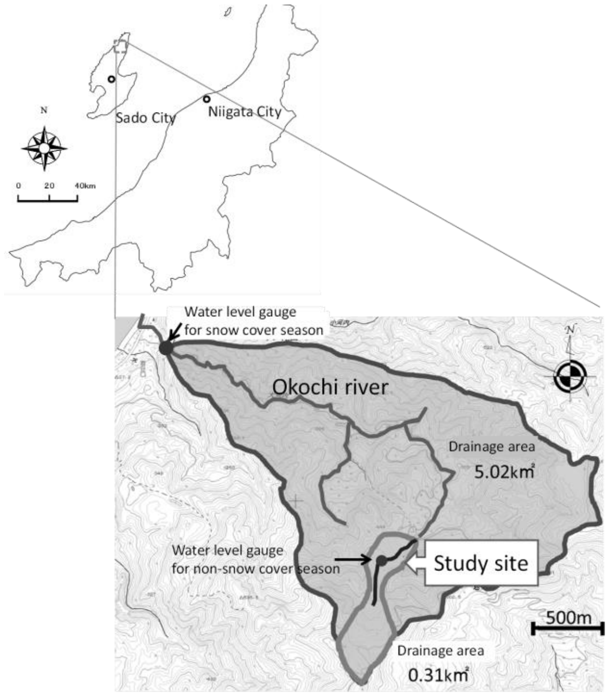

Fig.1 Located in the Okochi River at Osado Island, Niigata, Japan

manifest during flood events and that changes in step-pool morphology would be observed for a short period of time.

In this paper, the change in the number and form of step-pools during a three-year period are reported. Furthermore, temporal changes in the structure of step-pools were estimated by using hydrodynamic equations based on the dynamic conditions proposed by *Ashida et al*. (1984) under which step-pools are formed. The accuracy of the estimations is discussed by comparing the results of the estimations and field observations.

2. STUDY SITE AND METHODS

The study reaches are located in the Okochi River at Osado Island, Niigata, Japan (Fig. 1). The Okochi River is approximately 4.8 km in length, the mean gradient is 13.5%, and the drainage area is approximately 5.0 km^2. Thus, this river is a typical mountain stream with a small drainage area and a large mean gradient. The mean annual precipitation is approximately 1500 mm, and the mean annual temperature is about 8°C. The snow-cover period generally begins in December and continues until May. Peak snow-cover depth at the study reaches is approximately 2–3 m. A debris flow even occurred near the head waters of the Okochi River on December 23, 2010. The river bed at the upper reach was heavily disturbed. Four study reaches were established in the upper part of the river (referred to as reaches A, B, C and D, respectively, from upstream to downstream). A channel length, mean gradient, and drainage area of each reach are 40–130 m, 0.06–0.15 m/m, and 0.2–0.26 km^2, respectively (Table 1).

Table 1 Characteristics of study reaches

	Reach A	Reach B	Reach C	Reach D
Mean gradient (m/m)	0.147	0.12	0.151	0.062
Drainage area (km^2)	0.2	0.23	0.25	0.26
Surveyed channel length (m)	83	95	128	42

Table 2 Survey period and maximum discharge during time period until next survey

Survey period (yyyy/m/d)	Maximum discharge during time period until next survey(m^3/s)
2011/7/9-14	0.50 (2011/8/18)
2011/9/9,10	1.30 (2011/9/21)
2011/9/30-10/2	0.80 (2012/4/4)
2012/6/30-7/2	0.32 (2012/7/7)
2012/8/23-25	0.56 (2012/9/11)
2012/10/28-30	0.42 (2013/3/13)
2013/7/13-15	0.65 (2013/7/27)
2013/8/23-25	0.57 (2013/8/30)
2013/9/27-29	0.43 (2013/10/22)
2013/11/22-24	

Step-pool morphology at four study reaches was surveyed 10 times during non-snow-cover periods from July 2011 until November 2013 (Table 2).

Step-pool geometry can be defined by several morphometric features (Fig. 2) that have been measured using stadia rod and tape. For step geometry, step height, step-step drop, step length, step width, and the particle sizes of the rocks that composed step were measured, and the number of rocks that composed step was counted. For pool geometry, pool length, pool width, scour depth, and step-pool drop were measured. The (scour depth + step-pool drop) was made into step height in this research.

