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ORIGINAL ARTICLE

Using hydrogen, oxygen, and tritium isotopes to identify the hydrological factors contributing to landslides in a mountainous area, central Taiwan

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Abstract Over a 1-year period, 343 samples, including precipitation, creek, pond, and groundwater, were collected from June 2003 to May 2004. Analyses were performed for stable oxygen and hydrogen isotope compositions. Selected samples were also analyzed for tritium. The goal was to identify possible hydrologic factors contributing to a severe landslide in the Li-Shan area, central Taiwan. The isotope characteristics indicate that groundwater from Fu-Shou-Shan farm located up-slope from the landslide area is a major source for slope groundwater, in addition to precipitation. The groundwater is mainly recharged by pond water at Fu-Shou-Shan farm. According to the calculation of a two-end member equation with δ^{18}O, the contribution of farm groundwater to slope groundwater is significantly higher than that of precipitation, up to a factor of five. The estimated drainage efficiency of the existing system is only 23%. Draining off the slope groundwater in the up-slope region to decrease farm groundwater flow into the slope area is a feasible strategy to effectively reduce the risk of landslide.

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Introduction

Taiwan is located at the collision area between the Philippine Sea plate and Eurasian plate in the western Pacific Ocean (Fig. 1a) and has been tectonically active with an uplift rate of 2–5 mm/year since Pleistocene orogeny (MOEA 1982). The areas of steep mountain terrain above 1,000 m and the hills/terraces between 100 and 1,000 m in elevation make up 32 and 31% of Taiwan, respectively. In addition to the steep topography, more than 200 recorded earthquakes per year occur. These quakes, accompanied by the active tectonics, persistently weaken the rocks (Tsai 1986).

Typhoons and thunderstorms during the wet season from May to October bring about 78% of the annual precipitation (2,515 mm), primarily in the mountainous region (WRA 2003). The heavy precipitation in rainy season causes a high erosion rate of 3–6 mm/year (Dadson et al. 2003), and also numerous landslides in mountain and hill regions.

Mass load and slope gradient are two major factors affecting slope stability in the slide-prone area. Water also plays an important role for the mass movement in the slope region. During a heavy rain event, infiltrated rainwater will increase the mass load of the slope and provide extra pore water pressure that can reduce shear resistance and eventually cause slope failure (West 1995). Engineers usually drain the excessive slope groundwater with a drainage system to maintain slope stability. In addition to precipitation, surface water or groundwater from adjacent catchments may

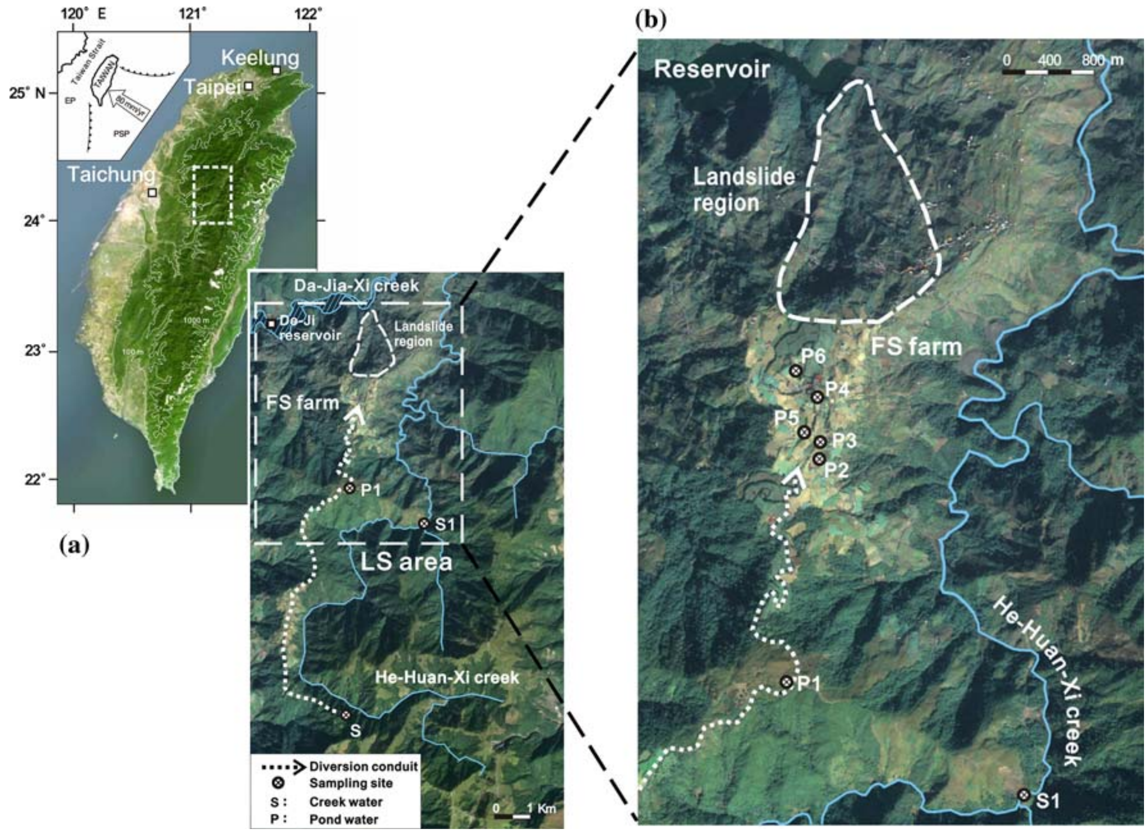

Fig. 1 Images of study area. **a** Sampling sites of creek water samples (S and S1) near LS area; the landslide region lay beside the FS farm and near the De-Ji reservoir. **b** Sampling sites of ponds in FS farm

also contribute significant amounts of water to a slope region and promote the probability of landslides. Because precipitation is difficult to predict; one effective way to reduce the risk of landslides is to investigate and control water sources other than precipitation, i.e., local surface and groundwaters.

Learning how and what sources recharge slope groundwater in a landslide region will provide effective methods for landslide prevention. Using artificial tracers to identify the groundwater sources on a regional scale is very difficult. Most artificial tracers are solutes of water and are often limited by the questions of how, when, and where to put in the tracer and retrieve the sample for verification (IAEA 1983). By contrast, environmental isotopes such as hydrogen, oxygen, and tritium are compositions of water molecule. They best approximate water behavior (Clark and Fritz 1997; Criss 1999) and can serve as suitable tools for tracing water pathways and contributions.

Stable isotopic compositions of water are constantly fractionated by temperature, topography, season, and evaporation effects. Unique hydrogen and oxygen isotopic signatures can be differentiated from waters formed in various environments (Dansgaard 1964; Criss 1999; Yurtsever and Gat 1981). Hydrogen and oxygen isotope compositions in water are hardly affected by water-rock reaction under normal temperatures (Fritz 1981; McCarthy et al. 1992; Lee et al. 1999). This conservative nature of stable isotopes renders them applicable tracers to investigate hydrologic relations between different water bodies.

