A Hydrogeological Study for the Hiroshima August 2014 Disaster

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Abstract

Hydrogeological study has been carried out to unravel the main factor of the Hiroshima August 2014 disaster at Asa district, Hiroshima city, caused by sudden heavy rain. The study was done using topographic analysis, measuring the drought specific discharge, searching for the points of spring water and its volume, and observations of the rainfall runoff response. Along with the geologic structure and topographic features, the drought specific discharge, which is closely related to the amount of base flow is assessed to reveal the main factor of the disaster.

Since it is difficult to forecast disasters caused by heavy rainfall even with the most advanced technology, it is necessary to improve disaster prevention, especially at locations prone to slope failure and collapse. This requires extensive geological surveys and careful investigation of hydrogeological conditions, particularly the measurement of base flow in mountainous regions during the drought season.

Keywords: hydrogeology, weathering, drought specific discharge, water budget, storage-ability.

1. Introduction

On 19 and 20 August 2014, a local heavy rain was recorded in the Asa district of Hiroshima city with a one-day precipitation of 535.4mm that included a concentration of 217.5mm over a three-hour period in 20th August midnight. The heavy rain caused great and serious damage in the Asa district, especially in Yagi area, where the disaster related to debris flow affected hundreds of houses, 74 people died and 44 persons were injured. The mountain range (500m～600m msl.) strikes NE-SW direction in the Asa district and several tens of steep and narrow mountain streams are flowing from north to south or northwest to southeast directions in this district.

The present authors carried out hydrogeological studies in between October 2014 and March 2015 (20 working days total) and measured the discharge during the drought season in November at the affected Asa district in order to determine what factors triggered the disaster and to assess the probability of similar events in the future.

2. Study area

The hydrogeological studies and measurements of discharges were done at the southeastern side of the mountain range stretching NE-SW direction from Mt. Gongen-yama (397m msl.) to Watashi-ba in this district (Fig.1). The study area is divided into 16 basin blocks (Divides), where the disaster mainly occurred. While doing so we focused our concentration on the two areas namely, Midori-i area (No.4 to No.6 divides) and adjoining Yagi area (No.7 to No.11 divides) to compare the hydrogeological characteristics and water balance of divides in each discharge basin. Debris flow did not occur in the former area, while the latter was severely affected. Depending on the data, we would like to propose a disaster prevention plan and also a plan suggesting the ways of study and examination for the sudden disasters in future.

3. Hydrogeology

(1) Topography

The study area is situated in the southern end of the foothill of Chugoku mountain range, which extends to NE-SW direction. The mean height of the mountain around Midori-i area (No.4-No.6) is about 300-400m (msl) and that of Yagi area (No.7-No.11) is 500-600m (msl). The elevation differences from the start to the end of mountain streams are about 300 and 500m, respectively. The mean inclination of the stream is 1/4～1/6 for the former, while that is 1/2～1/3 for the latter. Though the width of the river valley in Midori-i area is about 40m, watercourse is only several ten centimeters to 1m wide. Thus the valley is a U-shaped and the mountain is having gentle and stable slope. The terraced paddy fields are predominant in this valley and it is continued from the end of the

