Rainfall-recharge-runoff processes through bedrock groundwater: implications for triggering of deep-seated catastrophic landslides

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Abstract

We observed discharge from bedrock springs and fluctuations in deep groundwater level in bore holes in a high-relief steep hillslope along a high-angle strike-slip active fault underlain by accretionary sedimentary rock, western Hira Range, central Japan. Bedrock in this area is extensively fractured through active faulting and gravitational hillslope deformation, resulting in a characteristic hydro-geological structure. Rainwater percolated through thin soil cover recharges the deep groundwater body expanding in a fissure network in bedrock. This bedrock aquifer is separated by subsurface walls of impermeable fault gouges, and the groundwater overflow maintains the discharge from persistent springs aligned on a similar altitude. Quick raise in deep groundwater level were observed in response to large rainfall events in summer seasons, demonstrating high connectivity of shallow soil-water to the deep bedrock aquifer through fractures. Discharge from the springs correlates well with the upslope groundwater level with a cubic or quadratic function, suggesting constraints of bedrock aquifer by subsurface geological structure such as beddings and foliations. The functional relationship between them may provide a potential way to infer bedrock groundwater level based on spring runoff monitoring in hillslopes with high susceptibility to deep-seated catastrophic landsliding.

Keywords: bedrock groundwater, deep-seated landslide, spring, hydrological monitoring

1. Introduction

Groundwater storage in bedrock buffers rainwater infiltration and drainage in hillslopes, maintaining base flow in mountain streams. Many hydrological studies demonstrated significant contribution of groundwater in bedrock to rainfall-runoff system in mountainous watersheds (e.g., Onda et al, 2001, Katsura et al., 2008, Kosugi et al., 2006, 2008, 2011). However, infiltrated water flow paths and mechanisms of quick/slow responses of such deep groundwater remain controversial. Fast fissure flow or pressure propagation through rock fractures may bear the prompt raise of groundwater level in bedrock during a rainstorm (Gabrielli et al., 2012; Salve et al., 2012; Fujimoto et al., 2014), while slow water convergence for a long traveling distance may contribute to the delayed or seasonal groundwater fluctuation (Abbott and Stanley, 1999). We need direct observation of infiltrated water behavior into bedrock for better understanding of deep groundwater system, which should depend on subsurface hydro-geological structure.

Bedrock groundwater in the specific geological condition causes deep-seated rock mass movements, when water storage exceeds a critical level for slope stability by intense rainwater infiltration. Mechanical and hydraulic discontinuity in bedrock often functions as a potential sliding surface for a catastrophic landslide, especially in areas underlain by accretionary sedimentary rocks and volcanic rocks in active orogens. In fact, dip-structures by beddings or faulting appeared at slip scars in several cases of recent bedrock landslides in SW Japan (Chigira et al., 2013). Almost no information is available for how these subsurface discontinuities affect bedrock groundwater behavior and storage capacity that limits the rainwater amount to be safely drained from the hillslope. A proper hillslope conservation and disaster mitigation need knowledge of bedrock groundwater dynamics and pore-pressure fluctuations in bedrock with such hydro-geological conditions leading to a catastrophic landslide.

A clue to infer groundwater system in a hillslope is springs that drains bedrock groundwater directly from the deep aquifer. It is well known that distribution of bedrock springs reflects geological structures. These springs may align on a contact between land surface and groundwater table, or may arise at an outlet of preferential flow paths such as rock fissures or permeable fault bands. In any cases, spatial distribution and temporal runoff fluctuation of such bedrock springs should reflect the subsurface hydro-geological structure and groundwater dynamics in it.

Monitoring of spring runoff may provide useful information for predicting pore-water pressures in bedrock, if a functional relationship exists between runoff amount and groundwater level. This relationship must be controlled by the local hydro-geological structure, hence we are also capable to estimate subsurface water flow system by the simultaneous observation of spring discharge and bedrock groundwater level. Once a functional relationship is established between them, this approach enables us to evaluate hillslope stability based on spring discharge that is easily observable than bedrock groundwater fluctuation.