Tritium is a radioisotope of hydrogen with a half-life of 12.43 years (Unterweger et al. 1980). The background (pre-atomic bomb) levels of cosmogenic tritium have been determined to be 5–10 TU (Tritium unit = one tritium atom per 10^{18} protium atoms) in the troposphere (Kaufman and Libby 1954; Allison and Hughes 1977). A peak concentration of tritium, produced by thermonuclear testing was measured at 10,000 TU in precipitation of the northern Hemisphere during the mid-1950s and -1963s (Ingraham 1998). Since nuclear testing in the area ceased in 1963, tritium concentration in precipitation has significantly dropped and returned to background levels. With the relative short half-life of tritium, it is hard to distinguish water formed between pre- and post-mid-1950s (Ingraham

1998). Tritium is still a useful tracer for differentiating old groundwater from current meteoric water if background values are available.

The location of this case study, Li-Shan (LS), is in central Taiwan (Fig. 1b), and has been a popular resort in the upstream catchments of Da-Jia-Xi river. A significant landslide of 182 ha occurred at LS in April 1990 following successive rainfall events. Most government and civil buildings of LS were destroyed and this famous tourism spot suddenly became a hazardous area.

Drainage systems including wells, pipes, and galleries, have been constructed continuously to drain groundwater within the slide body to stabilize the slope (Fig. 2a). Although the drainage systems have reduced the slope slip rate, the drainage has other sources besides precipitation providing the high landslide risk in LS. The drainage system drained off considerable water even in the winter dry season (Lai 2000). The additional water source was suspected to come from Fu-Shou-Shan farm (FS) located upslope to the LS landslide area (Fig. 1b), but there was no clear proof.

The purposes of this study are (1) employ hydrogen, oxygen, and tritium isotopes as natural tracers to identify the possible sources of slope groundwater in LS landslide area, and (2) to evaluate the drain efficiency for the ongoing drainage system by analyzing the isotopic and hydrologic data between various water bodies. If the additional source besides precipitation can be identified, drainage practices in the slope region can be greatly improved.

Study area

LS is located at the upstream catchments of Da-Jia-Xi basin adjacent to the De-Ji reservoir (Fig. 1b). The annual mean rainfall from 1991 to 2004 was 2063 mm based on records of FS meteorological station; 68% of rainfall fell during the local rainy season from April to September, 1 month ahead of the Taiwan average. The local dry season is from October through March.

Geologically, bedrock in the LS area consists of the Miocene Lushan Formation, black to dark gray argillite, slate, and phyllite (MOEA 1975). Because of the active tectonic uplift in Taiwan, fluvial erosion valleys with down-incised and U-turned landscape are common. In addition, platforms of *Ecktreppe* (paleo-fluvial terrain with high, wide, and flat landform located at the divide between two valleys) are notable around the LS area (Lin 1957). Sand and gravel layers with coarse sediment are found in the *Ecktreppe* owing to fluvial deposition. *Ecktreppe* is suitable for farming or inhabitation in mountainous areas due to its gentle landform.

The geological survey of the post-landslide event in 1990 by Energy and Resources Laboratories (ERL) indicated that the landslide region was an ancient weathering slide body lying above the fresh basement (Fig. 2b; ERL 1993). The slide body is composed of weathering slate with debris and clay soil; its structure is loose and poorly cohesive. Due to lithological monotony, it is hard to stratify the slate strata. ERL (1993) divided the slide profile into five sections depending on varying degrees of weathering components. The slide plane occurred at 30–60 m below ground (Fig. 2b).

The FS farm, located directly above the LS landslide area, has an area of 155 ha (Fig. 1b). Irrigation water in this farm comes from ponds that are supplied from He-Huan-Xi creek, a tributary of Da-Jia-Xi river, at site S by a closed diversion conduit with siphon function all year round (Fig. 1a). The creek water is gravity-transported to pond P1 with a flow rate of 8 m^3/min. From P1, the water transfers to other ponds via conduits (Fig. 1b). Although irrigation mainly relies on pond water, rainwater serves as a major supplement during the rainy season.

Sampling and analytical methods

Water samples from precipitation, creek, pond, and groundwater were collected from June 2003 to May 2004. Sampling locations are shown in Figs. 1 and 2. Surface and groundwaters were sampled one to three times per month during the study period, and precipitation were collected on each raining day.

Mu-Lan Bridge (S1) and water-taken site (S) are two sampling sites of He-Huan-Xi creek (Fig. 1a). Because site S is very difficult to reach by traffic, water samples of S were only taken in June and August 2003. Pond waters were taken from six representative irrigation pools of FS farm, labeled as P1, P2, P3, P4, P5, and P6 (Fig. 1b). Groundwaters were taken from the existing drainage system designed to stabilize the slide slope, sites including wells of W1, W2, W3, W4, W6, W15 and W16; galleries of G1 and G2; transverse pipe HB-4 (Fig. 2a). In short, HB-4, W1, W2, W3, W15, W16, and W4 are lined sequentially from up to down along the slope (Fig. 2b). Two galleries (G1 and G2) transect the slope with 350 and 550 m in length, respectively, and are used to gather and drain off the groundwater in slope.

All waters, including 119 creek and pond samples, 153 groundwater samples, and 71 precipitation samples

