Chapter IV Observations of hydro-geomorphic processes

IV-1: Hydro-geomorphic properties of investigated watersheds

Intensive hydro-geomorphic observations were undertaken in a third-order basin (CL basin) and two first-order watersheds (C1 and C3) in the CL basin (Figure 11). CL basin has a drainage area of 0.128 km^2, and includes 19 observation sites for a manual discharge measurement (Figure 12). These observation sites are divided into spring sites and first-order stream sites, which are referred to as S and L in the end of each basin number, respectively (e.g. O31S and O31L for O31 basin). Since the positions of spring sites vary with time due to runoff conditions, two or more spring sites exist in a first-order basin (open circles in Figure 12). The altitude and drainage area of these sites are shown in Table 3. Location of each site was verified with an altitude meter. Drainage area was measured on the 1:25,000-topographic map with graphic software (Canvas 8).

Figure 13 shows the detailed topography of the two first-order watersheds (C1 and C3). This map is based on the measurement with a hand compass (Ushikata Syokai, Model S-27) and an electronic measure (Sonin, Pikkyori 75). Both north-facing watersheds adjoin one another. Observation was mainly conducted at the channel-head sites (C1L and C3U) located at points about 30 m downstream of the channel heads. Observation site C3L is located where the first-order channel joins a higher-order channel. Photos 4 and 5 indicate the landscape of the channel heads in C1 and C3 watersheds, respectively. The channel head of C1 watershed (C1H: 4,700 m^2, $\theta_c = 26°$) is classified as Type-G channel head with lower channel gradient and larger sources. The bedrock appears to be filled with sediment around the channel head (Photo 4). The channel head of C3 watershed (C3H: 810 m^2, θ_c =

38°) is classified as Type S, and has channel gradient steeper than C1 (Photo 5).

Table 4 shows hydro-geomorphic properties of each watershed. Local channel gradient was defined as the channel gradient between an observation site and the point 10 m upstream. Basin relief ratio is the maximum relative height within the basin divided by the long-axis length of the basin (Schumm, 1956). C1L site has a drainage area of 7,200 m^2, local channel gradient of 0.384, and relief ratio of 0.72. C3L site has a drainage area of 5,100 m^2, local channel gradient of 0.394, and relief ratio of 0.81. C3U site has a drainage area of 1,700 m^2, local-channel gradient of 0.758, and relief ratio of 1.03. Thus, C3 watershed has a larger relief ratio and smaller drainage area than C1 watershed.

Figure 14 shows the profile and regolith depth for a slope segment A – A' in C1 watershed (Figure 13). The slope profile was surveyed with the slope measuring devise described above. The depth of regolith was measured with a cone-penetrometer (Tsukuba Maruto, Co.; a cone diameter of 25 mm, a weight of 5 kg). The hardness of regolith was given by the Nc-value, which is the number of impacts required for a 10-cm penetration. The depth where the Nc-value firstly exceeds 30 is defined as the bedrock-regolith interface (Ohsaka *et al*., 1992). The average depth of regolith for 6 investigated sites was 1.3 m (Table 4). The regolith is poorly developed on the ridge (Figure 14). Ratio of bedrock outcrop (bedrock-outcrop area to total area) in C1 basin is only 5 % (Table 4), i.e., bedrock is partly exposed on ridge and channel (Figure 13).

In contrast, bedrock outcrops widely exist on ridge and channel in C3 watershed (Figure 13). Ratio of bedrock outcrop in C3 watershed (19 – 20 %, Table 4) is larger than that in C1, and many bedrock outcrops comprise steep cliffs. Rock fragments are accumulated at the base of bedrock cliffs, constituting a talus-like slope segment. Figure 15 shows the profile and regolith depth for a slope segment B – B’ (Figure 13). Regolith at the lower part of B – B’ has 1 – 2 m depth. Cone-penetrating tests showed a sharp boundary between regolith and bedrock. Bedrock is exposed at the middle point of this profile. The upper part of B – B’ is steep slope with the angle of 52°. Many bedrock outcrops exist around the upper part of this profile. Depth of regolith was investigated with a handy auger at the upper part of B – B’, where cone-penetrating tests could not be conducted. The investigation showed a shallow regolith of about 0.5 m.