Here we show how spring distribution and discharge correlates with groundwater in bedrock for a case in a high-relief steep hillslope underlain by accretionary sedimentary rocks. Observations were carried out for precipitation, runoff from springs, and groundwater level in boreholes. These data demonstrated geo-structural constraints on expansion of bedrock aquifer, which seems to control pore-pressure raise that affects occurrence of bedrock landslides.

2. Study site

The study site is a hillslope adjacent to an active strike-slip fault, Hanaore Fault, in south western Hira Range, SW Japan (Fig. 1A). The eastern area of the Hanaore Fault is thought to have actively uplifted during the late Quaternary to form the Hira Range with remaining low relief surfaces on its ridge crest. A major valley, upper Ado River, along the fault deeply incises the terrains to form gorges walled by steep lower side-slopes. Topography in these area are dominated by high-relief (>300 m), steep (>30°) hillslopes.

Bedrock in this area is Jurassic accretionary sedimentary rocks, Tamba-Mino Belt, consisting of sand–mud alternating beds, chert, and muddy chaotic rocks. The strata show beddings and foliations with a general attitude of north–south strike with west dipping. The substrates beneath the eastern part of the study area is thermally metamorphosed by the contact with Cretaceous granitic intrusion that is presently exposed in the eastern part of the Hira Range. High-angle sub-faulting of the Hanaore Fault system and porphyritic dykes often observed along the Ado River with both north–south directions.

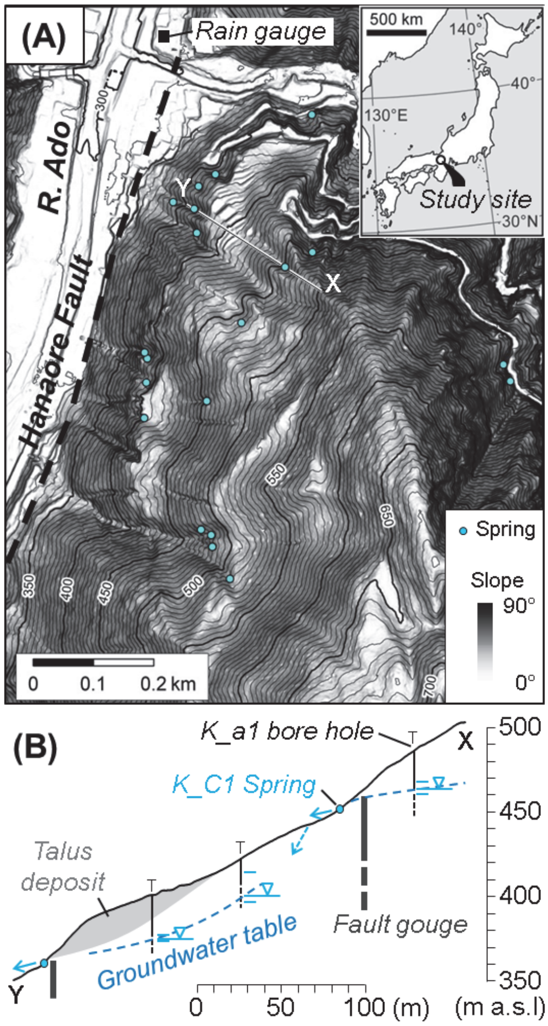

Fig. 1 Topographic map of the study site (A) and hillslope profile surveyed (B). Three borings were drilled on the profile and used as observation well with a screen for depths represented by broken lines. Groundwater tables are indicated by max, mean and min levels during 2013-2014.

Climate in this area is characterized by humid temperate condition with mean temperature of 11 °C and average annual precipitation of 1800 mm. About 40% of rainfall is supplied by frontal activities and typhoons in summer and fall seasons. The area receives snowfall equivalent to ~500 mm in winter. Natural vegetation under this climate would be an evergreen broadleaf forest, but in the present day, planted coniferous forest occupies the majority of hillslopes.