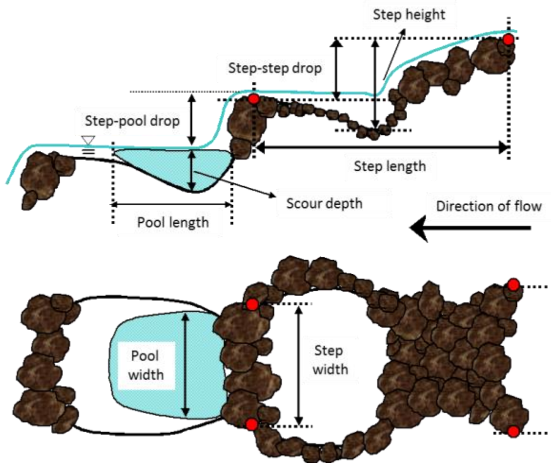

Fig. 2 Definitions of geometric features of a step-pool

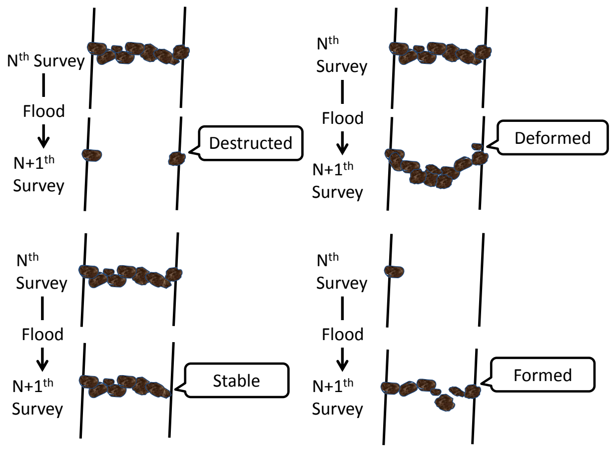

Fig. 3 Definitions of structural change in a step-pool

At each survey, photographs were taken at each step-pool. Temporal changes in the structure of each step-pool were detected by comparing photographs taken during the current survey with those from previous surveys.

A step-pool that existed in one survey but not in the following survey was categorized as “destructed.” However, if a step-pool existed at the almost same location at one survey, as well as the following survey, and any major rocks that composed main body of the step were replaced, it was categorized as “deformed.” If a step-pool remained at the almost same location at one survey as in the following survey and no major rocks that composed main body of the step were replaced, it was categorized “stable.” In the case of a newly formed step-pool at the location where no step-pool previously existed, it was categorized as “formed” (Fig. 3).

During the non-snow-cover period, a water level gauge was installed between reaches B and C, and the water discharge of the stream was monitored. During the snow-cover period, water discharge at the study site was estimated from both the precipitation records monitored at the Sado station, Field Center for Sustainable Agriculture and Forestry, Niigata University, which is located 4 km southwest of the study site, and the water discharge monitored 3.6 km downstream from the study site.

Ashida et al. (1984) proposed the dynamic conditions under which step-pools are formed are followings.

1) The river bed is formed by mixed-grain-size particles.
2) The flow of the river is supercritical.
3) The river bed particle with mean grain size can be transported by the flow.
4) River bed particle with maximum grain size cannot be transported by the flow.

Dynamic conditions 2) to 4) are represented by the following equations (1) to (3).

$$\frac{h}{d_m} \leqq \left(6.0 + 5.75 \log \frac{h}{\alpha d_m}\right)^2 s\tau_{*m} \tag{1}$$

$$\tau_{*m} \geqq \beta \tau_{*cm} (\beta > 0) \tag{2}$$

$$\tau_{*m} \leqq \tau_{*c\max} \cdot \frac{d_{\max}}{d_m} \tag{3}$$

where: h : depth of the flow, αd_{m} : equivalent roughness (α = 2.6), s : the specific weight of sediment (s = 1.65), $\tau_{*m}=u_*^2/sgd_m$ (u_* : friction velocity), τ_{*cm} : non-dimensional critical tractive force of the sediment particle with the mean particle size (d_m), τ_{*cmax} : non-dimensional critical tractive force of the sediment particle with the maximum particle size (d_{max}) , β : coefficient which represents activity of particle segregation(β= 1)

The structural changes of step-pools between each survey were estimated by hydrodynamic equations based on equations (1) to (3). Discharge of the study site, in addition to step-pool and river-channel geometries were used for the estimations.