Samples of regolith were collected from 1 m depth of CTR1 trench in C1 and at gully-wall G in C3 (Figure 13). Grain size distributions of these samples were analyzed with the method of JIS A 1204. Regolith at site G in C3 watershed mainly consisted of gravels (80 % in weight) and sand (17 %). Silt and clay accounted only 3 %. Median grain size of the gully-wall sample in C3 watershed (41 mm) is larger than that of the regolith sample in C1 watershed (2.0 mm).

IV-2: Spatial distribution of stream flow

IV-2-1: Methods

Discharge was measured at 19 sites in CL basin (Figure 12) manually with a vinyl bag, a bucket, a measuring cylinder and a timer. Observations were conducted in total nine times for various runoff conditions including seven cases of low flow (base flow) and two cases of high flow (storm flow). Discharge was measured in the low-flow condition on 19 January, 28 April, 21 May, June 29, 31 July, 20 August, and 26 September in 2002, and in the high-flow condition on 11 July and 2 October in 2002.

Figure 12 shows location of 19 observation sites, and Table 3 shows data on drainage area and altitude of these sites. Since spring sites in a first-order stream fluctuates with time in response to runoff conditions, all spring sites in each basin are numbered (e.g. O19S-1, O19S-2). Bedrock channels were selected for the observation sites to reduce the leakage of stream flow into channel bed. One observation time making the round of 19 sites required 2.0 – 3.7 hours. The arrows in Figure 12 indicate the route for observation in all cases except for the first observation on 19 January 2002.

Channel profiles in C1 and C3 watersheds, and five first-order basins (O19, O25, O27, O31, and O35) were surveyed from confluence to channel head with the slope measuring devise described above. Spring positions in these basins were mapped on the channel profiles in each observation.

IV-2-2: Results

Table 5 indicates antecedent precipitation and runoff condition in each observation of nine times. Antecedent precipitation index (API_{30}) is calculated with the following equation defined by Mosley (1979):

$$API_{30} = \sum_{i=1}^{30} \frac{P_i}{i} \qquad (3)$$

Here, P_i is the daily rainfall on the i-th day before the date of observation. Rainfall data at 'Kanuma' AMeDAS station of JMA were used for the calculation. Runoff conditions were classified in terms of API_{30} into three states: *base-flow condition in a dry season* (API_{30} < 10 mm: on 19 January and 28 April), *base-flow condition in a rainy season* (10 mm < API_{30} < 100 mm: on 21 May, 29 June, 31 July, 20 August and 26 September), *storm-flow condition* (API_{30} > 100 mm: on 11 July and

2 October). Successive rainfalls were observed just before the observation in the storm-flow condition. Total storm rainfalls at 'Kanuma' AMeDAS station on 11 July and 2 October were 250 mm and 111 mm, respectively.

Table 6 shows stream discharge at 19 sites with time for all cases. Figure 16 illustrates the spatial distribution of stream discharge for four cases including a case of base-flow condition in a dry season (19 January 2002: Figure 16a), a case of base-flow condition in a rainy season (29 June 2002: Figure 16b), and two cases of storm-flow condition (11 July and 2 October 2002: Figures 16c and 16d).

On the base-flow condition in the dry season (19 January 2002: Figure 16a and Table 6), small stream flows with 1 – 10 $\times 10^{-9}$ m s^{-1} (equivalent to 1 – 10 mL/s) were observed at only six first-order channels, and the rest were completely dried up. On the base-flow condition in the rainy season (29 June 2002: Figure 16b and Table 6), stream flows with 1 – 100 $\times 10^{-9}$ m s^{-1} (equivalent to 1 – 100 mL/s) were observed at 11 first-order channels, whereas five observation sites (O23L, O24S, O25L, O34S, and O37S) had no stream flow. On the storm-flow condition (11 July and 2 October 2002: Figures 16c and 16d, Table 6), stream discharge was observed at all observation sites. Discharge of 100 – 10,000 $\times 10^{-9}$ m s^{-1} (equivalent to 0.1 – 10 L/s) was 10 to 100 times larger than that on the base-flow condition.

Temporal variation in spring positions is quantitatively analyzed with the ephemeral channel length, which is defined as the distance from a spring to a channel head along a channel profile. If the first-order basin has no stream flow, then the ephemeral channel length is equal to the length of the first-order channel. Reduction in ephemeral channel length means that a spring approaches to a channel head. In turn, an increase in ephemeral channel length means that a spring locates away from a channel head.