In the Hira Range, we have poor records of deep-seated catastrophic landslides. An earthquake in AD1662 (Kanbun Earthquake) in the northern part of Hanaore Fault caused a deep-seated catastrophic landslide, so called Machii-Kuzure, which shuttered the Ado River until its outburst at few weeks later (Imamura and Inoue, 2002). The most recent rainfall-triggered deep-seated catastrophic landslides occurred in 18-20 Aug 1992 by rainfall about 600 mm per 2 days; the event caused landslides with a volume of 10^5 m^3 at two locations near the field site. In the airborne LiDAR (Light Detection And Ranging) based topographic image, many landslide scars and gravitational deformation scarplets are visible on the hillslopes (Fig. 1A, Matsushi et al., 2014).

3. Method

3.1 Field surveys

Hydro-geological field surveys were conducted in the selected hillslope. Location of major springs was mapped using portable GNSS tools with LiDAR images, with measurement of rough amount of discharges. Distribution of lithology was investigated with description of attitudes of beddings, joints, and foliations. Outcrops of thick band of fault gouges were also located at head hollows at springs and along gullies surveyed.

A long-sectional survey line was set to carry out detailed hydro-geological observations (Fig. 1B). Soil thickness was surveyed by cone penetration soundings for few-meter intervals at the upper part of the slope profile. A thin piezo-pipe was installed at each sounding site to check water seepage into soil layer from bedrock. Geological structures beneath the soil layer was investigated with boring cores extracted by drilling into bedrock at three sites along the slope profile (Fig. 1B).

3.2 Hydrological observations

Discharges were monitored at the spring named K_C1 on the profile (Fig. 1B). We set a V-notch weir at the spring outlet, and measured the height of overflow by a water-pressure sensor (PA-830-101G, Copal Electronics Corp.). The overflow height (in mm) were converted to runoff amount (in L/s) based on in-situ calibration. Temperature and electrical conductivity (EC) of the inlet water also monitored (by HOBO UA-001-64 and U24-001, Onset Computer Corp., respectively). All these data were recorded at 5 or 10 min intervals by data loggers.

Groundwater fluctuation in bedrock was monitored using the bore holes named K_a1 (Fig. 1B). The bore holes were screened at depths below normal groundwater tables, so they function like wells into bedrock aquifer. Temporal changes in water level in the bore hole were monitored by a pressure sensor (S&DLmini, OYO Corp.). Groundwater temperature and EC were also measured at the bottom of the bore holes. At the uppermost bore hole, subsurface profile of temperature were recorded at depths of 1.50, 2.50, 3.95, 5.85, 10.85, 17.80 and 30.60 m below surface.

Meteorological observations were carried out at narrow flat space nearby the surveyed slope (Fig. 1A). Total precipitation were measured by a heatable dipping bucket rain gauge with 0.2 mm resolution. In winter season, snowfall were received by a 1.00 m^2 lysimeter, and snow melting were recorded by a dipping bucket flow meter with 0.125 mm resolution. Air pressure was monitored by a barometer to calibrate the pressure sensor in bore holes.

4. Results and discussion

4.1 Spring locations and groundwater distribution in bedrock

The spatial distribution of major springs shows two series of north-south alignments with two distinct ranges of altitudes (Fig. 1A). The higher group appears from 450 to 500 m a.s.l (above sea level), while lower springs are located below 400 m. Several springs have irregularly large amount of discharge (>5 L/s) even at the higher altitude, regardless of their relatively small topographic contributing area. Almost all these springs accompany outcropping of clayey black fault gouges containing mudstone and quartz fragments. Indeed the alignment of the two groups of springs matches to the lines of high-angle sub-faults of the Hanaore Fault. In addition, the springs were often located within scars of past bedrock landslides or at the end of scarplets formed by gravitational slope deformation (Fig. 1A, Matsushi et al., 2014). These facts indicate that the distribution of bedrock aquifer may be constrained by faults accompanying impermeable gouges as subsurface water-damming structure, and groundwater may gush out to form springs at the insection of the fault gouge.

