On the Characteristics of the Slopes with Shallow Landslides Being Triggered by Typhoon Talas, 2011 in the Nachigawa River Basin, Japan

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In September 2011, many landslides occurred in the town of Nachikatsuura, Wakayama Prefecture, in an area in which alternation of sandstone and mudstone (sedimentary rock of Kumano Group) and granite porphyry (Kumano acid igneous rock) are located. We carried out surveys that focused on the topography, geology and hydrology to investigate the mechanisms of landslide in the area. Many landslides occurred around the geological boundary of alternation of sandstone and mudstone and granite porphyry. Additionally, many soil pipes were distributed on the landslide surfaces. The groundwater in the granite porphyry were more sensitively to variations of rainfall than that in alternation of sandstone and mudstone. In this area, comprised of different geological compositions, groundwater levels increased rapidly during heavy rainfall along the boundary of the two layers, which we interpret as a large amount of groundwater in granite porphyry. Then subsequent landslide occurred as a result of a rapid increase in pore pressure in the soil.

Key words: Large-scale landslide, alternation of sandstone and mudstone (sedimentary rock of Kumano Group), granite porphyry (Kumano acid igneous rock), geological boundary, groundwater level.

1. INTRODUCTION

In August 2011, Typhoon Talas arose in the Mariana Islands. The typhoon moved slowly northwards and struck the Kii Peninsula of Japan. One area seriously affected by the typhoon was Wakayama Prefecture, part of the Kii Peninsula. In the Nachigawa River basin, located in Wakayama Prefecture, the Ichinono rain gauge (Wakayama Prefecture**, Fig. 2**) recorded 872-mm cumulative rainfall and 123-mm maximum rainfall per hour between August 31 and September 5. Additionally, the Irokawa rain gauge (Japan Meteorological Agency, near the Nachigawa River basin) recorded 1180.5-mm cumulative rainfall, and 50-mm maximum rainfall per hour over the same time period (**Fig. 1**). This heavy rain induced many landslides and led to debris flow from eight mountain streams. As a result, 29 people were killed and around 2400 buildings were damaged, including the UNESCO World Heritage Site Kumano Nachi-Taisha Shrine, [*Association of the Bereaved of the Nachi Valley Flood*, 2012; *Kinoshita et al.*, 2012].

In Japan, many landslide events have occurred and, hence, many studies have focused on such events. There already exist several methods of risk assessment that employ various parameters [*e.g.*, *Akiyama et al.*, 2011; *Hiramatsu et al.*, 2011; *Uchida et al.*, 2009]. The geology of the town of Nachikatuura can be divided primarily into alternation of sandstone and mudstone (sedimentary rock of Kumano Group) and granite porphyry (Kumano acid igneous rock). To prevent or reduce such serious damage, it is critical to understand the characteristics and mechanisms of landslide in the area.

To clarify the mechanisms of landslide occurred in Nachigawa River Basin, we assessed the damage, the structure of the soil layers, and the hydrological

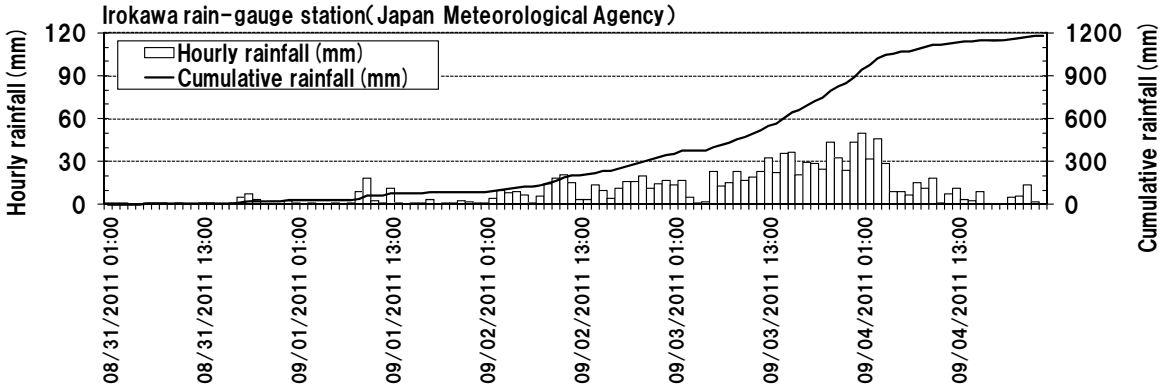

Fig. 1 Hourly rainfall and cumulative rainfall at the Irokawa observation station, the Japan Meteorogical Agency, on Wakayama Pref.