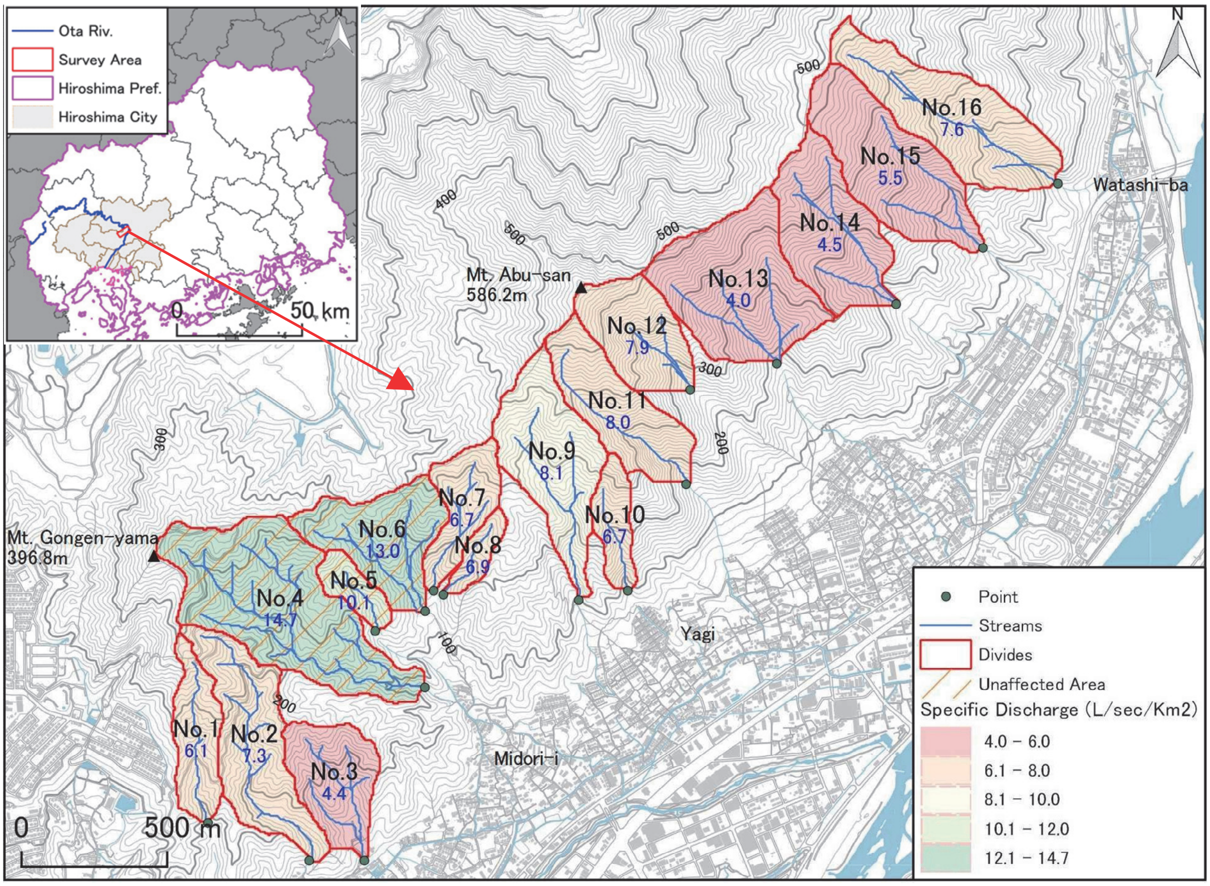

Fig.1 Study area, sixteen divides and specific discharge values

stream to the head. While in the Yagi area, width of the valley is nearly same as that in the Midori-i zone, but the watercourse shows 1-2m in width. The valley of Yagi area is V-shaped and streams are flowing on steep surface with many small and short falls. Weathered soil, over 10m in thickness covers the top of the valley walls. Alluvial cones are formed at the river mouth everywhere in the studied divides.

(2) Geology

Granitoid is distributed around the divides No.1 ～No10, while the sedimentary rocks (changed to hornfels by contact metamorphism of granite) are mainly occupied in the middle to upstream in the divides No.11～No.16 area as roof pendant in this district. The thick colluvial soils cover the valley walls from top to bottom in every divide, except in the No.9 divide, which is covered by remarkably thicker colluvial soils. Granitoid (mainly consist of hornblende bearing biotite granodiorite) is solid and hard, and comparatively fresh. The weathering effects increase with height, but in a minor way. The weathering effects are broader and extend more deeply in the granitoid of Midori-i area (No.4 divide, Photo.1) than in Yagi-sawa area (No.9 divide, Photo.2).