The hypothesis of subsurface water dam-up by faults was verified by large difference in water levels across spring observed at the bore holes on the surveyed slope profile (Fig. 1B). Average water level at the upper bore hole is 463 m a.s.l., while it is around 400 m in the lower hole, indicating a large drop of groundwater table larger than 60 m. As the boring cores show highly fractured appearance even in a deeper part, the bedrock seems to retain unconfined aquifer with free groundwater table. The aquifer should be separated by the high-angle fault, and the groundwater overflows the top of its impermeable clayey gouge (Fig. 1B).

4.2 Characteristics of rainfall-runoff hydrographs and groundwater level fluctuation

Hydrographs observed at the K_C1 spring show seasonal fluctuations ranging in two orders of

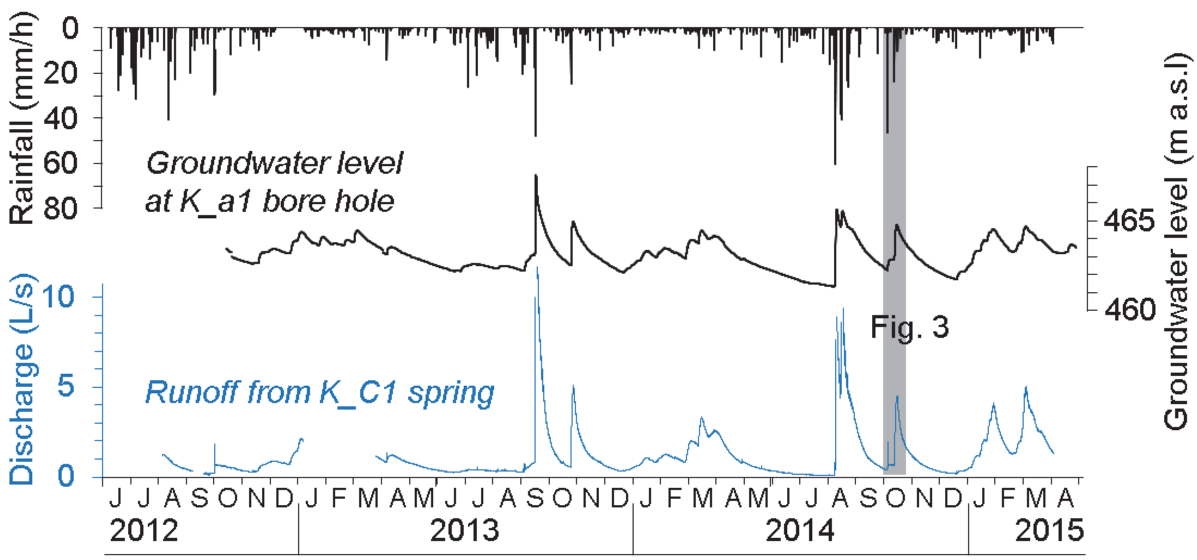

Fig. 2 Hydrograph observed at a bedrock spring (blue) and groundwater response in bedrock (black).

magnitude (Fig. 2). It shows drastic increase by large events of summer rainfall to the highest discharge of ~10 L/s and declines gradually within few months. The spring runoff has almost no response to the small rainfall events. In winter, the discharge exhibits gradual increase in response to snowfall and melting, forming rounded runoff summits up to ~5 L/s in contrast to the prominent peaks in summer seasons.

Groundwater levels observed in the K_a1 bore holes indicate a similar pattern to the spring discharge (Fig. 2). They changed in response to large events of rainfall and snowmelt over a range of few meters. Of note is that the groundwater level show a fast raise by a large rainfall supply even the water table is observed in the deep wells of 20 to 30 m below surface. Although the mechanism of this quick response of the bedrock groundwater is unknown at present, the lag-time of the peak of groundwater level from rainfall peak becomes shorter with increasing preceding effective rainfall (or snowmelt) (Fig. 2). This implies that wetness of soil or shallow part of bedrock plays an important role in percolating water or propagating pressure into deep bedrock aquifer, as pointed out also in recent studies (Gabrielli et al., 2012; Salve et al., 2012).