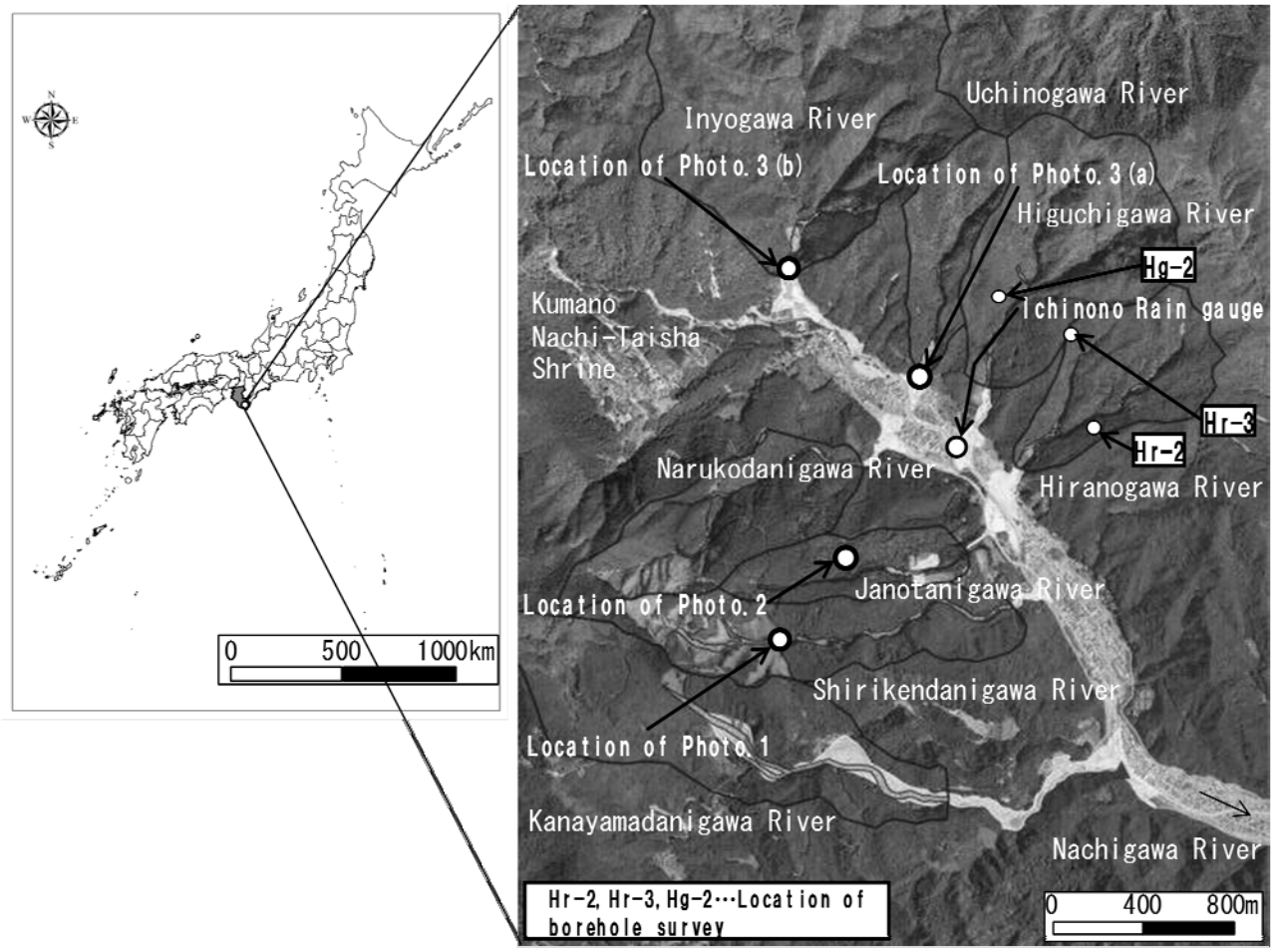

Fig. 2 Study Area

properties of the slope in the area. Surveys carried out were field, photographic, borehole, electric resistivity, and groundwater observations. Additionally, we conducted interview of local residents to elucidate the timing of landslides.

2. STUDY AREA

The study area is the Nachigawa River basin, located in Nachikatsuura Town, Wakayama Prefecture (**Fig. 1**, Area ~16.2 km^2, Mean longitudinal gradient of main channel of Nachigawa River ~9°). In the rainy and typhoon season, the monthly rainfall is >300 mm and annual rainfall is >2000 mm. The area is frequently attacked by typhoons. Additionally, the incidence of natural disasters due to typhoons and heavy rains has increased [*Nachikatsuura-town*, 2010]. Hence,

extreme caution is required during heavy rainfall and typhoons.

The geology of Nachikatsuura Town consists primarily of a Kumano acidic igneous rock layer formed by cooling of underground magma. The layer can be classified into rhyolite, rhyolitic tuff and granite porphyry. The study area comprises primarily granite porphyry of hard rock.

Sedimentary rock of Kumano Group consists of mudstone, siltstone, alternation of sand and mud, sandstone and conglomerate, and a little coal bed and are soft rocks [*Nachikatsuura-town*, 2010]. Because of differences in hardness, cliffs and waterfalls have formed in many locations (**Photo 1**).

In the study area, the gradient of the slope from the ridge to the geological boundary between alternation of sandstone and mudstone (sedimentary rock of Kumano Group) and granite porphyry (Kumano acid igneous rock) and is steep, but proceeds more gently from the geological boundary to the end of the slope.