3. RESULTS AND DISCUSSION

3.1 Temporal changes in the structure and number of step-pools for a three-year period

Although the stream bed was heavily disturbed by the debris flow event, severe riverbed degradation and riverbank erosion ceased during the course of several months. Therefore, the mean value of river-channel and step-pool geometries over each reach remained nearly constant during the three-year period since the first survey in July 2011 (Fig. 4).

The total number of step-pools varied between 140 and 170 pieces during the three-year period.

There appears to be little correlation between the peak discharge of flooding among each survey and the change in the total number of step-pools (Fig. 5).

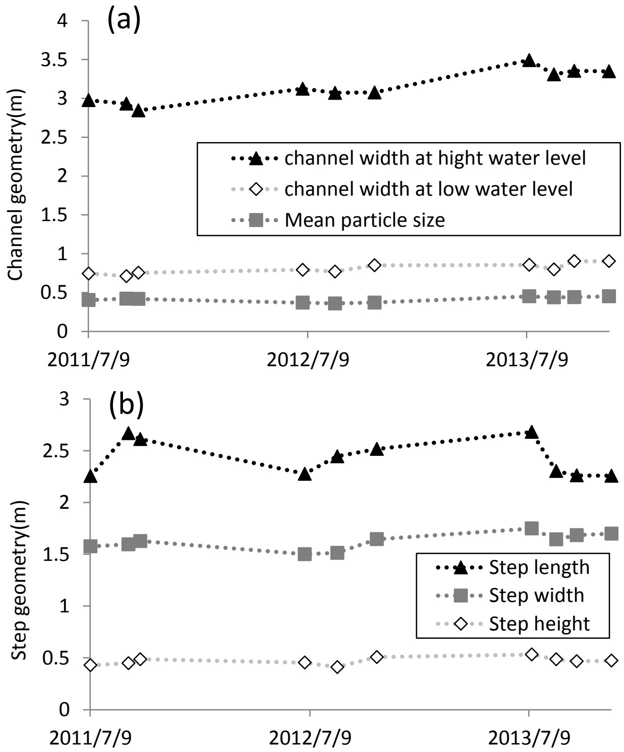

Fig. 4 Change of (a) channel geometry and (b) step geometry during a three-year period

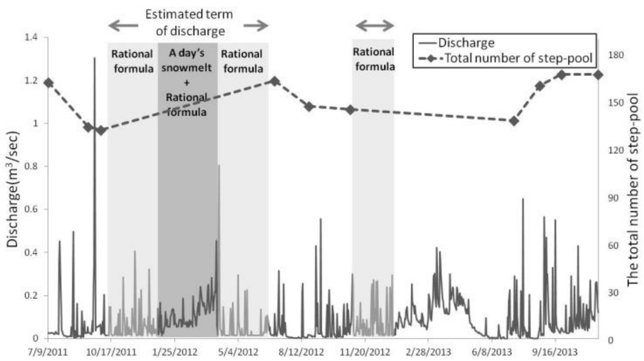

Fig. 5 Relationship between discharge and total number of step-pools at each survey

The temporal change in the number of destructed step-pools is small, compared with that of formed step-pools. Approximately 20% of the total number of step-pools, which existed at a survey (between 20 and 40), was destroyed until the following survey (Fig. 6). Stable step-pools, which did not change during a three-year period, were approximately 30, which was equivalent to approximately 20–30% of the total number of step-pools at each survey. Stable step-pools that did not change during a three-year period were located at the interval of 20–30 m, which was approximately 10 times the average river width at study site (Fig. 7).

There was no significant difference among zgeometry of formed, deformed, and destructed step-pools, i.e., height and particle size (Fig. 8).

As previously mentioned, during a three-year period since July 2011, the longitudinal and cross-sectional profile of the river channel at each reach changed significantly; the reach mean value of river-channel and step-pool geometries remained nearly constant and the total number of step-pools didn't change significantly. However, when attention was paid to each step-pool, many repeated the deformation, destruction, and reformation processes. It is believed that the reasons for nearly constant reach mean values in river-channel and step-pool geometries were attributed to the following:

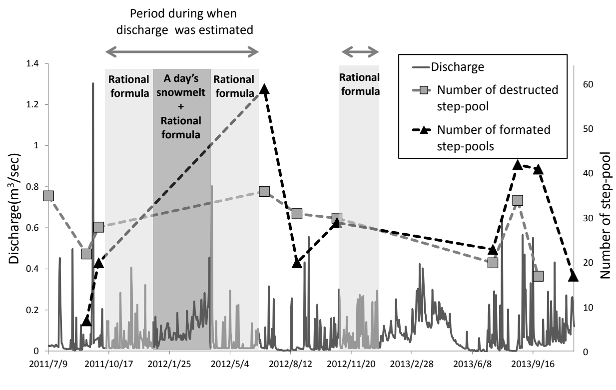

Fig. 6 Relationship between discharge and number of destructed and formed step-pools between each survey

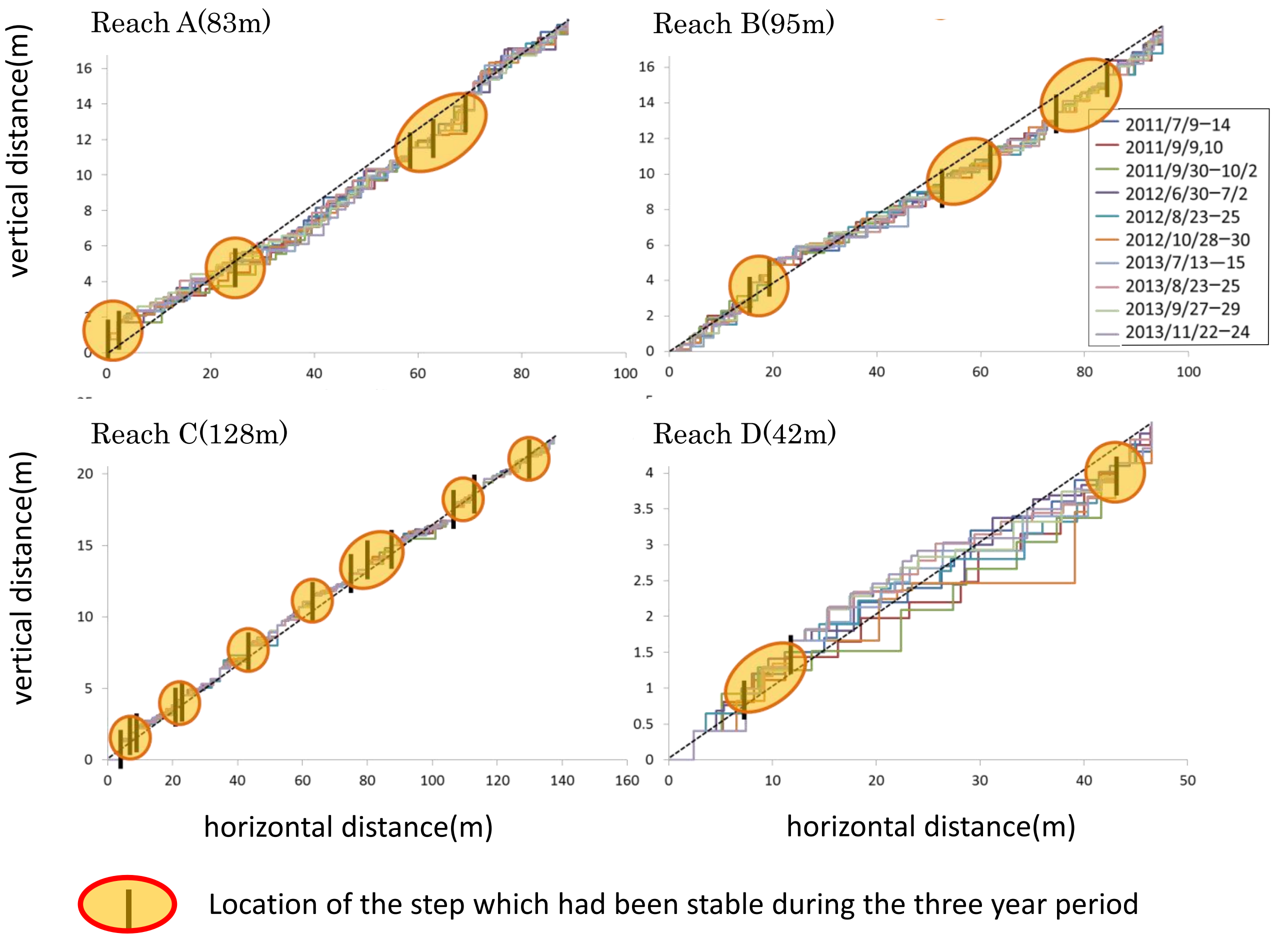

Fig. 7 Temporal changes of each reach during the three year period

(1) Because stable step-pools, which did not change for three years existed at the interval of 20–30 m, the difference in the elevation and the horizontal distance between the stable step-pools remained constant.

