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

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Abstract

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 towards 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

1 and the effects on soil water fluxes. These findings should improve the accuracy of models for
2 predicting surface hydrogeomorphological processes in mountainous hillslopes.

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5 **Keywords**

6 Groundwater seepage; Flux vector; Pressure head; Saturated area; Soil mantle; Hillslope
7 hydrology

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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 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

1 explained by bedrock groundwater levels, because a large quantity of groundwater is thought to
2 flow through bedrock fracture flow paths and seep from a relatively narrow area. These topics
3 are also poorly understood because of the lack of high-resolution observational data.

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

12 To overcome these problems, a novel exploratory instrument has recently been
13 developed, consisting of a moisture probe attached to a cone penetrometer. This combined
14 penetrometer-moisture probe (CPMP) enables instant exploration of subsurface soil water
15 distributions (Kosugi et al., 2009; Yamakawa et al., 2010). By applying the new CPMP in a
16 mountainous foot slope area, Masaoka et al. (2012) detected an area of high water content that
17 did not correspond to the topographic indices of either the ground or bedrock surfaces;
18 tensiometric measurements in the area found evidence of groundwater seepage. Following the
19 results obtained by Masaoka et al. (2012), we conducted hydrometric observations using
20 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°58'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 to 2010, Japan Meteorological Agency).

As shown in Figure 1a, the study area (74.0 m²) 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 lines denoted Lines A to F. Each observation point was referenced using the line name and a sequential number from the right edge; for example, point A-4 indicates the fourth point from the right edge on Line A (Fig. 2). Two additional upslope points were included, denoted V-1 and V-2, along Line V, perpendicular to Lines A–F (Fig. 2).

Figure 2 shows the locations of the 114 tensiometers in three-dimensions. Of these tensiometers, 59 were installed at the soil-bedrock interface, determined by a penetration resistance value, N_c , exceeding 100, according to studies conducted in granitic watersheds (e.g. Katsura et al., 2006; Kosugi et al., 2006). The value of N_c is calculated as the number of blows required for 10 cm of penetration with a Hasegawa-type penetrometer with a 60° bit, a cone diameter of 20 mm, a weight of 2 kg, and a fall distance of 50 cm (Nishimura et al., 1987). The 59 tensiometers installed at the soil-bedrock interface are referred to as bedrock (b) tensiometers

hereafter. Thirty six tensiometers were installed at a depth of 30 cm, and are referred to as shallow (s) tensiometers hereafter. The remaining 19 were installed in the middle layer, denoted (m), and installed between the shallow and deep tensiometers at depths of between 80 and 160 cm. Each tensiometer was named using the location number and the installation layer: for example, 'A-4s' indicates the shallow tensiometer located at point A-4. Tensiometers were attached to pressure transducers (PA-850-102V-NGF; Copal Electronics, Shinjuku, Tokyo, Japan). Values of ψ were recorded at 5-min intervals throughout the observation period using a data logger (CR1000; Campbell Scientific, Logan, UT, USA).

2.3. Other measurements

During tensiometer measurements, runoff from the spring located inside the old landslide scarp was also observed (Fig. 1a). Spring water was channeled into a 0.5-L tipping bucket. Accumulated bucket tips were recorded at 5-min intervals throughout the observation period. Subsurface trench flow from an artificial trench excavated ~2 m downslope from Line F was also observed (Fig. 1a). The trench was approximately 5 m long and excavated to the soil-bedrock interface determined by the penetration test. Depths to the bedrock surface along the trench face were variable (0.42-1.24 m, average = 0.88 m). The discharge from the trench face was corrected using tarpaulins and gutters and monitored using a 30° V-notch weir with a water-level recorder (DL/N70; Sensor Technik Sirmach AG, Sirmach, Switzerland) at 5-min intervals. A rain gauge was placed in an open space on the ridge near the study area (Fig. 1a).

2.4. Soil properties

We collected 100-cm³ soil core samples from surface soil layers (the A and B horizons) and subsurface soil layers (the C horizon) from a hand-dug pit near the study area (Fig. 1a; denoted as “soil sampling point”). For each soil sample, saturated hydraulic conductivity, K_s , was measured using the falling-head test. The water retention curve (i.e. the relationship between ψ and the volumetric water content, θ) was measured using the pressure plate method. Other parameters used in flux calculations were obtained by fitting the lognormal distribution (LN) model (Kosugi, 1996) to the water retention curve. The LN model is expressed as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = Q \left[\frac{\ln(\psi / \psi_m)}{\sigma} \right] \quad [1].$$

where S_e represents the effective saturation, θ_s and θ_r are the saturated and residual volumetric water contents, respectively, ψ_m is the pressure head at $S_e = 0.5$, σ is a dimensionless parameter characterizing the width of the pore radius distribution, and Q is the complementary normal distribution function defined as:

$$Q(x) = \int_x^\infty \frac{1}{(2\pi)^{1/2}} \exp\left(-\frac{u^2}{2}\right) du \quad [2].$$