So-called Masa is not observed in this district except around the top of Mt. Gongen-yama and along its ridge line. A few but comparatively large quartz-porphyry dykes trending NW-SE are intruded into the boundary between granitoid and sedimentary rocks (divides No.10 and No.11). No fault or sheared zones are observed in the granitoid area (divides No.1-No.10). The characteristics of the joint system and cracks (Photos 1 and 2) are different between the valley less-affected (divide No.4) and that severely affected (divide No.9) by debris flow calamity. In divide No.4, which was less-affected, showed a sporadic occurrence of joints and cracks in the field, but the joint system is large compared to other divides and degrees of adhesion is not good. Therefore we concluded that divide No.4 shows both high permeability and high discharge. On the other hand in divide No.9, though the three dimensional and small scale joints systems are comparatively well-developed, they are stuck firmly to each other. So the impermeable bed is forming in this divide.

4. Characteristics of the slope failure and hydro-geologic structures

(1) Yagi area (divides No.7～No.11)

Generally, two-types of collapses are observed in divides No.7 to No.11 in the Asa area. One was along the mountain slope (5 sites), where we observed debris with 1m to 1.5m in thickness and nearly 500m^3 of colluvial soils on the valley walls at a height of 30 to 50m from the river bed. The other was at the upstream head of the rivers (eleven sites; nine in granitoid area

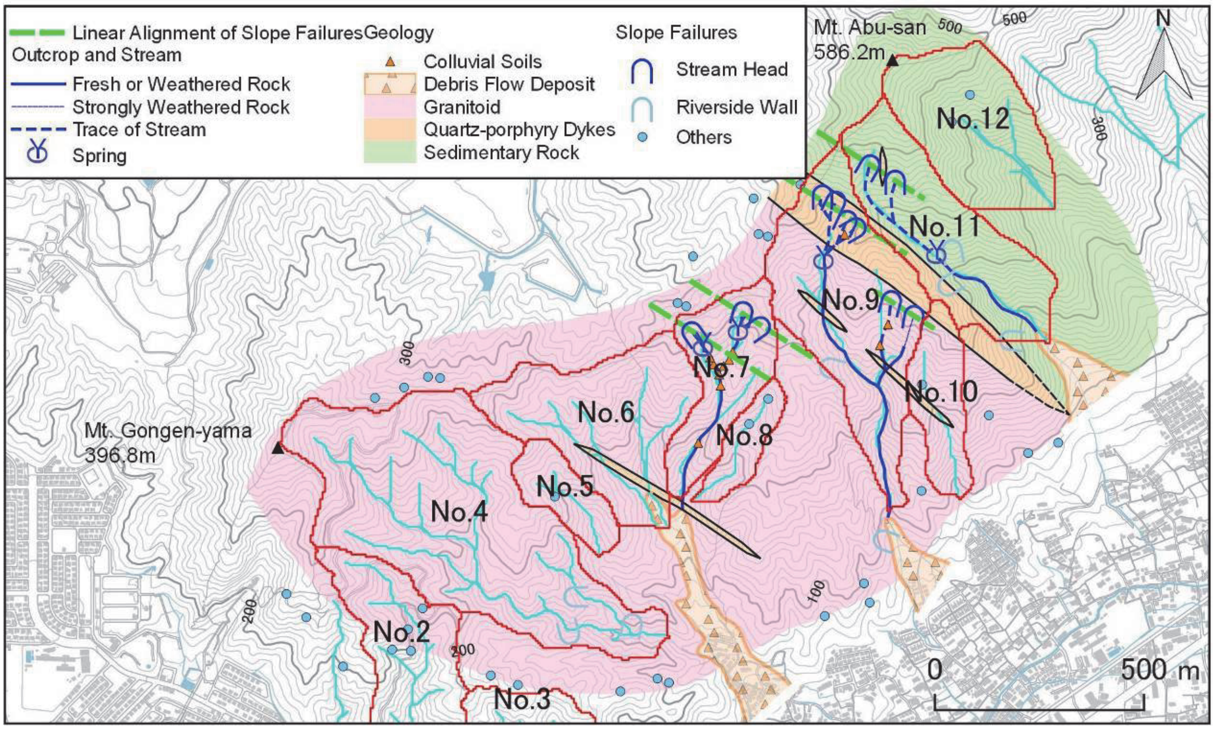

Fig.2 Geology of divides No.2 to No.12

and two in sedimentary rock area), where the collapse occurred at the southwest side of the mountain slope. However, the amounts of debris in the latter case are comparatively small (1m to 3m thick) and show only about 200 to 800m^3 colluvial soils (Fig.2).