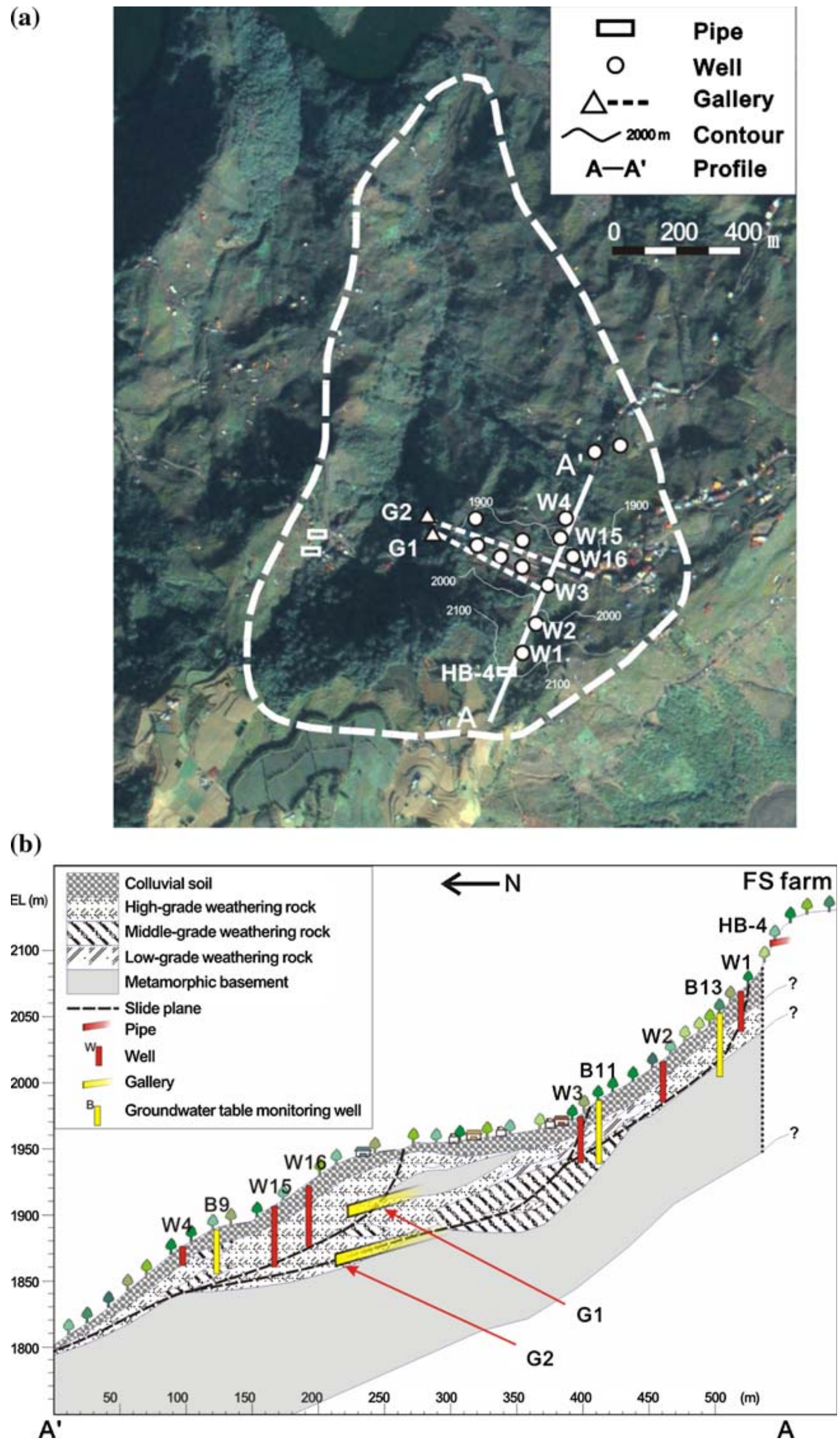

Fig. 2 Sampling location of slope groundwater in LS region. **a** The drainage system included wells, pipes, and galleries in the landslide region. Groundwater samples were taken from the drainage of the drain facilities on A–A′ profile in landslide slope. **b** Geological section of A-A′ of the landslide slope

were analyzed for oxygen and hydrogen isotopic compositions. In addition, nine of these samples were chosen to determine their tritium concentrations. Tritium concentrations of four precipitation samples in central and north Taiwan (i.e., sites of Taichung and Keelung; see Fig. 1a for their locations) were also measured for comparison.

Stable oxygen isotopic compositions were analyzed by well-known CO_2–H_2O equilibration method (Epstein and Mayeda 1953). The equilibrated CO_2 gas was measured by a VG SIRA 10 isotope ratio mass spectrometer. The hydrogen isotopic compositions were determined on a VG MM602D isotope ratio mass spectrometer after reduction of water to H_2 using zinc shots made by Biogeochemical Laboratory of Indiana University (Coleman et al. 1982). All isotopic ratio results are reported as the δ-notation (‰) relative to the international VSMOW (Vienna Standard Mean Ocean Water) standard and normalized on the scale that the $\delta^{18}O$ and δD of SLAP (Standard Light Antarctic Precipitation) are –55.5 and –428‰, respectively. The analytical precisions expressed as 1σ for the laboratory standards are ±1.3‰ for δD and ±0.08‰ for $\delta^{18}O$, respectively. The average differences of duplicate analyses of water samples are ±1.5‰ for δD and ±0.11‰ for $\delta^{18}O$, respectively.

Tritium was determined in the dating laboratory of National Taiwan University with liquid scintillation counter. Repeated analyses of samples and laboratory standards are 0.2 TU.

Results and discussion

Isotopic characteristics of precipitation and surface water

The relationship between the stable hydrogen and oxygen isotopes of precipitation during the study period (June 2003–May 2004) is showed in Fig. 3, and the regression line that represents the local meteoric water line (LMWL) is $\delta D = (8.21 \pm 0.07)\ \delta^{18}O + (13.51 \pm 0.59)$ ($r^2 = 0.99$, $n = 71$). This LMWL is similar to the global meteoric water line (GMWL) defined by Craig (1961), and also to the recent global relationship of $\delta D = (8.17 \pm 0.07)\ \delta^{18}O + (11.27 \pm 0.65)$ as described in Rozanski et al. (1993). In Fig. 3, the isotope data of surface water and groundwater of this study are all distributed along with the LMWL, indicating that the stable isotopes of both surface and groundwaters do not have effects of water-rock interaction or significant evaporation and can thus be regarded as conservative.

The stable isotope compositions of precipitation samples varied widely and exhibited distinct seasonal variations. The weighted mean values are –7.6 ± 3.5‰ for $\delta^{18}O$ and –49 ± 29‰ for δD, respectively; their coefficient of variation (CV) values are 46% for $\delta^{18}O$ and 59% for δD, respectively (Table 1). The mean $\delta^{18}O$ and δD for rainy season (April-September) are –8.7 and –59‰, respectively, and those for dry season (October-March) are –5.0 and –26‰, respectively. More depleted isotopic compositions are found in the summer rainy season than the winter dry season. This feature has been commonly observed in other regions of Taiwan (Liu 1984; Peng et al. 2002; Wang and Peng 2001), primarily due to the amount effect of precipitation.

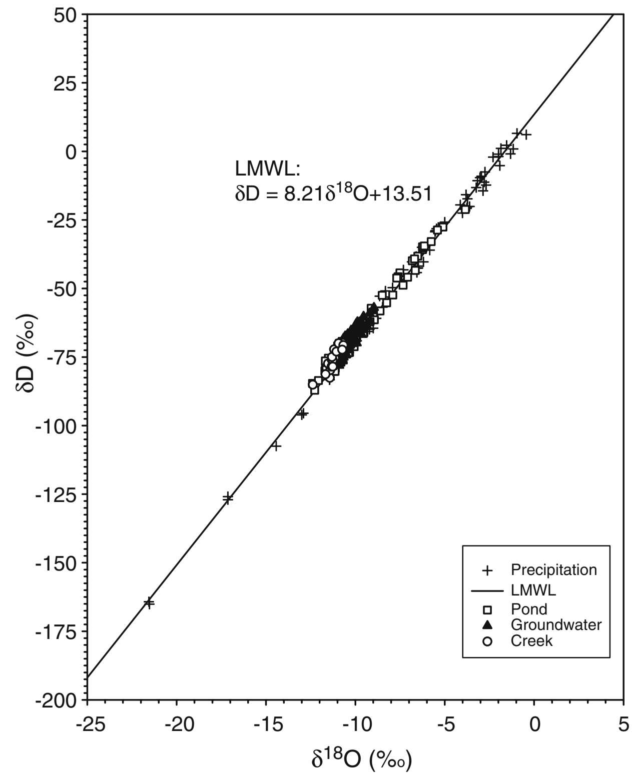

Fig. 3 Plot of δD versus $\delta^{18}O$ of precipitation, surface water, and groundwater samples in LS region. The local meteoric water line (*LWML*) is established as $\delta D = 8.2 \times \delta^{18}O + 13.5$ by data of local precipitation

The tritium concentrations (TU) of precipitation show a relative narrow range and can be taken as modern background values in Taiwan. The TU values of LS precipitation range from 1.5 to 3.2 TU and are similar to those of central and north Taiwan, such as Taichung and Keelung (Table 2 and Fig. 1). In addition, precipitation TU values show no significant difference between rainy and dry seasons (Table 2).