Values of all soil parameters in surface and subsurface soil layers are summarized in Table 1. The hydraulic conductivity function, $K(\psi)$, was estimated by substituting the optimized ψ_m and σ values into the following equation (Kosugi, 1996):

$$K(\psi) = K_s S_e^{1/2} \left\{ Q \left[\frac{\ln(\psi / \psi_m)}{\sigma} + \sigma \right] \right\}^2 \quad [3]$$

where the saturated hydraulic conductivity, K_s , was fixed at the geometric mean of samples for each soil layer.

The boundary between surface and subsurface soil layers was determined from an N_c value exceeding 30, because vertical profile of both N_c and K_s showed a sharp increase at the depth corresponding to $N_c = 30$ (Masaoka et al., 2012). Detailed descriptions of the penetration test and soil parameters at the study site are given in Masaoka et al. (2012).

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3. Results

3.1. Hydrological properties of groundwater seepage

This section gives an overview of hydrological processes at the study site before discussing detailed water fluxes around the groundwater seepage area. It also shows the effects of groundwater seepage on ψ distribution and the discharge hydrograph.

3.1.1 Saturated area in the soil profile

Figures 3a and 3b show the hyetograph and discharge hydrograph observed at the trench face (Fig. 1a), respectively, from 18 June to 18 July. Snapshot periods T1, T2, and T3 are selected in Figure 3 and their specifications summarized in Table 2. T1 is a no-rainfall period in relatively dry conditions just before the onset of the rainy season. T2 is at the peak of a heavy

rainfall event on 23 June (Total: 112 mm, Maximum: 12.7 mm/h). T3 is a no-rainfall period at the peak of base flow discharge throughout the observation period.

First, we focus on the distribution of the saturated area under no-rainfall conditions. Figure 4a shows the distribution of ψ for the snapshot period T1 in three-dimensions. A large saturated area lay in the middle and lower regions of the slope despite small antecedent rainfall (Table 2) and steep slope angle ($\sim 40^\circ$). The saturated area started from Line B and spread toward the lower region, branching at the center of Line D. Small saturated areas were observed scattered across the left side of the slope. Figure 4b illustrates the cross sections of ψ at T1 for Lines A to F. In Line B, a saturated area was located inside the depression of the bedrock surface at points B-4 and B-5. At these points, ψ exhibited an extremely high value ($\psi = 120 \text{ cmH}_2\text{O}$) at the soil-bedrock interface. The value of ψ was negative across the entirety of Line A, indicating that the large saturated area originated in the region between Lines A and B. At points C-6 and C-7 in Line C, ψ showed negative values at the bedrock surface, although ψ was positive in the middle part of the soil profile. The saturated area existed horizontally just above the line of $N_c = 30$ (i.e., the boundary of soil properties), indicating that vertical infiltration into deeper layer was intercepted by the low permeability subsurface soil (Masaoka et al., 2012). We found a similar saturated area distribution in Lines D and E.

3.1.2 Properties of discharge hydrographs

Figure 5b shows discharge hydrographs observed at the trench face and the spring (Fig.

1a) throughout the observation period. Note that the monitoring of trench flow stopped at 6 September due to the breakdown of the recorder. Trench flow was characterized by both direct runoff showing rapid peaks corresponding to individual rainfall events (Fig. 5a), and base flow showing gradual and significant increases after large rainfall events. Spring runoff showed a similar pattern to base flow in the trench. Such hydrographs are distinctive trends of bedrock groundwater levels and seepage through bedrock fractures (e.g., Kosugi et al., 2011; Katsura et al., 2014). Figure 5c shows the variation of ψ observed at tensiometer B-5b, where the saturated area emerged (Fig. 4b). The value of ψ was consistently positive and showed a similar pattern to both the trench base flow and spring runoff (Fig. 5b). Although the value of ψ was constantly positive at some other tensiometers located in the downslope region from B-5b, the similar variation of ψ was detected only at B-4b located adjacent to B-5b. Therefore B-5b is assumed to be the location where bedrock groundwater exfiltrates. The time-series variations of ψ at other tensiometers are discussed in later sections.