Focusing into individual runoff event, we can infer significant contribution of deep groundwater flow through bedrock to the discharge from spring. Fig. 3 represents a typical hydrograph in response to summer intense rainfall. The first small runoff peak appears promptly after the rainfall peak, and the large secondary peak follows with a lag time of few hours to days from the rainfall peak only for the event started 13 Oct 2014 (Fig. 3A). Temperature of the runoff water increases simultaneously with the first runoff peak then down back almost to the initial value

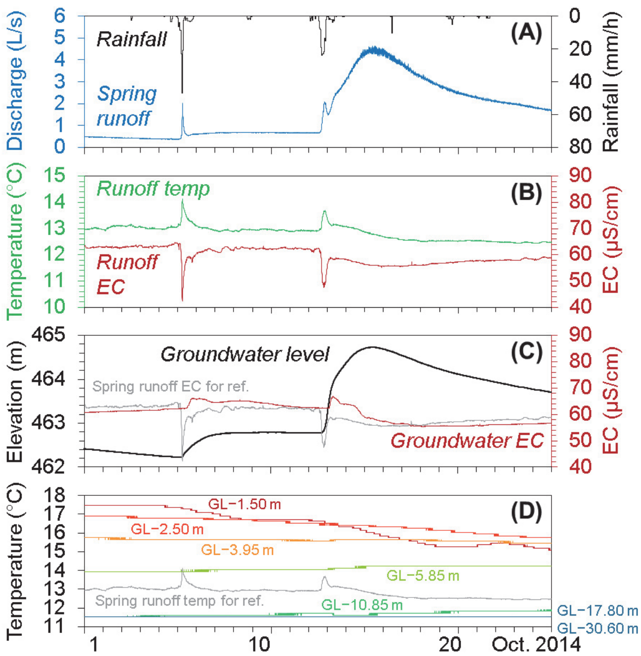

Fig. 3. Typical responses in spring runoff and groundwater level for intense summer rainfall events. (A) Rainfall and discharge at K_C1 spring. (B) Responses in temperature and electrical conductivity (EC) of the runoff water from the spring. (C) Responses in groundwater level and EC at the K_a1 bore hole. EC of spring runoff (grey) is indicated for reference. (D) Changes in temperature in the depth profile at the K_a1 bore hole. Temperature of spring runoff (grey) is indicated for reference.

even the discharge increases to form the secondary runoff peak (Fig. 3B). Electrical conductivity (EC) of the runoff water from spring drops during the first peak.

The groundwater level in bedrock show a similar response to the slow component of discharge (Fig. 3C). The timings of initiation of groundwater raise match to the initial runoff peak, whereas the change in EC of the deep groundwater delays to the response of the groundwater table. This strongly supports the idea that prompt pressure propagation due to rain infiltration into surface soil layer generates a piston-like flow through fractures in weathered upper bedrock, leading to a quick raise in deep groundwater level. This mechanism to connect surface rainwater to deep groundwater may play a significant role in triggering bedrock landslides.

The profile of subsurface temperatures was basically stable during these events (Fig. 3D), supporting the hypothesis of pressure propagation. The change in temperature of spring discharge can be explained by mixing of water components with different temperatures, most simply, of two endmembers of deep bedrock water of 11.5 °C and shallow soil water of 17 °C. Since the outlet of bedrock drainage for the K_C1 spring is covered by soil mantle, the runoff-water temperature may be buffered by warm soil overburden.

4.3 Connection between spring discharge and bedrock aquifer

The spring discharge shows a clear correlation to groundwater level at the upslope bore hole (Fig. 4).