Table 1 shows stable isotope compositions of S site were essentially similar to those of S1 for the summer of 2003; thus S1 was taken to represent the stable isotopic characteristics of He-Huan-Xi creek in this study due to the difficult sampling access to S site. The mean values of S1 are –11.3‰ for $\delta^{18}O$ (CV value = 4%), and –76‰ for δD (CV value = 6%), respectively (Table 1). Generally, S1 has relative heavier $\delta^{18}O$ and δD values in dry season than those in rainy season (enriched 0.3 and 4‰, respectively). Moreover, the mean $\delta^{18}O$ and δD of creek water (S1) are relatively lighter than those of precipitations by 3.7 and 26‰, respectively, indicating that the creek primarily derives from the catchments higher than LS region.

P1 pond is the major irrigation source for FS farming and is recharged from He-Huan-Xi creek (Fig. 1a).

Table 1 Monthly mean stable oxygen and hydrogen isotopic compositions for precipitation, surface, and drainage water in Lishan area

Samples	2003							2004					Rainy season (April-September)	Dry season (October-March)	Mean (CV)
	June	July	August	September	October	November	December	January	February	March	April	May			
(1) Oxygen isotope (unit in ‰)															
Precipitation[a]	–10.64	–10.26	–13.44	–8.79	–8.32	NA	NA	–4.73	–7.41	–2.99	–2.33	–6.93	–8.73	–5.04	–7.58 ± 3.50 (46%)
Stream															
S	–11.43		–11.75												
S1	–11.29	–11.41	–11.74	–11.47	–11.30	–11.31	–11.19	–10.69	–11.06	–10.94	–10.67	–10.74	–11.36	–11.11	–11.26 ± 0.41 (4%)
Pond															
P1	–11.39	–11.54	–12.40	–11.56	–11.57	–11.51	–11.68	–10.90	–11.14	–11.00	–10.13	–10.31	–11.51	–11.34	–11.44 ± 0.73 (6%)
P2	–11.12	–10.89	–12.07	–11.71	–11.64	–11.65	–11.04	–10.74	–10.04	–8.50	–6.82	–10.20	–10.98	–10.75	–10.88 ± 1.40 (13%)
P3	–11.14	–10.82	–12.27	–11.68	–11.25	–10.82	–10.24	–9.12	–8.62	–7.51	–9.61	–10.03	–11.29	–9.83	–10.69 ± 1.36 (13%)
P4	–8.99	–8.25	–10.07	–10.34	–10.43	–10.28	–9.43	–5.11	–7.61	–6.51	–6.25	–9.76	–9.31	–8.54	–8.99 ± 1.69 (19%)
P5	–9.56	–8.94	–10.79	–10.33	–10.16	–10.88	–10.78	–6.25	–7.69	–5.41	–6.69	–5.76	–9.35	–8.76	–9.11 ± 2.49 (27%)
P6	–9.45	–7.33	–9.18	–10.38	–9.93	–9.97	–7.91	–6.22	–7.08	–3.85	–6.14	–6.65	–8.73	–7.84	–8.36 ± 1.88 (22%)
Groundwater															
HB-4	–10.91	–10.99	–11.42	–10.75	–10.91	–10.93	NA	NA	–10.84	NA	–10.71	NA	–10.98	–10.90	–10.95 ± 0.24 (2%)
W1	–11.05	–10.89	–10.80	–10.80	–10.54	–10.88	–10.92	–10.88	–10.58	–10.66	–10.41	–10.49	–10.79	–10.71	–10.76 ± 0.23 (2%)
W2	–10.84	–10.94	–10.90	–10.60	–10.81	–10.93	–10.66	–10.70	–10.58	–10.57	–10.26	–10.66	–10.74	–10.72	–10.73 ± 0.19 (2%)
W3	–10.50	–10.61	–10.69	–10.71	–10.70	–10.84	–10.71	–9.96	–10.30	–10.51	–10.00	–9.81	–10.49	–10.53	–10.51 ± 0.32 (3%)
W4	–10.35	–10.34	–10.64	–10.53	–10.64	–10.43	–10.42	–10.30	–9.89	–9.92	–9.75	–9.66	–10.34	–10.32	–10.33 ± 0.34 (3%)
W15	–9.93	–10.65	–10.74	–10.28	–10.44	–10.43	–10.24	–10.19	–9.67	–9.54	–9.35	–10.17	–10.28	–10.13	–10.22 ± 0.44 (4%)
W16	–9.99	–9.21	–11.26	–10.14	–10.24	–10.46	–10.01	–8.96	–9.77	–9.59	–9.07	–9.18	–10.15	–9.84	–10.03 ± 1.02(10%)
G1	–10.85	–10.77	–10.96	–10.90	–10.91	–10.91	–10.98	–10.98	–10.96	–10.78	–10.60	–10.99	–10.87	–10.92	–10.89 ± 0.11 (1%)
G2	–10.71	–10.77	–10.87	–10.81	–10.80	–10.93	–10.76	–10.91	–10.85	–10.67	–10.62	–10.82	–10.79	–10.82	–10.80 ± 0.10 (1%)
(2) Hydrogen isotope (unit in ‰)															
Precipitation[a]	–75.2	–68.7	–97.4	–58.8	–52.2	NA	NA	–22.8	–44.0	–11.1	–8.4	–46.0	–59.1	–25.9	–48.5 ± 28.5 (59%)
Stream															
S	–81.6		–79.3												
S1	–79.0	–79.8	–79.5	–78.8	–78.5	–75.0	–72.2	–69.9	–73.0	–70.0	–70.7	–72.3	–77.7	–73.9	–76.1 ± 4.5 (6%)
Pond															
P1	–79.5	–78.4	–84.6	–77.8	–78.0	–75.4	–76.4	–70.0	–74.1	–71.0	–66.5	–68.5	–78.2	–74.7	–76.7 ± 6.3 (8%)
P2	–79.1	–73.7	–83.6	–80.0	–79.6	–81.1	–72.2	–69.3	–66.7	–52.5	–39.9	–70.8	–75.3	–71.6	–73.8 ± 12.0 (16%)
P3	–80.2	–72.3	–87.1	–78.9	–78.2	–71.4	–67.6	–57.2	–58.2	–44.3	–62.7	–69.3	–78.4	–65.0	–72.9 ± 12.1 (17%)
P4	–59.6	–55.2	–71.2	–70.1	–69.6	–70.3	–63.6	–27.6	–45.7	–38.2	–34.8	–64.2	–62.7	–54.9	–59.5 ± 14.5(24%)
P5	–66.4	–61.4	–75.6	–73.3	–69.8	–75.0	–74.1	–35.8	–46.2	–28.7	–39.2	–32.9	–64.0	–57.0	–61.1 ± 21.4 (35%)
P6	–63.5	–48.8	–62.1	–73.4	–68.0	–68.2	–52.4	–35.2	–45.9	–21.2	–34.5	–43.4	–58.7	–51.3	–55.6 ± 15.5 (28%)
Groundwater															
HB-4	–77.2	–74.2	–77.0	–72.4	–73.5	–70.5	NA	NA	–70.5	NA	–73.3	NA	–75.1	–72.0	–74.0 ± 2.6 (4%)
W1	–77.9	–76.6	–73.5	–76.2	–69.6	–74.9	–70.7	–70.1	–68.9	–68.2	–68.2	–69.8	–74.3	–70.3	–72.7 ± 4.1 (6%)
W2	–77.0	–75.4	–75.4	–72.5	–71.8	–70.2	–73.1	–69.4	–68.0	–67.4	–68.1	–75.1	–74.4	–70.2	–72.7 ± 3.5 (5%)
W3	–74.1	–71.6	–70.9	–76.5	–72.8	–74.1	–73.7	–62.9	–70.7	–69.0	–65.2	–64.8	–71.5	–70.8	–71.2 ± 4.0 (6%)
W4	–72.5	–70.2	–70.1	–74.3	–71.5	–66.6	–68.5	–70.0	–62.2	–63.0	–63.1	–66.6	–70.4	–67.6	–69.2 ± 3.8 (6%)
W15	–69.9	–71.3	–71.4	–69.7	–71.8	–71.6	–65.3	–65.8	–62.2	–60.2	–63.7	–67.3	–69.6	–66.9	–68.5 ± 3.9 (6%)
W16	–68.6	–59.1	–75.7	–66.8	–70.1	–68.1	–63.8	–57.0	–62.3	–65.1	–58.2	–61.9	–67.7	–64.4	–66.5 ± 8.3 (12%)
G1	–77.3	–71.8	–73.6	–78.1	–75.3	–75.8	–70.4	–70.9	–70.4	–70.7	–70.2	–73.5	–74.7	–72.7	–73.9 ± 2.8 (4%)
G2	–76.0	–72.6	–72.7	–74.8	–74.7	–70.0	–69.3	–70.7	–69.8	–71.9	–70.9	–72.8	–73.6	–71.6	–72.8 ± 2.3 (3%)