Figure 6a shows the relationship between ψ at B-5b and the spring runoff. More than 20 hours after the cessation of rainfall (denoted by yellow points in Fig. 6a), these parameters clearly showed a linear correlation. This confirms that the waveform of ψ at B-5b showed nearly the same pattern to the spring runoff. This strongly suggests the existence of a groundwater spring at the soil-bedrock interface at point B-5. As shown in the topographic map (Fig. 1a), both the spring and point B-5 are located at nearly the same elevation (1456 m). This also suggests that both waters derive from the same groundwater aquifer at the same water level.

Note that the relationship in Figure 6a does not show correlation at less than 20 hours after rainfall cessation (denoted by blue points in Fig. 6a). This is likely due to a considerable quantity of superficial flow mixed into the spring during large rainfall events, shown by relatively sharp peaks in the spring hydrograph corresponding to large rainfall events.

Figure 6b shows the relationship between ψ at B-5b and runoff at the trench face. More than 20 hours after the cessation of rainfall (yellow points in Fig. 6b), these parameters showed a distinct quadratic correlation. Such a quadratic correlation between water level and discharge implies satisfaction of the Dupuit-Forchheimer discharge formula (Childs, 1971), indicating that groundwater seepage flows down from point B-5 to the trench face as a saturated subsurface flow over a sloping bed. This strongly suggests that base flow in the trench runoff was supplied by groundwater seepage at B-5b.

This constitutes an overview of hydrological processes at our study site. A considerable amount of groundwater seeps from the bedrock surface at point B-5. The seep water flows down to the trench face as a saturated subsurface flow, creating a large saturated area in the middle and lower regions of the slope. The seep water is considered to consist mainly of base flow discharge from the trench. A detailed analysis focusing on flux vectors around the groundwater seepage is discussed below.

3.2. Flux vector around a groundwater seepage area

Properties of the water flux vector generated by the mixing of soil water and

groundwater around a seepage area are poorly understood. In this section, we analyze the magnitude and angle of water flux vectors in the soil mantle along Line V based on high-resolution ψ data.

3.2.1. Flux distribution in Line-V

To calculate flux vectors, q , in the vertical cross-section in Line V, we set triangular elements composed of three tensiometer position nodes as shown in Figure 7a. The elements are classified into surface and subsurface soils (Table 1) according to the soil boundary (i.e., $N_c = 30$; denoted by the dashed line in Fig. 7). The mean hydraulic gradient in each element was estimated from the hydraulic head (i.e., total head) in each tensiometer node, calculated as the sum of ψ and the vertical coordinates. In addition, K in each element was calculated using the functional K - ψ curves (Kosugi, 1996) shown in equation [3], and then q was calculated by multiplying K by the mean hydraulic gradient. Figures 8a, 8b, and 8c illustrate two-dimensional distributions of ψ in Line V at snapshot periods T1, T2, and T3, respectively (Fig. 3 and Table 2). Arrows in the figures denote the magnitude and direction of q . Note that no data exist from the top edge (ground surface) to the shallowest tensiometers installed at a depth of 30 cm.

3.2.1.1. No rainfall condition (T1)

Under no-rainfall conditions (T1; Fig. 8a), in the region between B-5 and F-4, ψ was mostly positive between the bedrock surface and the middle part of the profile. In the lower part of the soil mantle around B-5, ψ was extremely high (120 cmH₂O). The flux vectors pointed upward relative to the slope of the bedrock surface (elements 15 and 20; denoted by red circles

in Fig. 8). This shows that groundwater seepage around B-5 generated the exfiltration flux vectors in the soil mantle. In the upper part of the seepage area, the flux vector pointed almost vertically downward (element 14). In the lower part of the soil mantle around C-4, the flux vectors were mostly parallel to the bedrock surface (elements 16 and 12), indicating the occurrence of saturated lateral flow. In the region between D-4 and F-4, ψ was mostly positive but the value was not high ($-5 < \psi < 20$ cmH₂O) above the bedrock surface. Flux vectors pointed downward relative to the slope of the bedrock surface (e.g., element 8). In contrast, in the region between A-4 and V-2, ψ was negative and flux vectors showed vertical infiltration. In the middle part of the profile at A-4, the magnitude of the flux vectors was extremely low ($10^{-7} < q < 10^{-9}$ cm/sec) because K is low for this low ψ range.

3.2.1.2. Peak rainfall (T2)

At the peak of a rainfall event (T2; Fig. 8b), the region that was saturated at T1 expanded vertically toward the soil surface, and the connection of saturated areas between D-4 and E-4 grew. Flux vectors showed active infiltration in the shallow part of the soil mantle (e.g., element 14). Nevertheless, the flux vectors around B-5 continued to be directed upward (elements 15 and 20). On the other hand, in the lower part of the soil mantle around E-4 and F-4, ψ transiently increased up to 140 cmH₂O and strong exfiltration fluxes emerged in the area (e.g. element 8).