Figure 17 shows channel profiles of seven first-order basins (C1, C3, O19, O25, O27, O31, and O35) with the location of channel heads, perennial springs, and variable ranges of ephemeral springs. Here, a perennial spring is the spring, which continues to drain water even in the dry season (19 January and 28 April 2002). The minimal distance from the perennial spring to the channel head was 20 m in seven first-order basins. No perennial springs and no stream flows were found in three first-order basins (O25, O27 and O35) in the base-flow conditions.

Figure 18 shows the temporal variation in ephemeral channel lengths in seven first-order basins. Although the pattern of temporal variation varies with basin, all of the seven first-order basins had the annual variation in ephemeral channel length. Ephemeral channel length increased to 20 – 100 m on base-flow condition in the dry season (19 January to 28 April), and decreased to 5 – 40 m on the base-flow condition in the rainy season (21 May to 26 September). Ephemeral channel length decreased to the minimum (0 – 25 m) during the largest storm (11 July). In four first-order basins (C3, O19, O25 and O31), ephemeral channel length decreased to zero, i.e., springs were generated at the channel heads.

IV-3: Rainfall-runoff response at channel heads

IV-3-1: Methods

Stream discharge was observed at two sites, C1L (Photo 6) and C3U (Photo 7), located immediately below channel heads, and C3L site (Photo 8) located the downstream of C3U site (Figure 13). The devices for discharge measurement were a 3-inch Parshall flume at C1L site, and 5-inch Parshall flumes at C3U and C3L sites. A capacitive water depth probe (U6521J, Unidata) was installed in each flume. A tipping-bucket rain gauge (#7852M, Davis Instruments) was also installed at 15 m north of C3L site (denoted by R in Figure 13). An auxiliary rain gauge was installed at 5 m south of C1L site (denoted by R' in Figure 13). Water depth probes and rainfall gauges were connected with data loggers (Owl2c, EME systems), which records at intervals of 5 min in the year 2000 and 10 min after 2001. Table 7 shows the observation periods. Since rainfall and discharge cannot be precisely measured in winter because of freezing, stream discharge was observed only in rainy season (June to October). The rainfall events in winter are small in both frequency and magnitude. Data at C3U site include lacks caused by instrumental troubles.

The discharge Q and water level H at the flumes was directly measured in 5 – 15 times to obtain a regression curve, which coverts the water level to the discharge. The general form of the regression curve is shown by:

$$Q = \alpha_q H^{\beta q} \quad (4)$$

The constant 'β_q' is 1.55 for 3-inch and 5-inch Parshall flumes (JSCE, 1971). The constants 'α_q' were determined on regression analyses with the dataset of direct measurement of discharge. In the case that the unit of Q is litter per second and that of H is centimeter, the constants 'α_q' are calculated to be $\alpha_q = 0.1954$ (for C1 site), $\alpha_q = 0.329$ (for C3U site), and $\alpha_q = 0.2246$ (for C3L site).

IV-3-2: Results

Figure 19 shows hydro-hyetographs of four rainfall-runoff events at two channel-head sites (C1L and C3U). Three runoff events (Events B, C and D) were caused by typhoons.

A small event on 29 June 2001 (Event A, Figure 19) had the total rainfall of 53.0 mm and maximum 1-hour rainfall of 25.0 mm. Here, the maximum 1-hour rainfall is calculated based on rainfall data at intervals of 10 min. Since Figure 19 shows the rainfall data calculated every on the hour, the maximum of rainfall in Figure 19 is not equivalent to the maximum 1-hour rainfall described above. This storm included two sharp rainfall peaks (peaks 1 and 2 of Event A in Figure 19). At C3U site, stream flow did not respond to the rainfall peak 1, whereas a large runoff peak responded to the rainfall peak 2. At C1L site, runoff peaks responded to both of rainfall peaks 1 and 2. Peak specific discharge at C3U site (1.0×10^{-6} m s^{-1}) is twice as large as that at C1L site (0.46×10^{-6} m s^{-1}).

