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Processes of bedrock groundwater seepage and their effects on soil water fluxes in a foot slope area

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SUMMARY

The impact of bedrock groundwater seepage on surface hydrological processes in a foot slope area is an important issue in hillslope hydrology. However, properties of water flux vectors around a seepage area are poorly understood because previous studies have lacked sufficient spatial resolution to capture detailed water movements. Here, we conducted hydrometric observations using unprecedented high-resolution and three-dimensional tensiometer nests in the mountainous foot slope area of the Hirudani experimental basin (Japan). Our findings are summarized as follows: (1) a considerable quantity of groundwater seeped from the bedrock surface in the study site. A groundwater exfiltration flux occurred constantly from a seepage area regardless of rainfall conditions. Saturated lateral flow over the bedrock surface occurred constantly in the region downslope of the seepage area. Groundwater was likely to mixed with soil water infiltration and flowed toward the lower end of the slope. (2) During the wet season, the seepage area expanded ~3 m in the upslope direction along the bedrock valley in a single season. (3) The pressure head waveform observed in the seepage area showed gradual and significant increases after large rainfall events. However, the seepage pressure propagated within a relatively narrow area: a slope distance of ~4 m from the seepage point in the downslope direction due to the damping of seepage pressure. (4) Within the whole study area, groundwater seeped from a narrow area located at the bottom of the valley line of the bedrock surface. The shape of the seepage area changed along the valley line in the wet season. Overall, we reveal spatial and temporal variations in bedrock groundwater seepage under the soil mantle and the effects on soil water fluxes. These findings should improve the accuracy of models for predicting surface hydrogeomorphological processes in mountainous hillslopes.

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1. Introduction

Bedrock groundwater seepage, which supplies water from subsurface bedrock to the soil mantle, plays a significant role in hillslope hydrology. Recent studies conducted in headwater catchments reported a large contribution to water budgets from groundwater seepage (e.g., Uchida et al., 2003; Kosugi et al., 2006). The exfiltration of bedrock groundwater at an outcrop, referred to as a "spring", has been observed as an important indicator of hydrological processes in bedrock layers. Several studies have reported that spring discharge hydrographs tend to exhibit gradual variations, regarded as the main source of base flow discharge in headwater catchments (e.g., Dickinson and Whiteley, 1970; Hattanji and Onda, 2004).

Interactions between surface-water and groundwater in a foot slope area have recently attracted attention in hydrological research. Because surface-waters and groundwaters differ significantly in discharge volume, chemistry, temperature, etc., it is essential to understand mixing processes between these bodies for the prediction of streamflow generation and solute transport (McGlynn et al., 1999; Haria and Shand, 2004, 2006; Katsuyama et al., 2005; Banks et al., 2009). The most important effect of groundwater seepage is to generate a perennially-saturated area in the soil mantle; additionally groundwater seepage increases the storm flow generation rate by increasing saturated overland

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flow and subsurface lateral flow (Waddington et al., 1993; Tromp-van Meerveld and McDonnell, 2006).

Bedrock groundwater seepage can generate a perennially saturated area in the exfiltration water flux vectors. Mixing processes between surface-water and groundwater can be investigated by measuring the angle and magnitude of water flux vectors and soil moisture data. Hydrometric data at a high spatial and temporal resolution should be obtained by installing tensiometers or piezometers at small intervals across natural hillslopes. Although high-resolution hydrometric observations were conducted in previous studies, (e.g., Freer et al., 2002; Sherlock et al., 2002; Chappell and Sherlock, 2005; Rahardjo et al., 2008), few have detected flux vectors showing groundwater seepage. Results and unresolved questions obtained from these studies are summarized below.

Exfiltration water flux vectors have been observed in some slope hydrological studies. In a string of studies conducted in the Coos Bay experimental catchment, Oregon (Montgomery et al., 1997, 2002), a vertical hydraulic gradient between the bedrock and soil layers showed transient exfiltration only during intense rainfall events because of rapid lateral saturated flow through near-surface fractured bedrock. In contrast, Terajima and Moroto (1990) measured the cross-sectional distribution of pressure heads along a valley and detected exfiltration water fluxes occurring constantly under no-rainfall conditions. In general, such perennial exfiltration fluxes are considered an indicator of bedrock groundwater seepage and a source of base flow discharge.