3.2.1.3. Peak of base flow (T3)

At the peak of base flow (T3; Fig. 8c) when groundwater seepage discharge is

assumed to be at its maximum, the saturated area expanded considerably to the upslope region between A-4 and V-1 and the shallow part of the soil profile. Flux vectors in the saturated area indicated the occurrence of active lateral flow in both the lower (e.g., element 16) and shallow (e.g., element 14) parts of the profile. Above the bedrock surface around A-4, ψ showed high positive values ($\psi = 50 \text{ cmH}_2\text{O}$) and the angle of the flux vectors was flatter compared to that of the bedrock surface, suggesting the generation of exfiltration flux, although the vectors pointed downward. In the region between E-4 and F-4, the high ψ values with exfiltration fluxes occurring at T2 (e.g., element 8) disappeared and recovered entirely to the former condition found at T1 (Fig. 8a)

3.2.2. Time-series variation of flux vectors

As described above, the magnitude and angle of the flux vector around the seepage area varied depending on both instantaneous rainfall conditions and groundwater seepage discharge. We analyzed time-series variations of flux magnitude and angle to further clarify the mixing process between rainfall infiltration and groundwater exfiltration.

Figures 9c to 9h show temporal variations in flux magnitude and angle throughout the observation period within the elements shown in Figure 8. A red line in each figure denotes the local slope of the bedrock surface below each element; for example, the red line shown in Figure 9c (element 20) denotes the slope of the bedrock surface between A-4 and B-5. If the angle of flux exceeds this line, exfiltration flux is assumed to occur within the element. The

value of the angle is represented as shown in Figure 7b. The value of the magnitude is denoted by the color gradation in each element (the maximum and minimum values of $\log q$ are shown in each figure).

3.2.2.1. Above the seepage area

Within elements 20 and 15 (Figs. 9c and 9d, respectively) located in the deeper part of the profile above the seepage area around B-5, the angles of flux consistently exceeded the local slope of the bedrock surface. We observed no rapid increases or decreases with individual rainfall events (Fig. 9a). Both magnitudes and angles showed gradual increases corresponding to the peaks of ψ at B-5b (denoted by arrows in Fig. 9b). This indicates that the flux vectors were predominantly controlled by groundwater seepage rather than rainfall infiltration.

Within element 14 (Fig. 9e) located in the shallower part of the profile above the seepage area, the angle of flux mostly showed infiltration. Although the angle showed an upward flux on several occasions (e.g., on 17 August and 16 September), this was not due to groundwater seepage because the peaks did not correspond to the peaks of ψ at B-5b (denoted by arrows) and the magnitude of the flux was quite small during upward periods. The upward peaks were probably due to evaporation, because they occurred after long periods without rainfall. However, the angle of flux increased slightly, corresponding to the peaks of ψ at B-5b (denoted by arrows), and indicating the mixing of groundwater seepage from the deeper part of profile.

3.2.2.2. Downslope from the seepage area

Within element 16 (Fig. 9f), located just downslope of the seepage area, the angle of flux was steady and almost identical to that of the local bedrock surface. This indicates the occurrence of constant saturated lateral flow over the bedrock surface. Constant lateral flow also occurred within element 12 (Fig. 9g). The angle of flux was slightly lower than that of the local bedrock surface, suggesting mixing of the infiltration flux from the shallower part. Within element 8 (Fig. 9h), located more than 4 m downslope of the seepage area, the angle of flux was near-vertical during periods of no rainfall, indicating active infiltration.

4. Discussion

4.1. Spatial/temporal variation of flux vectors

High-resolution distributions of ψ and flux vectors at the snapshot periods (Fig. 8) therefore show noteworthy soil water movements occurring along Line V. First, groundwater seepage around B-5 generated exfiltration flux vectors above the bedrock surface not only in the no-rainfall period (T1; Fig. 8a) but also at the peak of rainfall (T2; Fig. 8b). Second, exfiltration flux vectors only occurred around A-4 at the peak of base flow (T3; Fig. 8c). Third, high ψ values with exfiltration fluxes occurred in the lower region of the slope only at the peak of rainfall. In previous studies, many types of flux vector showing groundwater seepage have been reported (Terajima and Moroto, 1990; Montgomery et al., 1997, 2002; Haria and Shand, 2006) and these studies support our results. In this study, we successfully and comprehensively

observed evidence of groundwater seepage flux based on intensive hydrometric data.