NA not available

[a] Weighted mean value

Table 2 Tritium concentrations of water samples in this study

Sample	Date	TU
Precipitation in Taiwan		
Lishan	25 July 2003	3.2 ± 0.3
	5 February 2004	1.5 ± 0.2
	21 June 2004	1.9 ± 0.2
Taichung	18 July 2004	2.2 ± 0.2
	8 February 2004	2.7 ± 0.2
Keelung	9 June 2004	3.0 ± 0.2
	8 December 2004	2.3 ± 0.2
Surface water and drainage in LS area		
S1	27 June 2003	2.1 ± 0.2
P1	26 June 2003	2.0 ± 0.3
W1	26 June 2003	2.0 ± 0.2
W3	26 June 2003	1.8 ± 0.2
W16	26 June 2003	2.0 ± 0.2
G1	26 June 2003	1.7 ± 0.3

The mean $\delta^{18}O$ and δD values of P1 have no significant difference with those of S1 both in rainy or dry seasons (Table 1). This similarity in stable isotopic signals confirms the P1 shares the same source with S1, and suffers little or no isotopic fractionation when transporting S1 water to P1. In addition, both S1 and P1 have TU values similar to modern LS precipitation range (Table 2), demonstrating the affinity among S1, P1, and modern precipitation.

Ponds at FS farm (P1-P6) can be classified as two groups according to their stable isotopic compositions and geographic locations (see Fig. 1b and Table 1). The isotopic compositions in south group (P1, P2 and P3) are relatively lighter than those of north one (P4, P5 and P6). The mean values of south group are –11.0‰ (ranging from –11.4 to –10.7‰) and –74‰ (ranging from –77 to –73‰) for $\delta^{18}O$ and δD, respectively. In contrast, the mean values for north group are –8.8‰ (ranging from –9.1 to –8.4‰), and –59‰ (ranging from –61 to –56‰) for $\delta^{18}O$ and δD, respectively. In Fig. 4a, $\delta^{18}O$ and δD of pond waters are all closely distributed along with the LMWL line, suggesting that these pond waters suffered little evaporation effect.

This isotope discrepancy between these two groups is due primarily to the pond size and proximity to the source. The south group (P1, P2 and P3) with lighter mean isotopic compositions is close to creek water (S1) and relatively large in size. The north group (P4, P5 and P6) is relative far from S1 and small in volume; the bottoms of north group ponds were paved with waterproof plastic liners to prevent leakage. Therefore, stable isotopic compositions of the north group ponds are easily affected by precipitation that displays relative enriched isotopic compositions. In Table 1, mean isotopic compositions in the north group ponds do show a closer relationship with that of precipitation, suggesting the north ponds carry significant signals from the precipitation (Fig. 4a).

In short, the salient isotopic features of precipitation and surface water (creek and ponds) can be very useful for identifying the source of slope groundwater in LS landslide region: (1) the modern background TU values in Taiwan's precipitation are in the range of 1.5–3.2 TU; (2) the LMWL derived from precipitation data in LS region is an important reference line; (3) the differences of stable isotope compositions between local precipitation and FS pond waters can be readily differentiated.

Isotopic characteristics and sources of slope groundwater

Lai (2000) calculated the water amount difference between precipitation recharge and drainage discharge with rudimentary data in LS landslide area; he clearly indicated that the slope groundwater should have additional water source besides precipitation. This study took the measured discharge data of drainage facilities in LS area from February to September 2000 to compare with the precipitation of the same period in the slope region (Fig. 5a). The data show that approximately 50×10^4 m^3 of water had been drained out by the drainage system, while 65×10^4 m^3 of precipitation recharged to the slope groundwater (Table 3) if the infiltration coefficient is taken as 0.15 (Lai 2000; ERL 1993) during the study period.

The minor difference (~15×10^4 m^3) between precipitation recharge vs. drainage discharge seems to indicate the LS drainage system is working efficiently to drain slope precipitation. However, the correlation coefficient between the drainage discharge amounts and precipitation recharges has a negative value (–0.22), strongly implying that slope groundwater should have additional sources besides precipitation (Fig. 5b). Moreover, though water levels of lower slope monitor wells B-11 and B-9 did fluctuate with rainfall events, the up-slope well (B-13) maintained a constant water table even in the dry period (Fig. 6).