A large event was observed from 9 to 11 September 2001 (Event B, Figure 19). This event had total rainfall of 234.0 mm and maximum 1-hour rainfall of 24.4 mm. Although the total rainfall of Event B was larger than that of Event A, the rainfall intensities of Events A and B were almost the same. Stream discharge increased on 10 September while rainfall started from 9 September. Stream discharge responded to three rainfall peaks from the afternoon of 10 September to the morning of 11 September (peaks 1, 2, and 3 of Event B in Figure 19). The lag time from the rainfall peak 3 (Figure 19) to the maximum runoff peak at C3U (20 min) was smaller than that at C1L (130 min). Discharge at C3U rapidly reduced after rainfall intensity decreased less than 5 mm h^{-1}. While the recession of discharge at C1L was slower than that at C3U, the discharge at C1L rapidly declined to the level of base flow in the afternoon of 12 September.

A larger runoff event was observed from 9 to 11 July 2002 (Event C, Figure 19). A typhoon passed around the investigated area and brought total rainfall of 250.2

mm and maximum 1-hour rainfall of 31.0 mm. The first intensive rainfall peak caused by a thunderstorm did not affect the runoff at both sites. Discharge increased from 10 July, and the maximum discharge at C3U (9.5×10^{-6} m s^{-1}) for three years (2000 – 2002) was observed on 11 July. The peak specific discharge at C3U (9.5×10^{-6} m s^{-1}) was larger than that at C1L (5.7×10^{-6} m s^{-1}). Characteristics of runoff response such as lag time were almost the same as Events A and B.

A storm event on 1 October 2002 (Event D, Figure 19) had total rainfall of 151.6 mm and maximum 1-hour rainfall of 44.0 mm. Peak specific discharge at C1L (4.1×10^{-6} m s^{-1}) was almost equal to that at C3U (5.4×10^{-6} m s^{-1}). The total rainfall of this event was smaller than that of Event B, while peak specific discharges at both sites were larger than those of Event B. Since the maximum 1-hour rainfall of this event was largest among the four events (Events A – D), rainfall intensity should affect the larger peak specific discharge of Event D. Lag time and the recession of runoff response were similar to those of Events A – C.

The largest maximum 1-hour rainfall for three years (2000 – 2002) was 72.0 mm on 26 August 2001. However, precise runoff responses at C3U and C3L sites were not available, because debris was captured by these flumes in response to several large rainfall events from 5 August to 1 September. The bedload transport from 5 August to 1 September will be discussed in the section IV-5-2.

IV-4: Pressure head of subsurface water in a slope segment

IV-4-1: Methods

Pressure head of subsurface water in the slope segment B – B' beside C3U site (Figure 13) was automatically monitored with the tensiometers, which have pressure transducers (RSUxx, Irrometer Company Inc). Figure 15 shows the profile and the structure of regolith for the slope segment B – B'. As described in the section IV-1, a bedrock outcrop is located at the middle part of this slope segment. The upper part consists of very steep slope with an angle of 52°, while the lower part also has a steep angle of 41°. At the foot of this slope segment, outflow of subsurface water from a soil pipe was frequently observed in the storm flow.

Four nests of tensiometers (B02, B08, B13 and B22) were installed along the slope segment B – B' (Figure 13). Number of site (02 of B02) indicates the distance along the slope profile in meter from the foot of B – B': B02, B08, B13 and B22 are located 2 m, 8 m, 13 m, and 22 m upslope from the foot, respectively. At B02, tensiometers were installed at depths of 30, 45, and 70 cm. At B08, installation depths were 30, 65, and 95 cm. At B13, installation depths were 15 and 30 cm. At B22, installation depths were 25 and 45 cm. Data loggers recorded the pressure-head values at intervals of 20 min. Tensiometric measurements were started on 9 June 2001. The observation periods are shown in Table 7. Pressure heads could not be measured in winter because of freezing.

IV-4-2: Results

Figure 20a illustrates the temporal change in pressure-head distribution on the slope profile of B – B' in Event A (29 June 2001). Hydrograph of this event was shown in Figure 19. Pressure-head distributions were shown for three stages: (1) before the rain, (2) at the rainfall peak and (3) seven hours after the rain stopped. While no groundwater table was observed before the rainfall event (1), positive pressure heads and a groundwater table appeared on the bedrock-regolith boundary at the rainfall peak (2). Pressure heads at the bedrock-regolith boundary of B02 and B08 sites increased up to +30.2 cmH_2O. However, pressure heads decreased seven hours after the rainfall stopped. The temporary groundwater table disappeared 14 hours after the rainfall stopped.