Moreover, time-series variations of flux magnitude and angle (Fig. 9) further show the mixing process between rainfall infiltration and groundwater exfiltration occurring along Line V. First, above the seepage area, an exfiltration flux of groundwater seepage may be expected to occur regardless of rainfall in the deeper part (elements 20 and 15; Figs. 9c and 9d, respectively), and rainfall infiltration is likely to be mixed in the shallower part of the soil profile (element 14; Fig. 9e). Second, groundwater seepage did not occur in the downslope region from the seepage area around B-5. In this region, saturated lateral flow over the bedrock surface occurred constantly. Flux vectors indicated the occurrence of dominant lateral flow just downslope from the seepage area (element 16; Fig. 9f), and the mixing of infiltration water flowing toward the lower end of the slope (elements 12 and 8; Figs. 9g and 9h, respectively). Although most studies on the interaction between groundwater and surface-water discuss the dynamics of bedrock groundwater at the hillslope scale (e.g., Haria and Shand, 2006; Banks et al., 2009), flux vectors generated by groundwater seepage in soil layers have not been discussed. Ours is the first study to clarify the effect of groundwater seepage on near-surface hydrological processes in which water movement and sediment transport actively occur. Our findings may contribute to the prediction of surface hydrogeomorphological processes such as streamflow generation, stream bank erosion, solute transport, and shallow landslides induced by groundwater seepage in mountainous hillslopes.

By analyzing the angle of flux vector at the soil-bedrock interface, we successfully

distinguished between the seepage area and saturated areas. The saturated area exhibiting an exfiltration flux at the soil-bedrock interface can be determined as the area of groundwater seepage. Other saturated areas are considered to be generated by receiving lateral flow from upslope. In the seepage area around B-5, groundwater seeped consistently. However, temporal groundwater seepage were detected around A-4 (Fig. 8c) and E-4 (Fig.8b). The mechanism of these temporal seepage is discussed in later sections.

4.2. Fluctuations in the shape of the seepage area

As described above, we detected a saturated area exhibiting an exfiltration flux above the bedrock surface at A-4 only at the peak of base flow (T3; Fig. 8c). In this section, we verify whether the saturated area is the expansion of the seepage area from B-5. Figures 10b to 10h show the time-series variations of ψ at tensiometer nests located along Line V (except V-2b) from 18 June to 18 July.

At A-4b (Fig. 10c), ψ was negative and showed a rapid decrease during low base flow periods (e.g., T1 and T2). However, ψ was positive and showed gradual variations during the high base flow period (e.g., T3). The waveform was nearly identical to that of B-5b (Fig. 10d). This indicates that the groundwater seepage area around B-5b expanded in the upslope direction to A-4b only during high base flow periods. Thus, the saturated area exhibiting an exfiltration flux around A-4b, shown in Figure 8c, is confirmed as an expansion of the seepage area. The value of ψ remained negative at V-1b (Fig. 10b) located upslope of A-4b, showing that the

seepage area did not expand to V-1b even during the highest base flow period. According to the distributions of the saturated areas at T1 and T3 (Figs. 8a and 8c, respectively), the seepage area expanded ~3 m upslope in one season.

In contrast, the seepage area did not expand downslope, because the flux vector showed constant lateral flow throughout the observation period within element 16 (Fig. 9f). Although the waveform of ψ at C-4b (Fig. 10e) showed similar characteristics to that at B-5b, this effect is attributed to the propagation of seepage pressure.

The expansion of the seepage area is thus clearly shown by variations in ψ and flux distributions. Our observations comprehensively capture evidence of expansion that has been reported piecewise in previous studies (Terajima and Moroto, 1990; Haria and Shand, 2004; Katsura et al., 2008). Moreover, this study is the first to observe the expansion distance based on high resolution data. This can be closely related to the rate of direct runoff, because the saturated area increases the storm flow generation rate by increasing subsurface lateral flow (Tromp-van Meerveld and McDonnell, 2006).

4.3. Propagation of seepage pressure

The unique waveform of ψ observed at A-4b and B-5b (Figs. 10c and 10d, respectively) shows a distinctive trend in groundwater seepage. However, this waveform may diminish through downward propagation of pressure. The process and reach of pressure propagation is essential for investigating the presence of groundwater seepage. In this section,

we analyzed the propagation process of the ψ waveform exhibiting a distinct groundwater seepage trend.

At B-5m (Fig. 10d) located just above B-5b in the middle part of the profile, the shape of the ψ waveform was similar to that at B-5b. However, the range of variation was smaller than that of B-5b. This indicates that seepage pressure propagates upward from the bedrock surface to the middle part of the profile.