The angle of the flux vector is determined by the mixing of infiltrating rainwater and exfiltrating groundwater. Terajima and Moroto (1990) reported that exfiltration flux vectors under no-rainfall periods transiently reversed at the peak of rainfall infiltration. In contrast, Haria and Shand (2006) observed a vertical hydraulic gradient in soil and bedrock in a near-stream hillslope. They showed that, during wet seasons, an exfiltration flux was constantly present from shallow bedrock into soil, regardless of rainfall conditions. However, these studies lacked sufficient spatial resolution to capture detailed water movement around the seepage area because they were originally designed to explore broad areas using scattered instruments at relatively low resolution. There is therefore still little understanding of flux vectors in the process of groundwater exfiltration and mixing with surface-water.

The area of groundwater seepage is thought to fluctuate with variations in groundwater levels in bedrock layers. Terajima and Moroto (1990) reported that an area showing an exfiltration flux appeared in a region upstream of the perennial seepage area several hours after the cessation of rainfall events, suggesting the expansion of the seepage area due to rising groundwater levels. Uchida et al. (2003) observed a temporal fluctuation in soil water levels along a valley and estimated that the ratio of the seepage area to the whole catchment area changed by between 0.5% and 2.0% through the preceding rainfall conditions. In contrast, Haria and Shand (2004) and Katsura et al. (2008) reported that saturated water levels observed at soil piezometers showed a similar waveform to groundwater levels observed at deep bedrock wells. Soil water levels disappeared when bedrock groundwater levels fell below certain values, indicating a diminishing area of groundwater seepage. However, the number of studies measuring the seepage pressure waveform in the soil mantle is quite limited, because the waveform may be damped through the propagation of seepage pressure toward downslope regions. Moreover, the fluctuation in the shape and range of the seepage area cannot simply be explained by bedrock groundwater levels, because a large quantity of groundwater is thought to flow through bedrock fracture flow paths and seep from a relatively narrow area. These topics are also poorly understood because of the lack of high-resolution observational data.

In most previous studies, groundwater seepage was discovered as a result of hydrometric observations conducted along a cross-sectional line set along a valley. However, regions of groundwater seepage are thought to be strongly controlled by geological constructions such as fault lines (e.g., Manga, 2001) and do not correspond simply to surface topographic factors such as valley beds; the relationship between the location of groundwater seepage and topographic/geological factors has not been thoroughly discussed due to the lack of study cases. Therefore, fast and effective techniques for exploring groundwater seepage under the soil mantle have not been developed until recently.

To overcome these problems, a novel exploratory instrument has recently been developed, consisting of a moisture probe attached to a cone penetrometer. This combined penetrometer–moisture probe (CPMP) enables instant exploration of subsurface soil water distributions (Kosugi et al., 2009; Yamakawa et al., 2010). By applying the new CPMP in a mountainous foot slope area, Masaoka et al. (2012) detected an area of high water content that did not correspond to the topographic indices of either the ground or bedrock surfaces; tensiometric measurements in the area found evidence of groundwater seepage. Following the results obtained by Masaoka et al. (2012), we conducted hydrometric observations using unprecedented high-resolution and three-dimensional tensiometer nests in the study site. On the basis of observational data, we analyzed water flux vectors in and around the seepage area to investigate (1) the temporal/spatial variation of flux vectors around a seepage area, (2) the fluctuation in seepage area shape, (3) the propagation process of seepage pressure, and (4) the distribution of a seepage area and its dependence on topographic factors.

2. Materials and methods

2.1. Study site

We performed observations in a headwater basin of the Hirudani experimental basin (82.1 ha) at the Hodaka Sedimentation Observatory of the Disaster Prevention Research Institute, Kyoto University, in Gifu, central Japan (36°25′N, 137°585′E; Fig. 1a). The Hirudani experimental basin is located in a headwater area of the Jintsu River, where several previous sediment discharge and transport studies have been conducted (e.g., Fujita et al., 2002). Stream water chemistry was reported to vary in small inner watersheds as a result of the complex geological structure of the basin—mainly composed of Mesozoic mélange, Warudani lava, and a granitic ring dike (Masaoka et al., 2014). The mean annual air temperature is 9.5 °C, and the mean annual precipitation is 1980 mm, a quarter of which falls as snow in winter (1979–2010, Japan Meteorological Agency).

As shown in Fig. 1a, the study area (74.0 m^2) is located at the foot of the valley side-slope. The study area, with a mean gradient of 40°, is underlain by weathered granite porphyry and covered by shrubs, ferns, and herbaceous species. The soil is classified as a Cambisol (brown forest soil). The surface topography across the slope is planar and gently concave. An old landslide scarp lies adjacent to the slope and a spring is located inside the scarp.

2.2. Tensiometer measurements

From 18 June to 15 November 2011, soil pore water pressure was continuously monitored (soil matrix pressure head, ψ) using 114 tensiometers installed at 59 observation points in the study area (Fig. 1a). Of these points, 57 were located along six horizontal

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