Figures 20b and 20c illustrate the temporal changes of pressure-head distribution in more intensive storms of Event B (9 September 2001) and Event C (9 July 2002) for three stages: (1) before the rain, (2) at the rainfall peak and (3) immediately after the rain stopped. The runoff responses to these storm events were described in the section IV-3 (see Figure 19). The data were not available at 30 cm of B02 in Event B, at 30 cm of B08 in Event B, and at B22 in Event C because of instrumental troubles. At the rainfall peak (2) in both Events B and C, pressure heads on the bedrock-regolith boundary turned to the positive value, and groundwater table appeared in the regolith. At 3:00 on 11 September in Event B, pressure head on the bedrock-regolith boundary at B02 increased up to +46.5 cmH_2O. The groundwater table in Event B disappeared 25 hours after the rainfall ceased. Immediately after the rainfall peak (2:40 on 11 July 2002) of Event C, pressure head on the bedrock-regolith boundary at B02 increased up to +56.7 cmH_2O, and recorded the maximum over three years (2000 – 2002). The groundwater table in Event C disappeared 20 hours after the rain ceased.

IV-5: Bedload transport and rockfall

IV-5-1: Methods

Bedload transport was measured at two channel-head sites (C1L and C3U, Figure 13) and one downstream site (C3L, Figure 13) from 11 June 2000 to 4 May 2003 (Table 7). At C1L site, a plastic container was installed at the point 3 m downstream of the flume (Photo 6). At C3U and C3L sites, wire nets with mesh of 1 cm were used as bedload traps (Photos 7 and 8), because channel slope is very steep (> 35°) and most of the channel sediment consists of gravel without fine-grained particles. The nets were fixed with small anchor bolts on bedrock channels, and were also fixed to tree trunks with wires. This reinforcement of the traps gives the resistance to the debris accumulation with about weight of 100 kg. The net-type traps were installed at the points 5 – 10 m downstream of the flumes.

Rockfall was observed with rockfall traps installed at the base of a small bedrock cliff (R-1) and steep slopes (R-2) in C3 watershed (see Figure 13 for the location). A rockfall trap consists of a vinyl sheet (3.6 × 5.4 m) fixed to tree trunks with ropes (Photo 9). Rockfall observation was started on 29 January 2000.

Trapped bedload or rockfall sediment was collected every month in principle. Bedload was also collected immediately after large storm events. Intervals for sample collection were prolonged up to two months in winter. Leaves, twigs and woody debris were removed from samples as far as possible. All bedload samples at C1 site were weighed with an electric balance in a laboratory after they were dried in an oven at 110 °C for 24 h. The weight of rockfall and bedload at C3L and C3U sites was measured with an electric balance without oven drying. The heavy samples, which exceed 2 kg in weight, were weighed in situ with a spring balance. Since the water contents of gravels are small enough to be negligible, no revisions of water contents were made in gravelly samples at C3U and C3L.

IV-5-2: Results of bedload observation

Figure 21 shows bedload yield in all observation periods from 11 June 2000 to 8 February 2003. All observation periods in each year are marked with letters (A-O), since the interval of each observation period was not the same. Figure 22 shows the temporal change in cumulative transported bedload from 11 July 2000.

Events of bedload transport mainly occurred in rainy seasons from May to October (Figures 21 and 22). The largest event of bedload transport at C3U and C3L occurred from 5 August to 1 September 2001 (Period I in Figure 21b). Three large rainfall events were observed during this period (an event on 10 August, total rainfall, R_{total} = 91.0 mm, maximum 1-hour rainfall, R_1 = 58.6 mm; an event on 21 August, R_{total} = 131.2 mm, R_1 = 23.0 mm; and an event on 26 August, R_{total} = 99.8 mm, R_1 = 72.0 mm). Bedload traps at C3U and C3L sites were torn by debris (Photo 10), and consequently the bedload yield could not be precisely verified in the period I. The large amount of debris including bedload and woody debris was also captured on the flumes of C3U and C3L sites (Photo 11). Bedload captured by trap and flume at C3U site was over 200 kg. Based on the volume and density of captured debris at C3L flume, bedload yield at C3L was estimated to be over 500 kg. However, bedload yield at C1L was only 1.1 kg in the same period.