At C-4b and C-4m (Fig. 10e) located downslope of B-5b, the ψ waveforms also show a similar shape with a smaller variation compared to those at B-5b. Since we detected no exfiltration flux around C-4b (Figs. 9f and 9g), the waveforms were likely due to damped propagation of seepage pressure from upslope, rather than local groundwater seepage. In the downslope region, heavily-damped seepage pressure was detected at D-4m (Fig. 10f), and no seepage pressure propagation was found at tensiometer nests E-4 and F-4 (Figs. 10g and 10h, respectively).

Such damping of seepage pressure is due to the spread of seepage water through a soil layer with high permeability. Between D-4 and E-4, soil permeability appears high because the surface soil layer is relatively thick compared to the upslope region (Fig. 7a). Thus the seepage pressure generated at B-5b was considered to diminish and disappear in this area.

Notably, seepage pressure can propagate within quite a narrow area: a slope distance of ~4 m from the seepage point downslope in the study area. The waveform disappeared completely even in the constantly saturated area formed by groundwater seepage. Our results

suggest that the ψ waveform observed in saturated areas does not always reflect the hydrograph of seepage discharge or base flow discharge of a slope. To detect the waveform of groundwater seepage, it is necessary to observe ψ as close to a seepage point as possible.

4.4. Ephemeral exfiltration flux

At E-4b (Fig. 10g), ψ was constant under no-rainfall conditions. However, ψ increased sharply to an extremely high value ($\psi = 120 \text{ cmH}_2\text{O}$) with individual rainfall events, and declined immediately to the base value just after the cessation of rainfall. Similar ψ characteristics were also detected at F-4b and F-4m (Fig. 10h). Around these points, exfiltration fluxes were generated ephemeraly at the peak of rainfall (e.g., element 8; Fig. 8b). This response is not considered to be the process of vertical infiltration or lateral flow in the soil mantle because ψ did not show such a spiky response in shallow layer (E-4s and E-4m; Fig. 10g) or upslope area (D-4b; Fig. 10f).

In previous studies, Montgomery et al. (1997, 2002) reported similar hydrological responses: a sharp increase in ψ with the generation of exfiltration flux in a near-surface fractured bedrock layer. It was suggested that rapid lateral saturated flow through heterogeneously-distributed bedrock fractures may lead to locally high ψ and resulting transient exfiltration fluxes only during intense rainfall periods. That is, a local downslope decrease in fracture conductivity can drive flow upward into the overlying soil layer. In our study, the angle of the flux vector within element 8 (Fig. 9h) remained predominantly in the vertical downward

direction during no-rainfall periods, suggesting that the infiltration of soil water into bedrock is constant. This implies high permeability of shallow bedrock in this area, probably due to developed fractures, as in the case reported by Montgomery et al. (1997, 2002).

Although an exfiltration flux occurred, this process is completely different from the groundwater seepage detected at B-5b exhibiting a constant exfiltration flux and gentle variations in ψ . This process, with an ephemeral exfiltration flux, is considered a form of direct runoff process. Thus in this study, we observed two types of exfiltration flux with different peak timings in the same hillslope. Since exfiltration fluxes lead to shallow landslides (e.g. Brönnimann et al., 2013), our results may predict the timing of landslides associated with rainfall intensity. Additionally, the ψ response did not clearly correspond to rainfall intensity: ψ increased only slightly or not at all after July 2011 at E-4b and F-4m (Fig. 10g and 10h, respectively). Further analysis is needed to clarify the mechanism of these irregular responses.

4.5. Spatial distribution of seepage area

In this section, we examine the relationship between the spatial distribution of the seepage area and topographic factors in the ground and bedrock surface. Figure 1b shows a ground surface topographic map. Figure 1c shows the topographic map and soil thickness distribution of the bedrock surface. We detected the spatial distribution of the seepage area across the whole study area by calculating angles of flux vectors using the method shown in Figure 7. To calculate the flux vectors, triangular elements (Fig. 7a) were set on the bedrock

surface for all pairs of longitudinally-adjacent observation points in the study area (e.g., C-2 and D-2). Flux vector angles within elements were calculated as described above. Figures 11a to 11c show distributions of angular difference between flux vectors and the local bedrock surface at T1–T3, respectively. A positive value of angular difference indicates an exfiltration flux relative to the slope of the local bedrock surface. Each figure also shows the distribution of the saturated area at the soil-bedrock interface. In each figure, the saturated area exhibiting an exfiltration flux can be determined from the area of groundwater seepage.