In divide No.9, four occurrences of collapse in the vicinity of the river head (375m to 480m msl.) of Yagi-sawa. The slope failure (1.5m to 3m in thickness of surface soil) occurred along the deteriorated and softened cracks in bed rock caused by weathering, where colluvial soils and severely weathered part of host rocks collapsed in to shallow hollows on the slope. Those four sites extend NW-SE and are possibly controlled by geotectonic movement. Along the left tributary of Yagi-sawa, two places of slope failures were occurred at 270m to 260m (msl.). Both cases occurred at the outcrops of deteriorated granitoid and at a surface moistened by spring water.

(2) Midori-i area (divides No.4-No.6)

In Midori-i area, we observed only three occurrences of collapse in the downstream area, but the proportions are comparatively small.

5. Characteristics of the water budget in the study area

The debris flow disasters occurred at all the above- mentioned divides except No.4 to No.6 (Fig.1).

Hydrological indices in 16 drainage areas are as follows (Table 1). Catchment area ranges between 0.03 ～0.29km^2, while the coefficient of catchment shape with 0.14～1.06 showing comparatively slender form.

The river density is between 0.006 and 0.013, irrespective of the area affected and un-affected by debris flow. It is to be noted that the mean river inclination is 0.38 at Yagi-sawa (divides No.7 to No.10), the debris flow affected area. In comparison,

Photo.1 Strongly-weathered granitoid in divide No.4

Photo.2 Characteristics of joint system and cracks in divide No.9

Table 1 Topographic and hydrological indices of watershed in debris flow affected and unaffected area

Divides No.	Bed rock	Occur or not of debris flow	Area of divides A [km²]	Length of the river (stream) L [m]	Mean width of the divide 2R=A/L [m]	(2R/L)	Relative height of the river H [m]	Mean inclination of river floor H/L	Total Length of the Stream ΣLn [m]	Drainage density ΣLn/A [1/m]	Number of the Drainage ΣN	Drainage frequency ΣN/A [1/m²]
No.1	Granitoid	Occur	0.079	621	127	0.20	185	0.30	643	0.0082	3	3.8E-05
No.2			0.166	1,080	154	0.14	235	0.22	1,582	0.0095	15	9.0E-05
No.3			0.105	507	208	0.41	129	0.26	1,129	0.0107	9	8.5E-05
No.4		not	0.288	1,150	250	0.22	268	0.23	3,169	0.0110	27	9.4E-05
No.5			0.034	266	129	0.49	87	0.33	317	0.0092	3	8.7E-05
No.6			0.133	505	264	0.52	161	0.32	1,487	0.0111	10	7.5E-05
No.7		Occur	0.075	507	148	0.29	172	0.34	811	0.0108	7	9.3E-05
No.8			0.026	333	77	0.23	114	0.34	333	0.0130	1	3.9E-05
No.9			0.165	765	216	0.28	263	0.34	1,176	0.0071	7	4.2E-05
No.10			0.048	387	124	0.32	185	0.48	387	0.0081	1	2.1E-05
No.11	Sedimentary rocks	Occur	0.130	712	183	0.26	337	0.47	712	0.0055	1	7.7E-06
No.12			0.110	322	342	1.06	169	0.52	731	0.0066	9	8.2E-05
No.13			0.215	481	446	0.93	256	0.53	1,284	0.0060	7	3.3E-05
No.14			0.162	613	264	0.43	302	0.49	1,399	0.0087	6	3.7E-05
No.15			0.184	631	292	0.46	266	0.42	1,019	0.0055	5	2.7E-05
No.16			0.194	868	224	0.26	412	0.47	1,327	0.0068	11	5.7E-05

at Midori-i area not affected by debris flow the inclination is 0.29 (divides No.4 to No.6), as shown in Table 1. Based on this data, we examined hydro-geological factors such as the mechanisms of rainfall penetration, runoff and discharge during the drought season in the Asa district.