The deep groundwater that came from other catchments was firstly suspected as the additional source for slope groundwater in LS landslide region. Even though the landslide region beside the FS farm platform is surrounded by down-incised valleys; it is unlikely to have significant deep groundwater from other catchments. Furthermore, had slope groundwater derived from the deeper aquifer underneath, it should show very low TU values due to the long transient path. The tritium concentrations in slope

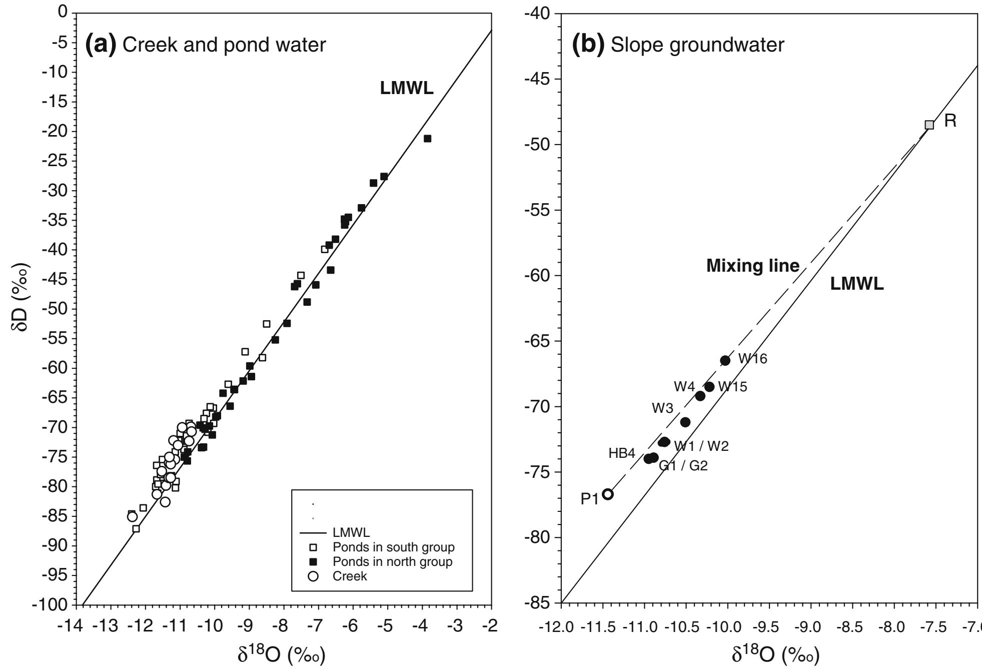

Fig. 4 Plot of δD vs. δ^{18}O of surface and slope groundwater samples. **a** The isotopic compositions in south group ponds are similar to that of creek water, whereas those of north group ponds are relatively heavier and close to precipitation. **b** Each slope groundwater samples distributed along the mixing line between the mean values of pond water (P1) and precipitation

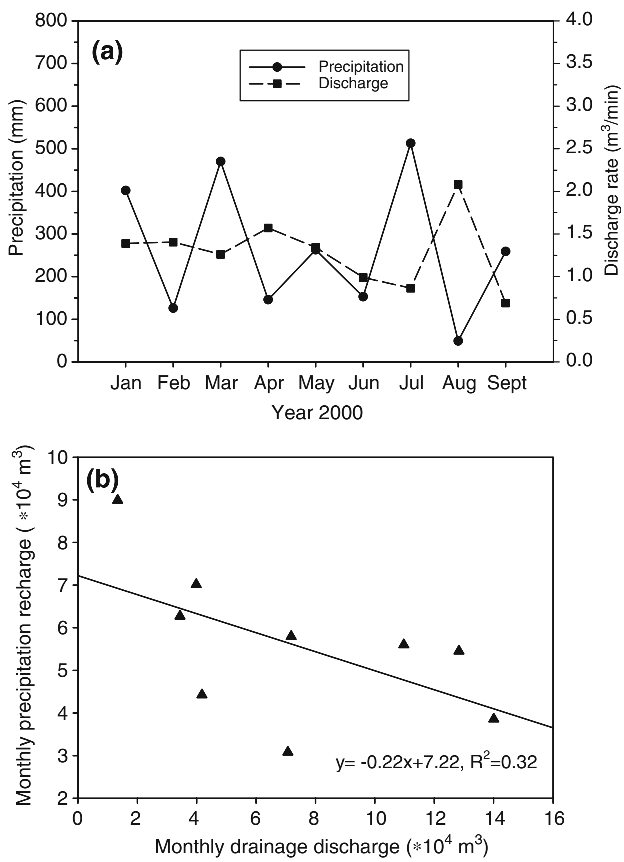

Fig. 5 **a** Monthly precipitation and discharge rate of drainage facilities during February to September 2000. **b** The relationship between the water amounts of drainage discharge and the precipitation recharge during February to September 2000

groundwaters (1.7–2.0 TU) are comparable with those of surface or precipitation waters (Table 2), ruling out the possibility of deep groundwater from other catchments. Therefore, it is concluded that the slope groundwater is mainly sourced from contemporary meteoric water in the LS area, and FS pond waters are the most probable source for slope groundwater besides precipitation. Isotope characteristics between slope groundwater and meteoric water are further compared to identify slope groundwater sources.

The mean values of all slope groundwater are –10.6‰ for δ^{18}O (ranging from –11.0 to –10.0‰), and –71‰ (ranging from –74 to –67‰) for δD, respectively (Table 1). These slope groundwater mean values are relatively lighter than those of precipitation (δ^{18}O = –7.6‰, δD = –49‰) and FS north group ponds (δ^{18}O = –8.8‰, δD = –59‰), but similar to FS south group ponds (δ^{18}O = –11.0‰, δD = –74‰). The isotope-signal similarity between south ponds and slope groundwater suggests that south ponds are the most likely source for slope groundwater, because these ponds are not covered with impermeable media on the bottom and may infiltrate through FS area to the LS slope region.

The δD vs. δ^{18}O plot of Fig. 4b clearly shows that slope groundwaters distribute along the mixing line between P1 and precipitation (R) mean values. This feature demonstrates that P1 pond water (from He-Huan-Xi creek) and local precipitation are the two main sources for slope groundwater in LS landslide

Table 3 Calculated water amounts of monthly precipitation recharge vs. drainage discharge during February to September 2000 in LS landslide area

Date	Precipitation (mm)	Amount of precipitation recharge[a] (m^3)	Discharge rate of drainage (m^3/min)	Amount of discharge[b] (m^3)
February	402	109,746	1.389	56,004
March	126	34,398	1.405	62,719
April	470	128,310	1.262	54,518
May	146	39,858	1.571	70,129
June	263	71,799	1.342	57,974
July	153	41,769	0.991	44,238
August	513	140,049	0.864	38,569
September	49	13,377	2.081	89,899
October	259	70,707	0.690	30,802
Total		650,013		504,852

[a] The area of slope region is 185 ha; the infiltration coefficient is taken as 0.15 (=precipitation of respective months × 0.15 × 155 ha)

[b] The discharge amount is calculated as discharge rate × 60 × 24 × days of respective months

area. Isotopic signals of slope groundwaters also show distinct spatial distribution. Groundwaters from up-slope region show a close isotope relationship with P1 and those of down-slope region exhibit higher isotopic proximity with local precipitation. Though G1 and G2 locate at lower slope, they are actually deep slope groundwaters; thus, their stable isotopic compositions show similar isotope values to head slope groundwater (HB-4).

A conceptual flow model of the LS landslide area is illustrated in Fig. 7a to summarize the isotopic characteristics of water bodies. Precipitation serves as one of the main sources for FS pond waters and the slope groundwater. Pond waters in FS farm have been constantly recharged from He-Huan-Xi creek. Part of these south ponds accompanied with varied portions of precipitation becomes the FS farm groundwater (GW). The FS farm GW eventually flows down along the slope region (from HB-4 to W4). Precipitation shows relatively higher portion mainly on the mid- and down slope regions. Both G1 and G2 drainages are deep slope groundwater from higher altitude with very minor component of slope precipitation.