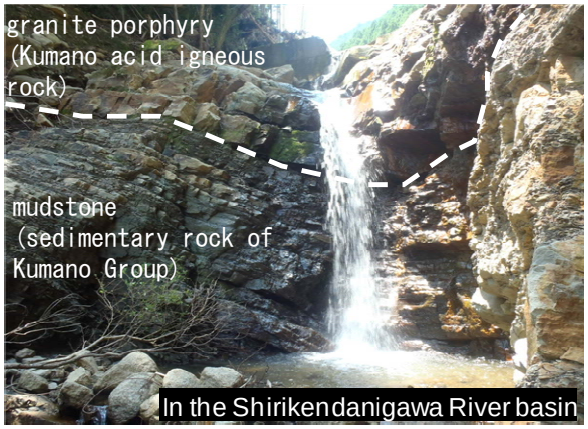

Photo 1 Geological boundary.

3. METHODS OF INVESTIGATION

In addition to the field survey, we conducted interview of local residents to elucidate the timing of the landslides. First, we conducted field surveys to understand the conditions in the study area. Second, we carried out a photo interpretation using aerial photographs, to clarify the locations of the landslides areas and the distribution of sediment discharge. Third, we conducted a borehole survey and specific resistance survey to study the structure beneath the ground surface. The specific resistance survey provides information on the distribution of groundwater and the geological boundaries. This information was also used to determine the position of the borehole survey. Finally, using these boreholes, we conducted groundwater level observations to investigate the relationships between groundwater and rainfall.

4. RESULTS

4.1 Field survey

The geological boundary of mudstone and granite porphyry was found at an elevation of 250 m a.s.l. and coincided with many landslides. The scale of landslide area along the geological boundary was very large, ~100 m in width, ~80-100 m in length, and tens of meters in depth. The form of landslide observed on the slope of granite porphyry was shallow landslides, ~1-5 m in depth. Additionally, we confirmed several soil pipes on the surface of landslide and no spring water was observed flowing from the soil pipes (**Photo 2**).