The second largest event of bedload transport was observed from 6 to 13 July 2002 (Period H in Figure 21c). Single rainfall event in this period had the largest total rainfall (250.2 mm, Event C of Figure 19) for three years (2000 – 2002). Bedload yield at C1L was 7.9 kg, and marked the maximum for three years. Although large bedload yields were simultaneously observed at C3U (6.8 kg) and C3L (71.4 kg), they were smaller than those of Period I in 2001 (5 August to 1 September 2001, Figure 21b).

Table 8 shows total bedload yield, Y_t, and the average annual bedload yield per unit area, Y_a/A. Among the three sites, C3L recorded the largest Y_t (> 647.1 kg), and C1L recorded the smallest (14.2 kg). The largest annual bedload yield per unit area was observed at C3U (> 0.0585 kg m^{-2} y^{-1}) and the smallest was observed at C1L (0.0007 kg m^{-2} y^{-1}, Table 8).

Rock fragments were occasionally trapped into the bedload trap at C3U in the winter, when intensive rainfalls were rarely observed. An example of sediment yield in winter is Period O in Figure 21a (26 November 2000 to 4 February 2001). Total amount of sediment yield in winter, Y_w, is shown in Table 8 for each season. Here, a period of winter is defined as the period when stream-flow observation was suspended (see Table 7). Sediment yields in winter at C3U were 23.2 kg in 2000 – 2001, 0.4 kg in 2001 – 2002, and 53.4 kg in 2002 – 2003. Sediment yield in winter at C3U for three years accounted for < 26% of the total bedload yield at C3U. Sediment yields in winter in years 2001 and 2003 were larger than that in year 2002. Trapped sediment in winter seems to have been caused by rockfall. The basis for this idea is discussed in the next section.

IV-5-3: Results of rockfall observation

Figure 23 shows the seasonal change in rockfall amount at R-1 and R-2 sites in C3 watershed. Most of the rockfalls in the summer of 2000 were caused by tree falls from a bedrock cliff above R-1 site probably due to the strong winds during a typhoon. Except for this event, rockfall activity was negligible during summer. Rockfalls with the amount of 3 – 5 kg were observed in the winter of 2000, 2001 and 2003. Freeze-thaw action probably caused the rockfall in winter, since the daily minimum temperature from December to March fell frequently below 0 °C.

Figure 24 shows the annual changes in rockfall amount in winter and meteorological data at the ‘Utsunomiya’ observatory, JMA. Although ‘Utsunomiya’ observatory is located 20 km northeast of the investigated area, meteorological conditions at 'Utsunomiya' are assumed to represent the investigated area. Figure 24a shows relationship between the rockfall amount and average temperature from January to February. Data from 2001 to 2003 indicate that the amount of rockfall increases with the decrease in average temperature. However, the winter of 2000 with a warm climate (average temperature 2 °C) had the larger amount of rockfall (5 kg).

Figure 24b compares the annual changes in winter rockfall with the number of snowy day from December to March. Here, a snowy day is defined as a day, with snow on the ground surface. A day, in which the snow fallen on a previous day still remains on the ground surface, is also counted as a snowy day. Thus, the snowy day does not always indicate a day with snowfall. Figure 24b clearly indicates that the rockfall amount increase with the number of snowy day. Snow supplies water through melting on the ridge, which is usually dry in winter. If the supplied water facilitates the development of ice in bedrock fractures, the rockfall amount may increase. Less snow as well as warmer climate in the winter of 2002 would weaken the rockfall activity.

The annual changes in sediment yield in winter Y_w at C3U is compared with the amount of rockfall in winter at R-1 and R-2 sites (Figure 25). Rockfall in the winter of 2000 were not included here, because the bedload observation started in June 2000. Figure 25 indicates that the sediment yield in winter at C3U reflects the rockfall amount. This consistency implies that the trapped sediment in winter mostly originated from the rockfall generated on slopes or bedrock cliffs. Since rainfall in winter was rare during the observation period (2000 – 2003), bedload transport in storm runoff did not contribute to the sediment yield at C3U in winter. Furthermore, in the spring of 2003, a small scar of rockfall was found immediately upslope of C3U site. This rockfall would contribute to sediment yield in the winter of 2003 at C3U site (53.4 kg).