(1) Characteristics of drought specific discharge in the Asa district

Measurements for all divides were done in January 11, 2015 and the results of both discharge and drought specific discharge are shown in Table 2 and Fig.1. As shown in Table 2, the mean discharge and its volume at granitoid dominant Yagi area (No.7 to No.10, debris flow affected area) are showing to 7.1 ℓ/sec/km² and 0.61mm/d. On the other hand, discharge and its volume of debris flow un- affected area, especially divide No.4 yield values of 14.7 ℓ/sec/km² and 1.27mm/d. This is a remarkable difference in discharge and volume between these two areas. Especially No.4 to No.6 (12.6ℓ/sec/km² and 1.09mm/d. in mean value) divides are showing twice values in compared to the mean values of all but three of the 13 divides (0.51mm/d.), where the debris flow had un-affected. This implies that occurrence of debris flow is related to the drought specific discharges. In compared to drought discharge in divide No.4 and No.9, discharge of the former is constantly increase by the downstream, while the latter do not increase (Fig.3).

The base flow in the drought season represents the groundwater discharges from basins and is indicative of permeability and/or storage-ability. In heavy rain conditions, the storage-ability in the Yagi area shows very low values (0.58～0.70mm/d.) and was affected by debris flow. However, the Midori-i area, which was not affected by debris flow, shows considerably higher values (0.87～1.27mm/d.). Hence, it implies that the recharge-ability of the base rock in the Yagi area is comparatively small than that of non-debris flow the Midori-i area.

Collating all these data it seems that the occurrence of debris flow depends on the difference of permeability or storage-ability of the geological basement body of the mountains.

(2) Comparison of water budget for both divides No.4 and No.9

Analysis using the tank model method is carried out to verify the river regime and to compare the

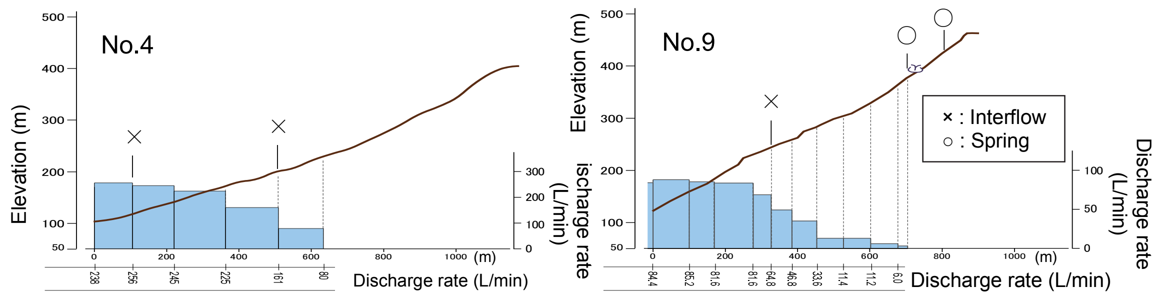

Fig.3 Topographic characteristics of the watershed in debris flow affected and un-affected areas