(2) Particle sizes composing the steps of formed step-pools were roughly as large as that of the deformed and destructed step-pools.

(3) It is known that step height tends to be approximately equal to the particle size of the composed step (*Okazaki et al*., 2006).

(4) For these reasons, between stable step-pools and channel geometry, the number of step-pools and mean step lengths remained nearly constant for three years.

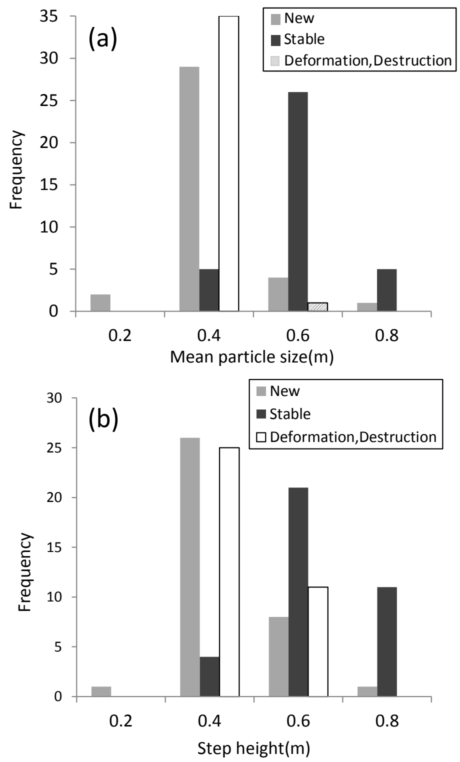

Fig. 8 Histogram of (a) mean particle size and (b) step height of stable, formed, deformed, and destructed step-pools

3.2 Accuracy of estimation of structural change of step-pools based on Ashida's equations

Estimated temporal changes in the structures of step-pools generally coincided with detected changes by using photographs (Fig. 9). However, the number of stable step-pools tended to be overestimated by the hydrodynamic equations.

Here, we consider the reasons that cause an overestimation of the number of stable step-pools.

If the hydrodynamic equations by *Ashida et al*. (1984) do not have problems, it is thought that there must be problems in either (1) evaluating non-dimensional critical tractive force (τ_{*cm}) of the rocks with the mean particle size (d_m) composed each step and non-dimensional critical tractive force (τ_{*cmax}) of the rocks with the maximum particle size (d_{max}) that composed each step or (2) evaluating non-dimensional tractive force (τ_{*m}).