In the Nachigawa River Basin, there were deposits from past debris flows (**Photo 3** (a)). Hence, it appears that sediment transport phenomena such as debris flow have occurred many times in the past in the area.

Photo 2 Soil pipes on the landslide slope.

4.2 Interview of local residents

To understand the approximate timing of the occurrence of the landslides and debris flows, we conducted interview of local residents of the Nachigawa River basin. According to the results of

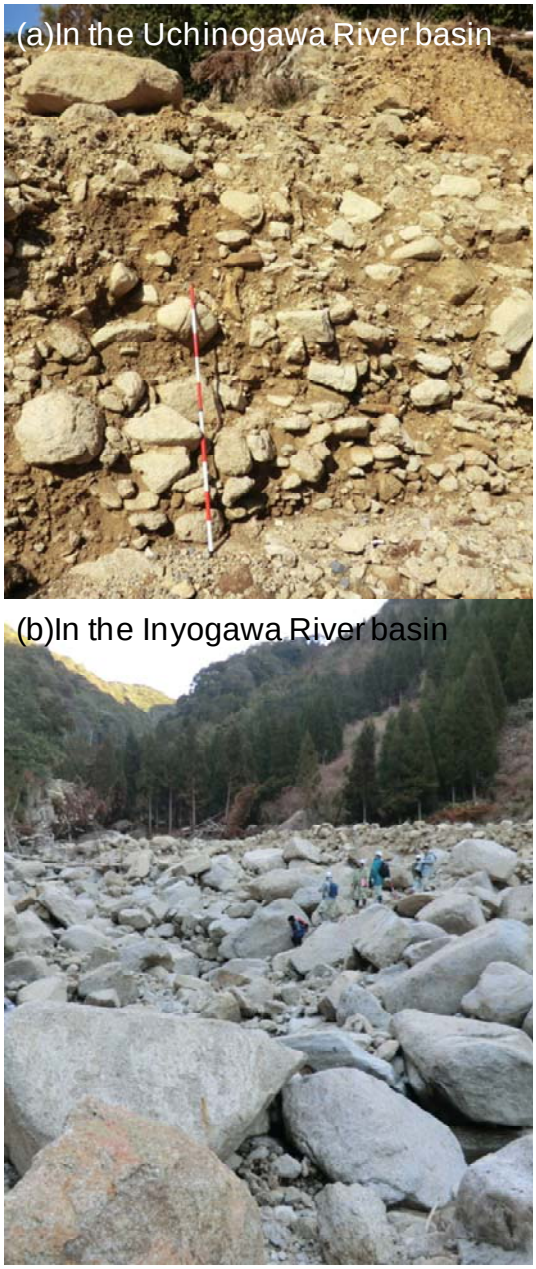

Photo 3 Old and new sedimentation due to debris flow. (a) Sedimentation from past debris flow. (b) Sedimentation from debris flow (September 2011).

this survey (**Table 1**), at around 22:00, September 3, 2011 water levels in the Nachigawa River were increasing, and sounds from cobbles transported along the river were heard. The hourly rainfall on this time was 30-50 mm, and the cumulative rainfall was ~800 mm (**Fig. 1**). After 1:00, September 4 loud sounds were heard in the Narukodanigawa River and Higuchigawa River valleys. Additionally, several local residents heard sound which should be induced by debris flow at Hiranogawa River and Kanayamadani River. According to this, it appears that debris flow and landslides occurred at several streams during this time period (1:00-3:00). Then, this time period coincide well with the peak of rainfall (**Fig. 1**).

4.3 Photographic survey

Using aerial photographs taken immediately after the disaster (September, 2011), we conducted a photographic survey. As a result, we found that most landslides moved down the slope in the form of debris flow, and reached the ends of valleys. Many of the landslides were distributed in the zone of the geological boundary at an elevation of 200-250 m a.s.l., and in the granite porphyry zone above the boundary.