Table 2 Measurement of discharge

Divides No.	Bed rock	Occur or not of debris flow	Area of divides A [km^2]	Discharge Q [L/min]	Water temperature Tw [℃]	Electric conductivity EC [μS/cm]	Specific discharge Q/A [L/sec/km^2]	[mm/day]
No.1	Granitoid	Occur	0.079	28.8	7.0	68	6.1	0.53
No.2			0.166	73.2	7.7	79	7.3	0.63
No.3			0.105	27.6	9.4	54	4.4	0.38
No.4		not	0.288	253.2	6.8	73	14.7	1.27
No.5			0.034	20.9	6.2	69	10.1	0.87
No.6			0.133	104.2	7.5	63	13.0	1.12
No.7		Occur	0.075	30.0	7.5	64	6.7	0.58
No.8			0.026	10.6	8.5	65	6.9	0.59
No.9			0.165	80.4	10.5	61	8.1	0.70
No.10			0.048	19.2	7.8	63	6.7	0.58
No.11	Sedimentary rocks	Occur	0.130	62.4	6.3	73	8.0	0.69
No.12			0.110	52.2	7.3	69	7.9	0.68
No.13			0.215	51.6	9.7	88	4.0	0.35
No.14			0.162	43.8	8.8	65	4.5	0.39
No.15			0.184	60.6	5.9	77	5.5	0.47
No.16			0.194	88.8	5.0	73	7.6	0.66
Total			2.114	1,007.5			121.5	10.5
Occur of debris flow (Granitoid)			0.664	269.8			6.8	0.59
Not occur of debris flow (Granitoid)			0.456	378.3			13.8	1.20
Occur of debris flow (Sedimentary rocks)			0.994	359.4			6.0	0.52

characteristics of the water budget in the two basins No.4 and No.9. Ten measurements of discharge are done from October 2014 to January 2015. The hydrographs represent precipitation per day in Hiroshima city and discharges in two studied basins (Fig.4).

Precipitation data at Hiroshima city is used due to non-availability of precipitation data from Yagi area. Therefore, the correct discharge of debris flow occurred has not been reproduced in the figure.

However, as shown in Fig.4, discharge in No.9 divide shows a distinct high in comparison to that in No.4 divide. Hence, it can be intuitively estimated that non-precipitation continued at No.9 is continued, the discharges would have been decreased.

According to the calculated budget in a year based on reproduced discharges, the volumes of surface runoff Qs in No.9 and No.4 divides are approximately 872mm/y. and 392mm/y., respectively, and hence the former is obviously showing high values in compared to the latter.

Trial calculation based on peak discharge (240mm/d., August 20th 2014 by the Meteorological Agency of Japan) in a day are carried out for both debris flow affected divides and un-affected divides. There is clear difference in the runoff between No.9 and No.4 divides as the discharge at the time of debris flow is estimated as 155mm/d. in the former and 77mm/d. in the latter.

Actual precipitation was over 200mm/3h. indicating that the debris flow occurred instantly at areas with less permeability and storage-ability along

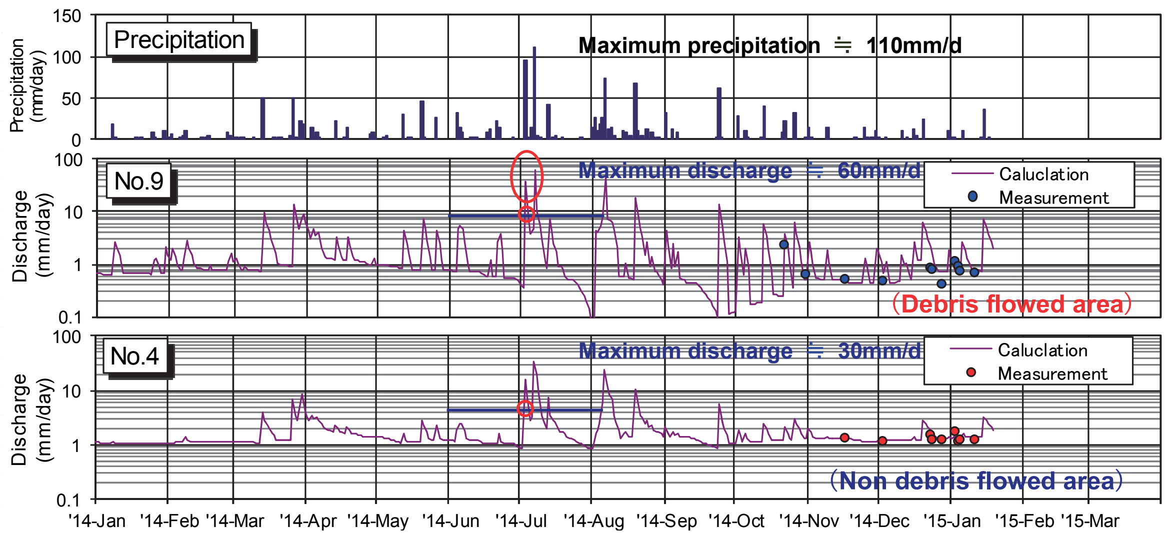

Fig.4 Discharge hydrographs for both debris flow affected divide (No.9) and un-affected divide (No.4)

with huge runoff by the oversaturated groundwater on the surface in basement rock body.