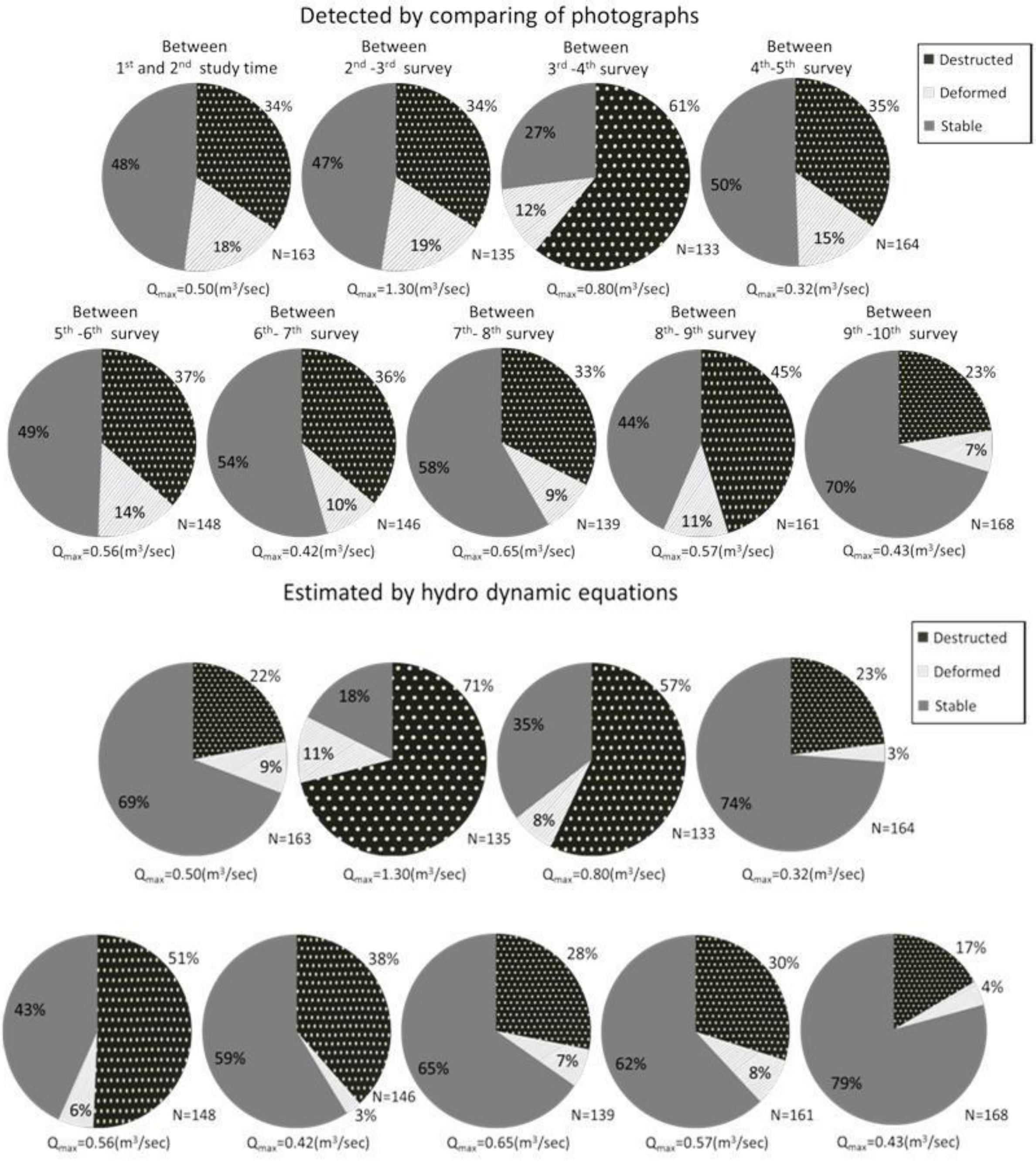

Fig. 9 Comparison between estimated structural changes of step-pools by using hydrodynamic equations and those detected

1) Evaluation of τ_{*cm} and τ_{*cmax}

The evaluation formula of non-dimensional critical tractive force on riverbed materials was developed under the condition that the river bed is composed of nearly uniform particles, and the depth of the flow is much larger than the particle size (*Ashida et al*., 1984). However, in mountain streams similar to the study site, riverbed particles should be treated as mixed-size particles, and the relative depth of the flow to the size of riverbed particle is rather small. Therefore, there may be error in evaluating τ_{*cm} and τ_{*cmax} in a mountain stream. However, there is no way to re-evaluate the value of τ_{*cm} and τ_{*cmax} at every each step-pool at present. Moreover, the result of the response analysis showed that changing τ_{*cm} and τ_{*cmax} did not improve the accuracy of the structural change of the step-pool.

2) Evaluation of τ_{*m}

The relationship between non-dimensional tractive force (τ_{*m}) of the rocks with the mean particle size (d_m) and the non-dimensional critical tractive force (τ_{*cmax}) of the rocks with the maximum particle size (d_{max}) composed each step. The straight lines in Fig.10 expressed the boundary line of the structural change of the step-pool between destructed and non-destructed based on the research of *Ashida et al*. (1984). A step-pool is estimated to be destroyed on the right side of the straight line. There are numerous data of step-pools in which structural change was incorrectly estimated. τ_{*m} of these data

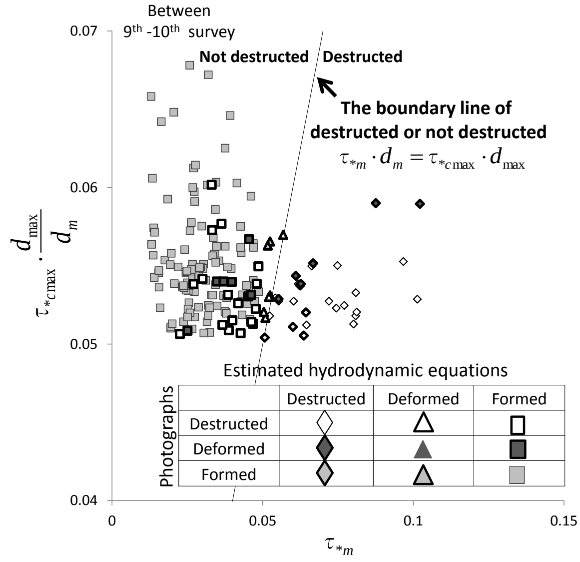

Fig. 10 Relationship between τ_{*m} and τ_{*cmax}

(between the ninth and tenth survey)