4.4 Borehole and electric resistivity surveys

To investigate the geological structure, we conducted a borehole survey and electric resistivity survey. The results revealed that in the Higuchigawa River Basin, in the right tributary of the Nachigawa River, the granite porphyry near the geological boundary displayed many cracks and groundwater (GL -22.4m) (**Photo 4**). Hence, it appears that groundwater flowed near the geological boundary. Additionally, alternation of sandstone and mudstone was a low specific resistance zone and granite porphyry was a high specific resistance zone (**Fig. 3**).

4.5 Groundwater observations

Using investigation boreholes, we observed the groundwater levels of the Higuchigawa (Hg-2) and Hiranogawa Rivers (Hr-2 and Hr-3) in the

Table 1 Results of the interview of local residents.

Time		Event	
9/3/2011	Until around 22:00	Water level of the Nachi River rose. Local residents heard sounds of flowing cobble in river channel. Local residents could not use roads.	
9/4/2011	Around 1:00	Locel residents, who had been evacuated to Iseki nursery at downstream of Nachigawa river, moved Ichinono elementary school at upstream.	
	After 1:00	Local residents heard big sounds from valley around debris-flow torrent of Narukodanigawa river and Higuchigawa river. Then, they confirmed flooded houses and water-covered roads.	Debris flow occurred
	Around 2:00	Local residents confirmed that some flood banks were broken by sediment from Shirikendani river and roads were broken.	
	Around 2:30	Local residents confirmed that debris flow occurred at Hiranogawa river. Then, they confirmed that sediment and coarse woody debris flowed to first floor of elementary school.	
	After 3:00	Local residents heard sounds that debris flow continues to flow down over a period of 20 minutes. (Kanayamadani River)	

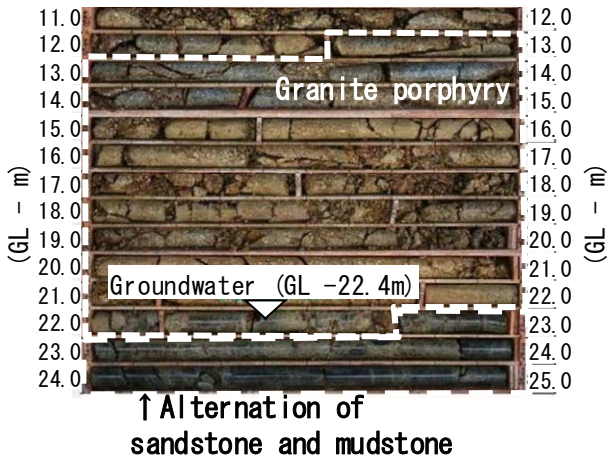

Photo 4 The borehole core (Hg-2).

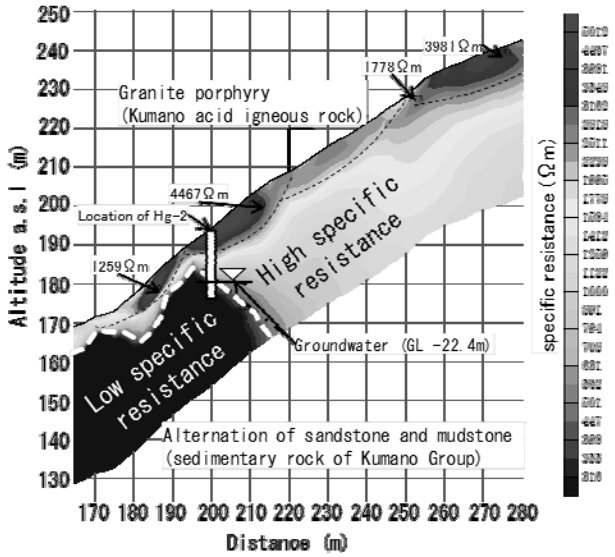

Fig. 3 Result of electrical resistivity tomography (in the Higichigawa river basin).