Evaluation of drained efficiency and the amelioration strategy

FS farm GW (pond water) and precipitations are two end sources for slope groundwater in LS landslide area (Fig. 7a). Thus, the fractions that each source contributes to slope groundwater can be calculated by a two-end member mass-balance equation in terms of δ^{18}O values. The equation is as follows:

$$\delta^{18}O_T = X\delta^{18}O_1 + (1 - X)\delta^{18}O_2 \quad (1)$$

where $X = Q_1/Q_T$, $(1–X) = Q_2/Q_T$, and $Q_T = Q_1 + Q_2$.

In Eq. 1, Q is the water amount, T the total water from waters 1 and 2, and X and $(1 – X)$ are the fractions of waters 1 and 2, respectively.

Figure 7b depicts the calculating results of pond water and precipitation fractions on each slope groundwater wells in rainy and dry seasons. Obviously, the precipitation fraction increases while pond water fraction decreases from up- to down-slope. In addition, precipitation has higher fractions in the rainy season than in the dry season. The salient feature in Fig. 7b illustrates the importance of pond water (FS farm GW) for slope groundwater due to its high proportions in each sampling well. The results also demonstrate that FS farm GW provides a persistent source to slope groundwater. In a heavy raining event, the excessive precipitation water plus the perpetual FS farm GW would easily exceed the limitation of slope stability and subsequently cause severe slope failure. If heavy precipitation in the area may trigger a landslide, the groundwater from FS farm is a hidden but very real factor for landslide conditions.

The amelioration strategy for landslides generally focuses on precipitation factor only and applies drainage systems to drain out excessive water along the slope. Apparently, this strategy would not be enough in the light of the current study results.

A semi-quantitatively evaluation for FS farm GW contributing to the slope groundwater relative to the precipitation is attempted with current isotope and limited hydrological data. The drain efficiency of the ongoing drainage system is then further estimated.

In Fig. 7a, FS farm GW (headwater of slope groundwater) can be represented by HB-4 (δ^{18}O = –11.0‰) as one of the inputs for slope groundwater. For the FS farm region, P1 pond (δ^{18}O = –11.4‰) and precipitation (δ^{18}O = –7.6‰) are the two end members for FS farm GW, which consists of 10.5% precipitation and 89.5% P1 water according to Eq. 1 (Table 4). Given the infiltration coefficient as 0.15 (Lai 2000; ERL 1993) and annual precipitation of 2,063 mm; the precipitation contributes 48×10^4 m^3/year of water to FS farm GW. The total storage of FS farm GW is then estimated as 460×10^4 m^3/year, with approximately 410×10^4 m^3/year from FS farm ponds (Table 4). Thus, FS ponds contribute a much greater fraction (up to a factor of eight) than precipitation to FS farm GW.

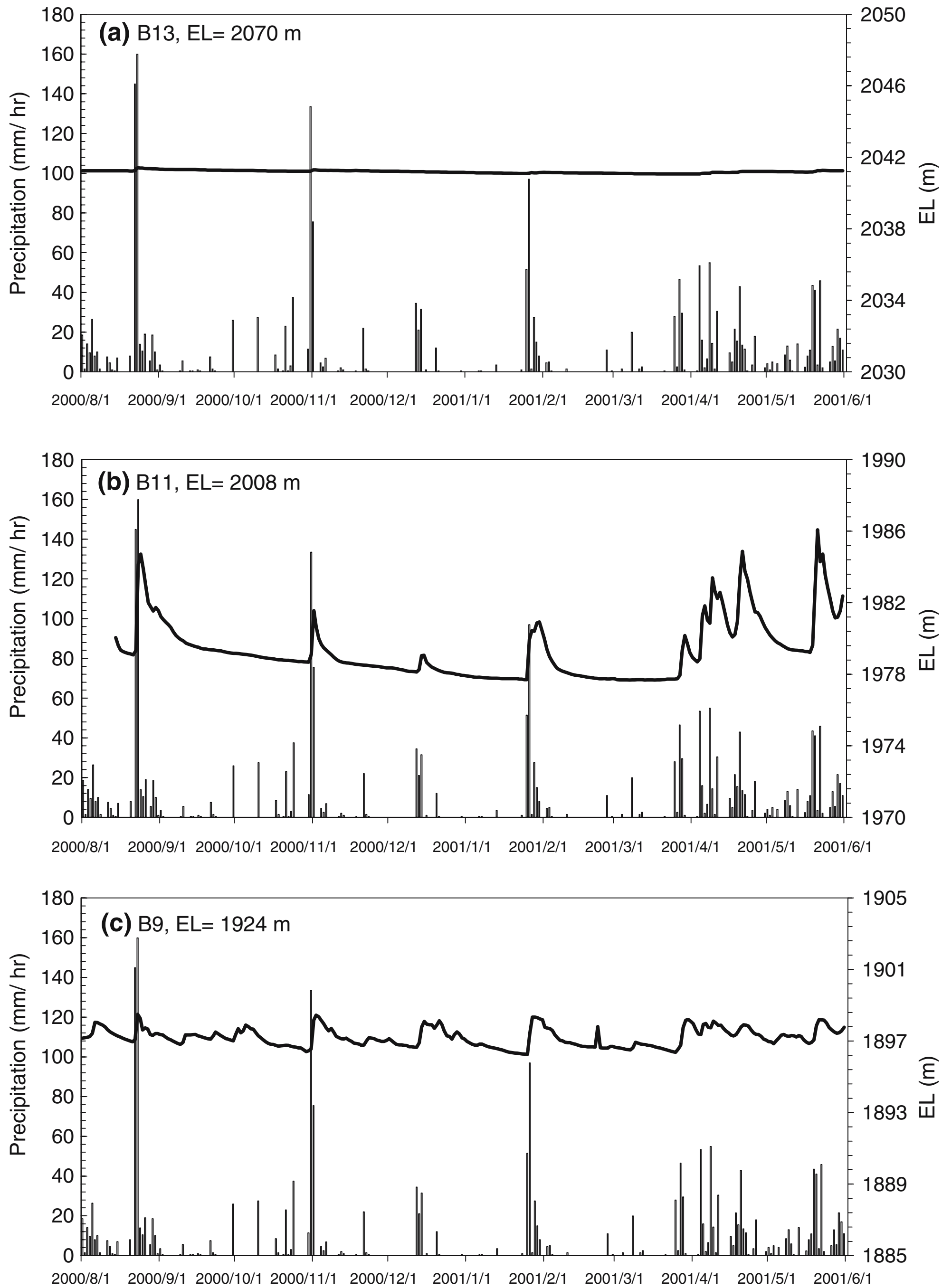

Fig. 6 Hydrographs with hourly records of precipitation and groundwater table in **a** up, **b** middle, and **c** down slope regions

For the slope region, the isotope composition of slope groundwater can be represented by the mean value ($\delta^{18}O = -10.5‰$) of all slope groundwaters excluding HB-4 (Fig. 7a). From Eq. 1, slope groundwater would consist of 85.3% slope headwater (FS farm groundwater) and 14.7% precipitation on average (Table 4). The precipitation contributes 56×10^4 m^3/year to slope groundwater based on the similar calculation. The total storage of slope groundwater is 380×10^4 m^3/year, in which 320×10^4 m^3/year is from FS farm GW (Table 4). FS farm groundwater plays an important role in recharging the slope groundwater relative to the precipitation (up to a factor of five).