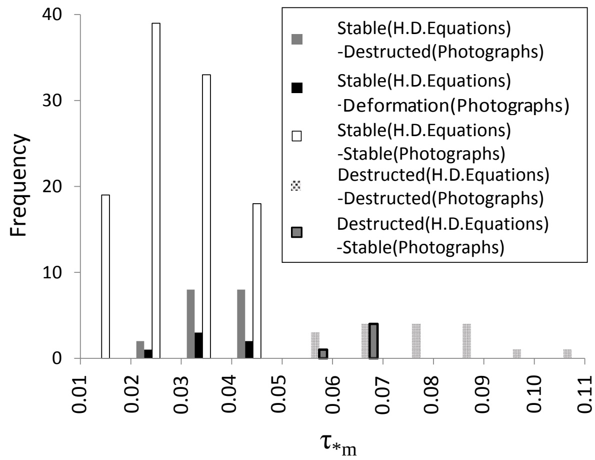

Fig.11 Histogram of comparison as a result of a photograph decipherment and conditional formula

(between the ninth and tenth survey).

Table 3 Relationship between accuracy of estimation of structural change of step-pool and τ_{*m}

(between the ninth and tenth survey).

Non-dimension tractive force	~0.019	0.02~0.029	0.03~0.039	0.04~0.049	0.05~0.059	0.06~0.069	0.07~0.079	0.08~0.089	0.09~0.099	0.1~0.109
Accuracy of estimation of Structral change of step-pool (%)	100	92.9	75	64.3	75	50	100	100	100	100

ranges approximately between 0.03–0.069 and the estimation accuracy in this range is low (Fig.

11;Table 3). Although the value varied slightly depending on the surveyed time period and the location of each step-pool, $\tau_{*m} \approx 0.05–0.06$ was the boundary value whether the step-pool was destroyed or not in this study period. τ_{*m} was computed from the particle size and the river-channel geometry (width and gradient) measured at each step-pool, and the discharge at each step-pool was estimated from the discharge measured in the middle of the study site using a water level gauge. Because the cross section is irregular and the flow is non-uniform in the mountain stream, the accuracy of the discharge estimation at step-pools tends to be low. Therefore, the accuracy of the estimated τ_{*m} also tend to low. If the value of τ_{*m} is in the neighborhood of the boundary, even a trivial estimation error of τ_{*m} may result in an incorrect estimation of structural change and decrease the accuracy of the estimation of structural change of step-pools by the hydrodynamic method.

4. SUMMARY AND CONCLUSIONS

In this paper, changes in the number and structure of step-pools were investigated during a three-year period in a mountain stream after a debris flow event. The following results were obtained:

(1) In this river, remarkable changes in channel geomorphology ceased within a half-year after the debris flow event. Thus, the mean value of river-channel and step-pool geometries over each reach remained nearly constant during a three-year period, and the total number of step-pools did not change significantly.

(2) Most step-pools had been deformed, destructed, and reformed repeatedly during a three-year period.

(3) Stable step-pools that had not changed for three years existed at a 20–30 m interval. Therefore, the difference in elevation and the horizontal distance between them were kept constant. Particle sizes composing the step-pools in which the structure had been changed during a three-year period were almost the same. Step height tends to be approximately equal to particle sizes that compose steps. Therefore, the number of step-pools and mean step lengths between stable step-pools that had not changed for three years remained nearly constant.

(4) Temporal changes in the structure of step-pools were estimated using hydrodynamic equations based on the dynamic conditions proposed by *Ashida et al*. (1984) under which step-pools are formed. The estimated temporal changes in the structure of step-pools generally coincided with detected changes using photographs, although the number of stable step-pools tended to be overestimated by the hydrodynamic equations. It was assumed that the overestimation of the number of stable step-pools occurred mainly because of errors in the evaluation of critical tractive force on each particle composing the steps.

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