Nachigawa River basin (**Fig. 4** and **Fig. 5**). **Fig. 1** shows location of Hg-2, Hr-2 and Hr-3. **Fig. 3** shows location of Hg-2. Hg-2 includes the geological boundary of the granite porphyry and alternation of sandstone and mudstone. Then, Hg-2 provides observation of the groundwater along the geological boundary. Hr-2 includes alternation of sandstone and mudstone and Hr-3 includes the granite porphyry.

We confirmed a relationship between the groundwater level and rainfall (Irokawa rain gauge). The groundwater level of Hg-2 changes slightly with associated rainfall. When daily rainfall exceeds ~100 mm, the groundwater level of Hg-2 undergoes a small increase and decrease rapidly after rainfall stops (**Fig. 4(a)** and **Fig. 5(a)**). Hr-2 is responsive to rainfall (**Fig. 4(b)** and **Fig. 5(b)**). Hr-3 is also responsive to rainfall (**Fig. 4(c)** and **Fig. 5(c)**), but does not decrease as rapidly as Hr-2 during it stops raining (07/06/2013-08/31 of **Fig. 5(b)** and **(c)**). Then, we confirmed that groundwater level variations depend on differences in the geology. Apparently, according to the conditions observed at Hr-3 (in the granite porphyry area), during heavy rainfall, there are a large amount of groundwater in the granite porphyry area. The existence of a large amount of groundwater appears to cause an increase in pore pressure in the soil. From these results, it appears that there were many landslides at the granite porphyry area.

The groundwater level along the geological boundary of the granite porphyry and alternation of sandstone and mudstone (Hg-2) displays slight variation associated with rain falling over a short period. From the photographic survey, we confirmed the existence of large-scale landslides at the geological boundary. We think that the landslide were associated with groundwater levels. However, **Fig. 5(a)** shows the groundwater level in Hg-2, in which, on June 20 and 26 the groundwater level increased up to the geological boundary, but then immediately decreased. Then, from these results, it can't conclude that there is clear association between groundwater and landslide; therefore, further observations of the groundwater level are required.

5. Conclusion

To gain a better understanding of the mechanisms of landslide induced by the heavy rainfall in the Nachigawa River basin, Wakayama Prefecture, September 2011, our study focused on various factors, including hydrological characteristics and geological structure. Our results revealed the following:

- Debris flow occurred almost simultaneously with the peak rainfall in the basin.
- In the granite porphyry (Kumano acid igneous rock) around the geological boundary, many cracks developed. Additionally, part of the granite porphyry was altered.
- Results of the borehole survey indicated that the perched groundwater existed around the geological boundary.
- Many of the landslides in the Nachigawa River basin were distributed in the granite porphyry (Kumano acid igneous rock) and the geological boundary (between granite porphyry and alternation of sandstone and mudstone).
- The responses of the groundwater levels in the area of the granite porphyry were associated with changes in rainfall intensity. However, the groundwater levels in the area of the geological

boundary of the granite porphyry and alternation of sandstone and mudstone (sedimentary rock of Kumano Group) changed only slightly with rainfall.

Therefore, it appears that the landslides in this area occurred as follows:

Heavy rainfall from Typhoon Talas penetrated into the Nachigawa River basin, causing rapid increases in groundwater levels in the area. In the granite porphyry, because of the existence of excessive groundwater, pore pressure increased rapidly. As a result, it appears that these events lead to landslides.

In this study, we investigated the mechanisms of landslide in the Nachigawa River basin. However, we did not attempt to answer the question: "*When*, *where* and *how* do landslides occur?" This requires the application of physical indices, and the understanding of groundwater in the basin and springwater exiting from the pipes. Furthermore, it is necessary to understand the relationship between rainfall and groundwater levels. Further, monitoring and observation of slopes, springs, and groundwater are required.