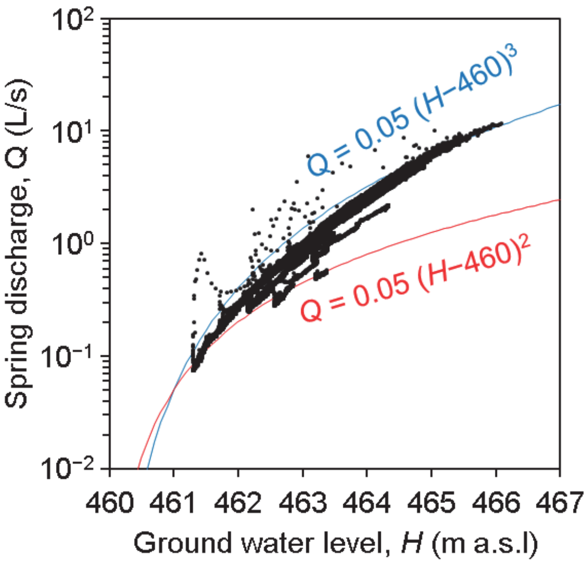

Fig. 4. Correlation between upslope groundwater level in bedrock and discharge from spring (black dots). Blue and red curves indicates a cubic and a quadratic function to explain the overflow drainage from bedrock aquifer.

This indicates that the groundwater drainage from bedrock is controlled by seepage through fractures with high connectivity, forming an unconfined aquifer in bedrock with a free water table. The relationship indicates a cubic function for the upper bound while it accords with a quadratic function for lower envelope. This suggests effect of geological structure for the cross sectional shape of the aquifer, that is capable to be approximated to a rectangular in the lower discharge, but changes to triangular in a condition of higher discharge (Fig. 4). This hydro-geological structure may be formed by a combination of high-angle faulting and low-angle beddings/foliations, but not certainly confirmed the mechanism at present that the aquifer drains different amount of spring discharge even in a similar condition of groundwater level.

The formulation may be applicable to estimate groundwater level (and might be pressure head) in bedrock from spring discharge. More data are needed to check spatial variability of this functional relationship between them, and specify which structure affect the groundwater recharge and drainage. Even though, we can find out a clue to infer groundwater states in deep bedrock from the spring runoff, by an easily accessible monitoring approach.

5. Conclusions

This paper reveals bedrock groundwater dynamics and its relation to spring discharge based on long-term field monitoring in a hillslope underlain by accretionary sedimentary rocks near active strike-slip fault system. Spatial distribution of springs and difference in groundwater level across a high-angle sub-fault indicate subsurface water damming by the

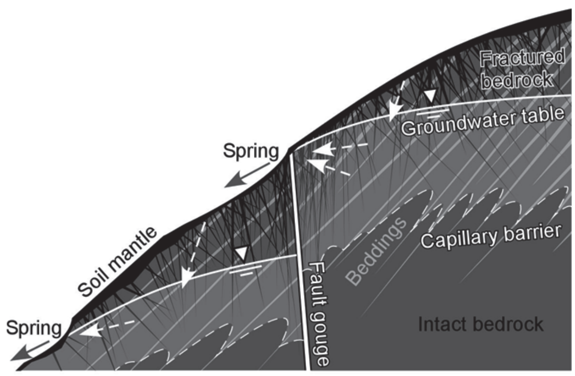

Fig. 5. Schematic illustrating bedrock aquifer system separated by high-angle impermeable fault gouge. Quick piston flow due to rainfall infiltration through fissures recharges the bedrock groundwater. The bedrock aquifer drains groundwater by overflowing of the subsurface dam as persistent spring discharge.

fault with impermeable clayey gouge. This bedrock aquifer system can be drawn schematically as Fig. 5. Rainfall infiltration recharges the bedrock aquifer by a piston-like flow through fractured upper bedrock, resulting in quick raise of the deep bedrock groundwater table. The bedrock groundwater drains by overflowing to form persistent spring discharge. A clear correlation between spring discharge and upslope groundwater level supports the formation of unconfined aquifer within the highly fractured bedrock. The functional relationship between them implies the constraint of cross sectional shape of aquifer by low-angle beddings or foliations. This type of groundwater retention in bedrock may cause a deep-seated deformation and/or landslide across the fault. Our results demonstrated the potential way to estimate pore-water pressure in bedrock by monitoring of spring discharge in order to assess slope stability.

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