6. Conclusion

Characteristics of the Hiroshima August 2014 disaster can be summarized as follows. The studied divides in the Yagi area, especially in divide No.9 formed as impermeable body due to the topographical conditions, viz., formation of V-shaped valley, steep inclination of river floor helping the stream flow in non-stagnation on the river floor, as well as geological conditions viz., lack of open cracks, shear zone, impermeable geological layer in the studied hard, massive granitoid with cracks being firmly closed and thick colluvial sediments on valley walls. We conclude that the abnormally heavy rain could not penetrate the granitoid mass, thus causing the water to rise and to flow down the steep river floor at tremendous speed while eroding out unstable soil on the valley walls. Thus, the debris flow occurred as an eventual outcome (Fig.5). These facts are supported by the measurement of drought specific discharge which is not increased in the impermeable body distributing area in the valley.

On the other hand, at divide No.4 in the Midori-i area with minimal damage the topographical factors pointed that gradual inclination of river floor, gentle mountain ridge and slope forming U-shaped valley with stable slope of thick weathering products in this area. While, altered clay or seams along the shear in granitoid mass can be seen, joint system or cracks are frequently open, many spring-out points are observed at places of mountain slopes. We conclude that this area can easily store water following a sudden heavy rain on the mountain and so no debris flow occurred in this area. This is also supported by the data result on drought specific discharge in this area.

It is recognized that the drought specific discharges are quite different between debris flow affected and un-affected areas by measuring of runoff. The debris flow occurred at less permeable and less storage-able area, in other words, it occurred at high discharge area during heavy rains. Specifically, difference of storage-ability of the mountain has a great influence on the occurrence of debris flow. This fact is demonstrated by the hydrogeological study and/or land use as in divide No.4.

7. Future study plan for disaster prevention

While we can assume that there will be an increase in disasters from debris flow due to sudden heavy rainfall, it is difficult to predict when and where the disasters will occur. It is advisable to define the potential sites according to the vulnerability of debris flow-related disasters. There is a great need for further studies on topography, hydrogeology and hydrology, especially the measurement of specific discharges during drought seasons. Thus, it will be easy to build up the disaster prevention plan, facility, proportions and arrangements of measures at the selected local places based on hydrogeological study, particularly, careful measurements of base flow in drought season are needed on a wider area.

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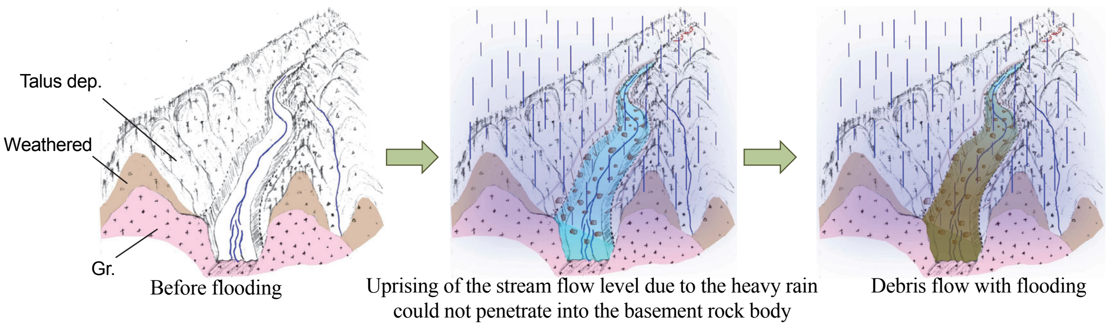

Fig.5 The illustration showing the flooding processes in Yagi-sawa area (Divide No.9)