At T1 (Fig. 11a), an area of groundwater seepage was detected around B-5, which has been described in the previous sections. No other seepage area was found in the study area. At T2 (Fig. 11b), ephemeral seepage areas emerged in the middle and downslope regions of the study area as well as the seepage area around B-5. At T3 (Fig. 11c), the seepage area around B-5 expanded upslope along Line V, passing through the valley line of the bedrock surface (Fig. 1c). The ephemeral seepage areas have disappeared and no other seepage areas were found in the study area.

Thus, in the study area, groundwater seeps perennially from a narrow area located at the bottom of the valley line of the bedrock surface (Fig. 1c), and not from the broader area regardless of topography. The location of seepage did not correspond to ground surface topography (Fig. 1b). Moreover, the shape of the seepage area changed along the valley line depending on the seepage discharge. These results suggest that groundwater seeps through cracks in the bedrock distributed along the bottom of the bedrock valley, since bedrock

topography is strongly affected by geological constructions. Recent studies demonstrated the effectiveness of dense bedrock topographical surveys for precisely predicting runoff generation (Freer et al., 2002) and shallow landslide occurrence (Uchida et al., 2009). Our results show that an intensive survey of bedrock topography may improve the accuracy of predicting runoff generation and landslide occurrence, as bedrock surface valleys may be related to the presence of cracks, which act as the flow path for groundwater seepage.

In contrast, the location of ephemeral seepage areas (Fig. 11b) did not correspond to either surface or bedrock topographies. This may be due to the heterogeneous distribution of fractures in near-surface bedrock. For now, it is hard to predict the location of such phenomena.

4.6. Conceptual model of the study site

Although recent hydrological studies demonstrated substantial impacts of bedrock groundwater seepage on hydrological processes in a foot slope area, properties of water flux vectors around a seepage area are less understood because previous studies have lacked sufficient spatial resolution to capture detailed water movements. The main unresolved issues are (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.

Based on the results we obtained using the high-resolution and three-dimensional tensiometer nest presented above, we developed conceptual models describing the detailed

process of groundwater seepage and its interaction with surface water. To this end, we provide the following potential solutions to the unresolved issues above:

(1) Figure 12a summarizes the process of flux vectors generated by groundwater seepage in the vertical cross-section of the soil mantle. Above the seepage area, flux vectors point upward relative to the slope of the bedrock surface, indicating groundwater exfiltration from bedrock to soil mantle. This exfiltration flux occurred regardless of rainfall conditions just above the seepage area (1 in Fig. 12a). In the region downslope of the seepage area, saturated lateral flow over the bedrock surface occurred constantly (2 in Fig. 12a). The mixing of infiltration water was also likely to occur through flow toward the lower end of the slope (3 in Fig. 12a).

(2) Temporal fluctuations in saturated area and variations in ψ clearly demonstrated the expansion of the seepage area. The seepage area expanded upslope a distance of ~3 m along the bedrock valley in a single season (4 in Fig. 12a). The seepage area did not show expansion in the downslope direction.

(3) Figure 12b summarizes the propagation process of seepage pressure in the vertical cross-section of the soil mantle (Fig. 12a). The ψ waveform observed in the seepage area showed gradual and significant increases after large rainfall events (1 in Fig. 12b). In the region downstream of the seepage area, the waveform of ψ showed a similar shape with less variation, indicating the damped propagation of seepage pressure from upslope areas (2 in Fig. 12b). The seepage pressure is heavily damped and does not propagate to the lower end of the slope (3 in

Fig. 12b). As a result, the seepage pressure propagates within quite a narrow area: a slope distance of ~4 m downslope from the seepage point.

(4) Figure 12c summarizes the distribution and fluctuation of the shape of the seepage area within the whole hillslope. 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 during the wet season. Additionally, we observed another type of exfiltrating flux: flux vectors pointed upward ephemerally at the peak of rainfall. The location of ephemeral exfiltration areas did not correspond to either surface or bedrock topographies.

5. Conclusion

We conducted hydrometric observations using unprecedentedly high-resolution tensiometer nests in a mountainous foot slope area of the Hirudani experimental basin, central Japan, and demonstrated that bedrock groundwater seepage consistently generated exfiltration flux vectors in the soil mantle. Detailed hydrological properties of bedrock groundwater seepage and their effects on soil water movements may be summarized as follows: (1) a considerable amount of groundwater seeped from the bedrock surface in the study site. The exfiltration flux occurred constantly from the seepage area regardless of rainfall conditions. Saturated lateral flow over the bedrock surface occurred constantly in the region downslope from the seepage area. Groundwater was considered to be mixed with soil water infiltration by flow toward the

lower end of the slope. (2) During the wet season, the seepage area expanded upslope ~3 m along the bedrock valley in a single season. (3) The waveform of ψ 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 downslope from the seepage point, due to damping of the 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.