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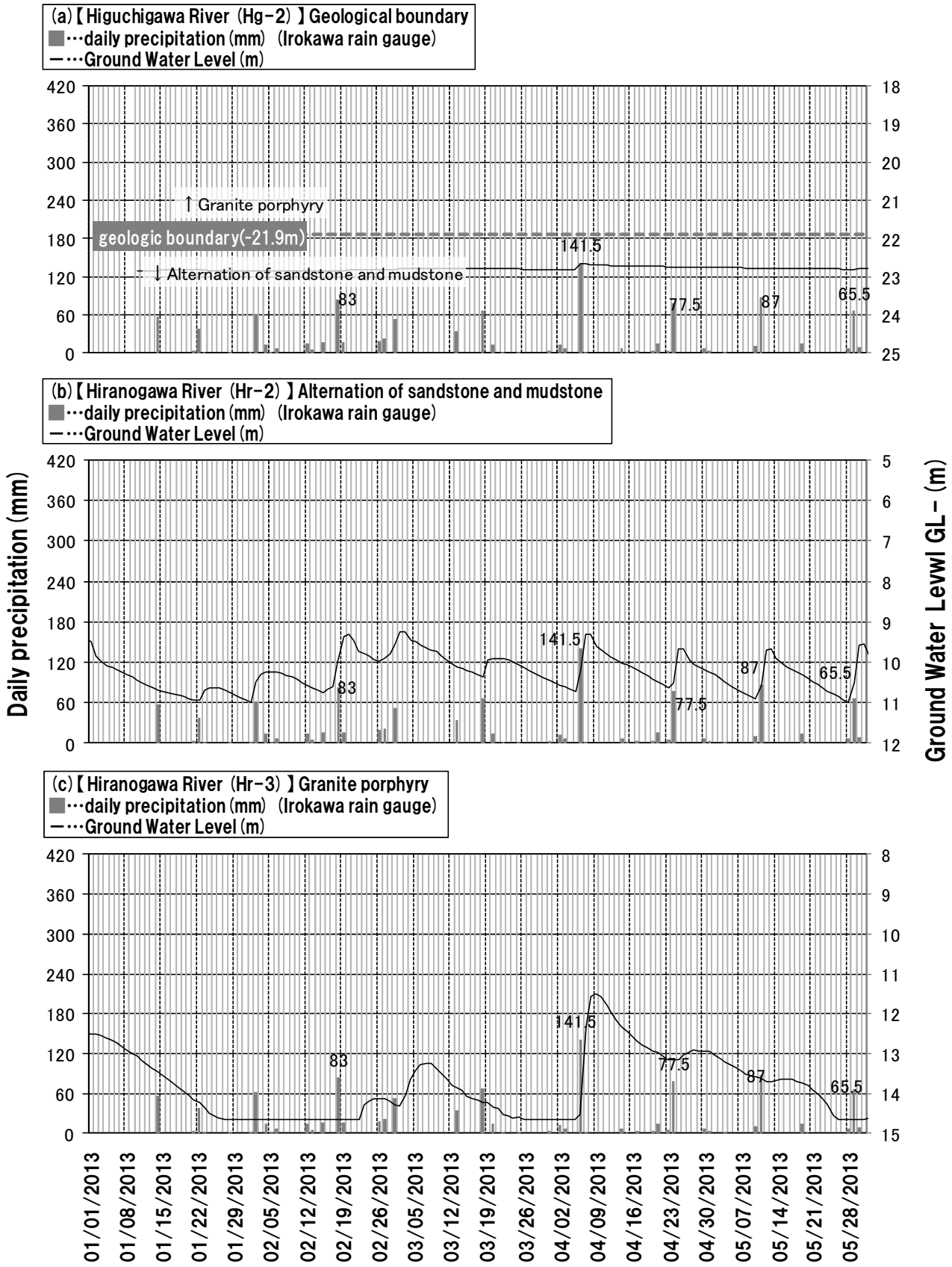

Fig. 4 Groundwater level (01/01/2013-05/31 Higuchigawa River and Hiranogawa River). (a) Geological boundary (Hg-2). (b) Alternation of sandstone and mudstone (sedimentary rock of Kumano Group) (Hr-2). (c) Granite porphyry (Hr-3).