The discharge rates for LS drainage system are in the range of 1.3–1.5 m^3/min (Table 3). Taking 1.4 m^3/min as the mean discharge rate, the LS drainage system would drain out the slope groundwater to about 74×10^4 m^3/year (=1.4 m^3/min × 60 × 24 × 365), which

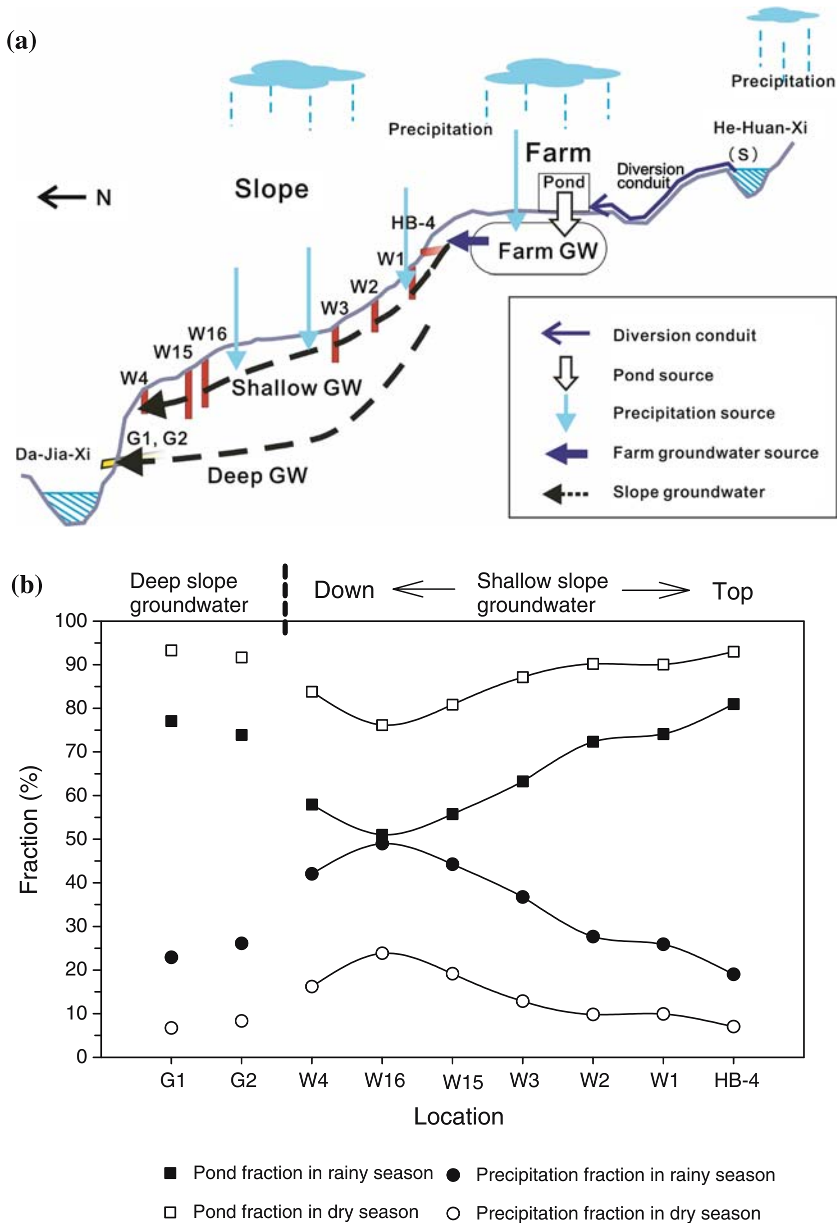

Fig. 7 **a** The conceptual flow model in LS landslide area. **b** The source fractions of pond and precipitation on each slope groundwater in rainy and dry seasons, respectively

Table 4 The fractions and water amounts of respective end-sources contributed to groundwaters in FS farm and slope regions

Groundwater region	End-source	Fraction (%)	Amount (×10^4 m^3)	Total (×10^4 m^3)
FS farm GW (–11.0‰)	Precipitation (–7.6‰)	10.5 ± 0.9	48[a]	460 ± 40[b]
	Ponds (P1, –11.4‰)	89.5 ± 7.9	410 ± 70	
Slope groundwater (–10.5‰)	Precipitation (–7.6‰)	14.7 ± 1.3	56[c]	380 ± 30[d]
	Farm groundwater (HB-4, –11.0‰)	85.3 ± 7.7	320 ± 60	

[a] Assuming the infiltration coefficient is 0.15. The area for farm region is 155 ha (precipitation amount = 2,063 mm × 0.15 × 155 ha)

[b] Total amount of farm groundwater (=48/0.105)

[c] Assuming the infiltration coefficient is 0.15. The area for slope region is 182 ha (precipitation amount = 2,063 mm × 0.15 × 182 ha)

[d] Total amount of slope groundwater (=56/0.147)

is close to the amount contributed by precipitation only (56 × 10^4 m^3). Considering the FS farm groundwater (320 × 10^4 m^3/year) is an unexpected source for slope groundwater and should be drained out, the drain efficiency of current LS drainage system is estimated as only 23% (=74/320).

Expanding the LS drainage system to promote the drain efficiency is possible theoretically. In reality, it is not only very hard to locate possible sites for draining slope groundwater, but also difficult to predict the precipitation infiltration in slope region. Although FS pond water is identified as a major source for slope groundwater in this study, it is nearly impossible to restrain the pond water from FS farm. Therefore, an alternate and suitable strategy to assist the current drainage system is to effectively drain out of the slope groundwater in the up-slope region above the farm. If FS farm GW recharge can be significantly reduced, the risks of landslide disaster in LS region shall be substantially diminished.

Conclusions and suggestion

Isotope results of water samples are useful in understanding the hydrologic pathways in LS area. Local precipitation and FS farm groundwater are identified as two principal sources for the slope groundwater. The LS slope groundwater consists of 15% in precipitation and 85% from FS farm groundwater. In comparison, FS farm groundwater is composed of 10% precipitation and 90% farm pond water. Because it contributes considerably higher fraction to slope groundwater than precipitation, the FS farm groundwater is regarded as the major factor for LS landslides.

The landslide amelioration strategy normally focuses solely on precipitation factor and relies heavily on a drainage system to remove excessive water in the slope. From current results, FS farm groundwater is the more important parameter than precipitation for slope groundwater and should be drained out efficiently. The drain efficiency of current drainage system in the LS area, however, is estimated to be only 23%, far less than enough to prevent LS landslides. Two difficulties are encountered: (1) it is very hard to locate possible sites for draining groundwater in slope region; (2) the restriction of pond water usage for irrigating at FS farm area is almost impossible. Thus, draining off the slope groundwater effectively in up-slope region is an alternate and feasible strategy to assist the current drainage system and to prevent excessive farm groundwater flowing toward the slope area. It is expected that if FS farm groundwater can be effectively removed in the up-slope region, the risks of landslide disaster in LS region shall be substantially decreased. This approach is applicable to landslide areas with similar problems elsewhere.

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