Our study demonstrates the spatial/temporal variation of bedrock groundwater seepage under the soil mantle and its effects on soil water fluxes. Our findings should improve the accuracy of models predicting near-surface soil hydrogeomorphological processes in mountainous hillslopes. The results also indicate a strong connection between surface and bedrock hydrological processes. Future goal is to build up a conceptual model to predict runoff generation and landslide occurrence in mountainous watersheds comprehensively accounting near-surface and bedrock hydrological processes. Our observations revealed the process of groundwater seep from bedrock and flow through near-surface soil layer. However, the properties of seepage water such as discharge hydrograph, chemistry, and residence time are still unpredictable because the dynamics of bedrock groundwater underlying surface processes remains undetermined. Future work should determine the hydrological processes of groundwater in deep bedrock by using intensive bedrock wells (e.g., Kosugi et al., 2011) as well as indirect geophysical explorations.

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Figure legends

Figure 1. (a) Map of the study area. (b) Ground surface topographic map and location number of all observation points. (c) Bedrock surface topographic map and soil thickness distribution.

Figure 2. Locations of 114 tensiometers (denoted by red dots) in three dimensions.

Figure 3. (a) Hyetograph, and (b) hydrograph of the trench flow. Snapshot periods T1, T2, and T3 are denoted by red dashed lines.

Figure 4. (a) Distribution of pressure head, ψ , at T1 in three dimensions. The opaque region indicates the saturated area. (b) Distribution of ψ at T1 for two-dimensional cross sections of Lines A to F. Dashed lines denote the boundary between surface and subsurface soil layers (i.e., $N_c = 30$)

Figure 5. (a) Hyetograph, (b) hydrographs of the trench flow and the spring (Fig. 1), and (c) pressure head, ψ , at tensiometer B-5b throughout the observation period.

Figure 6. (a) Pressure head, ψ , at B-5b vs. runoff, Q , at the spring. (b) ψ at B-5b vs. Q at the trench face. Point color denotes time elapsed since the cessation of rainfall events.

Figure 7. (a) Location of triangular elements for the cross-section of Line V for calculating flux vectors. (b) Representation of flux vector and bedrock surface angles used in Fig. 9. Note that no data exist from the top edge (ground surface) to the shallowest tensiometers installed at a depth of 30 cm.

Figure 8. Distributions of pressure head, ψ , for two-dimensional cross sections of Line V at (a) T1, (b) T2, and (c) T3, respectively. Rectangles denote the positions of tensiometer porous caps. Arrows denote the direction and volume of water flux vectors. Red circles and numbers denote the location of triangular elements shown in Figure 9(c)-(h).

Figure 9. (a) Hyetograph, (b) pressure head, ψ , at tensiometer B-5b, (c)–(h) angle and magnitude of flux vectors within triangular elements 20, 15, 14, 16, 12, and 8, respectively, throughout the observation period. Red lines denote the slope of the local bedrock surface.

Figure 10. (a) Hyetograph, (b)–(h) pressure head, ψ , at tensiometer nests V-1, B-5, C-4, D-4, E-4, and F-4, respectively.

Figure 11. Distributions of angular difference between flux vectors above the bedrock surface and the local slope of the bedrock at (a) T1, (b) T2, and (c) T3. Shaded areas show the distribution of the saturated area on the bedrock surface.

Figure 12. Conceptual models of hydrological processes at the study site.

Table 1. Soil hydraulic parameters θ_s , θ_r , ψ_m , σ , and K_s measured using the pressure plate method and the falling-head test, used in flux calculations.

	θ_s	θ_r	ψ_m [cm]	σ	Geomean K_s [cm/s] (minimum, maximum)
Surface soil ($0 < N_c < 30$)	0.534	0.247	-10.3	1.19	0.346 (0.134, 0.495)
Subsurface soil ($30 < N_c < 100$)	0.347	0.0496	-714	2.78	0.000441 (0.00007, 0.00388)

Table 2. Instantaneous runoff and rainfall, and rainfall accumulated in the antecedent three days, during the snapshot periods T1, T2, and T3.

	Date in 2011	Runoff, Q [m ³ /hr]	Rainfall [mm/hr]	Acc. rainfall in antecedent 3 days [mm]
T1	0:00 on 22 June	0.188	0	7.1
T2	10:30 on 23 June	0.822	12.7	84.6
T3	12:00 on 9 July	1.334	0	80

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Figure 1

- Tensiometer observation points
- Spring
- Rain gauge
- Soil sampling point
- ▭ Study area (74.0m²)
- ▭ Landslide scarp
- ▭ Trench face

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12