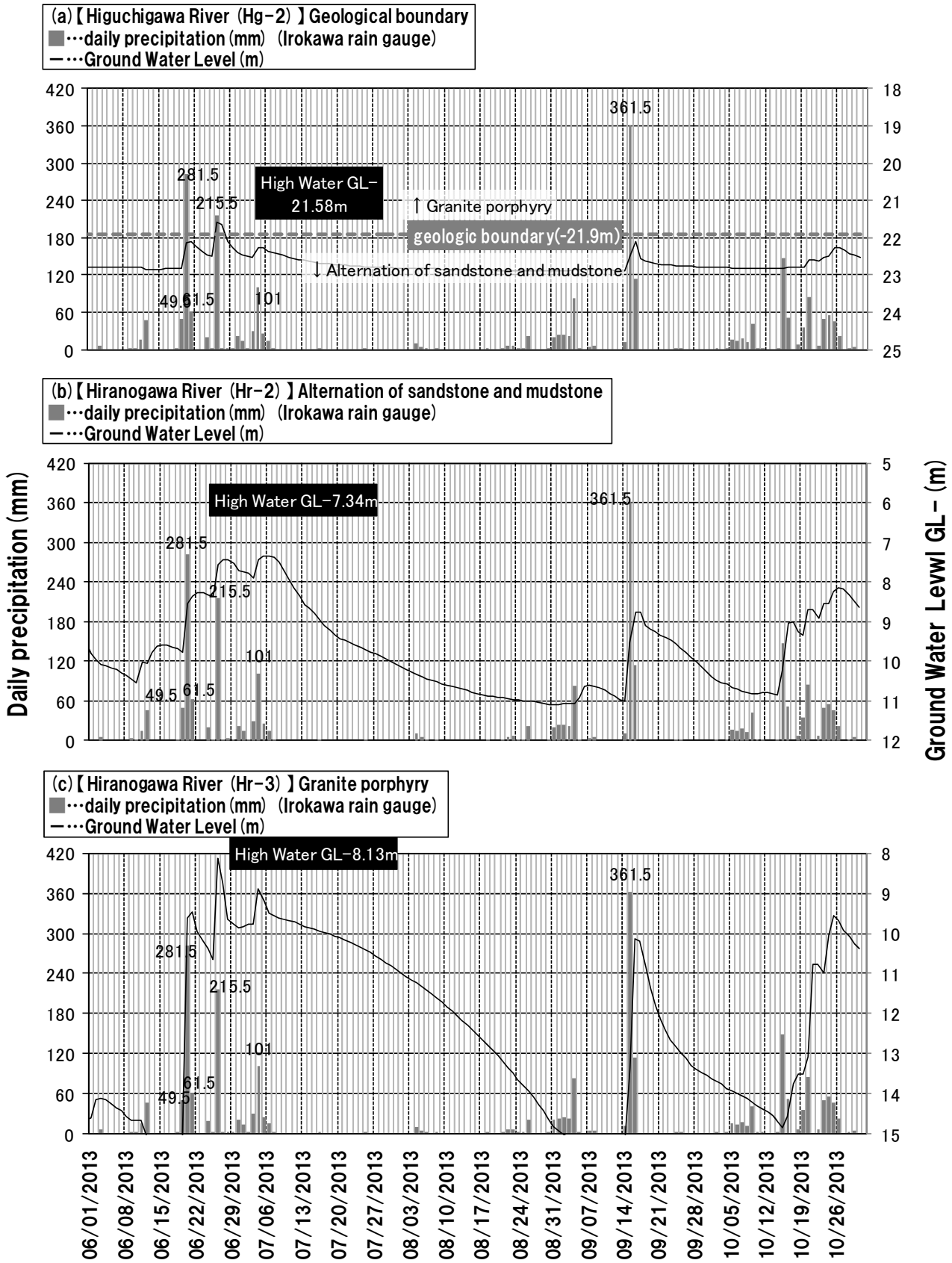

Fig. 5 Groundwater level (06/01/2013-10/31 Higuchigawa River and Hiranogawa River) . (a) Geological boundary (Hg-2). (b) Alternation of sandstone and mudstone (sedimentary rock of Kumano Group) (Hr-2). (c) Granite porphyry (Hr-3).