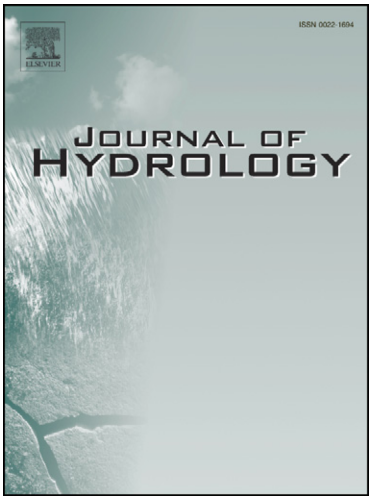

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Identification of groundwater sources of a local-scale creep slope: using environmental stable isotopes as tracers

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Abstract

Water plays an important role for slope stability and typically consists of local precipitation (LP) and original slope groundwater (OSGW); high amount of the OSGW leads the slope groundwater (SGW) easily to exceed the critical level that causes slope failure in a heavy raining event. This study was to verify the source and significance of the OSGW for a creep slope adjoining a hydropower plant, northern Taiwan by an environmental stable isotope approach. Isotope results indicate that the source of the OSGW derived from leaking of the water-transporting system of the power plant; the leaking fraction in the SGW is as high as 70−80%. High leaking component in the SGW indicates that the leaking water rather than local precipitation is the crucial factor for the mass movement of the creep slope. Since the mass movement poses a potential threat to the hydropower plant safety, the most important measure for the remedial project is to perform a comprehensive check and repair the leak of the water-transporting system.

Keywords: Environmental stable isotopes; Slope groundwater source; Creep slope; Taiwan.

1. Introduction

In addition to slope gradient and geological structure, water plays a critical role for the mass movement in the slide-prone region. Water in a slope serves not only a mass load of the slope, but also a lubricant between particles or strata (West, 1995). Serious slope failure is common during a heavy raining event because rapid infiltrated rainwater increases the slope’s load and provides extra pore water pressure to destroy the slope stability.

In addition to precipitation, surface water or groundwater from adjacent watershed may also contribute a significant amount in a slope, and become perennial slope groundwater, that is, original slope groundwater (OSGW). High amount of the OSGW indicates a high probability of landslide in the slide-prone region because local precipitation (LP) and the OSGW share the specified water storage of slope groundwater (SGW). If the OSGW component is high, the SGW may easily exceed the critical level that causes slope failure in a heavy raining event.

In general, drawing off the OSGW by drainage facilities such as well, pipe, and gallery can enhance the soil's pore capacity to take up more rainfall and moderate groundwater pressure in the slope during a raining event. However, the drainage system is an artificially passive facility for landslide amelioration; sometimes it is insufficient for mitigating excessive SGW. For example, it is not only very hard to locate potential sites for draining SGW efficiently, but also difficult to predict the LP infiltration in slope region. In a previous mountainous landslide study (Peng et al., 2007), the OSGW contribution to SGW can be up to about 85%, which is much greater than that from the LP. Therefore, an alternate strategy was suggested to identify and prevent the OSGW headwater flowing into slope regions, in order to assist the existing artificial drainage system for landslide amelioration (Peng et al., 2007). If the input of headwater recharge can be significantly reduced, the risks of landslide disaster shall be substantially diminished. Thus, a correct identification of recharge sources for the OSGW is very important in the slope study.

Using environmental tracers such as stable oxygen and hydrogen isotopes to identify the OSGW sources has proved very useful in the landslide study (Peng et al., 2007). The advantages of using stable isotope tracers to water source study are: (1) Hydrogen and oxygen isotopes are compositions of water molecule and best approximate water behavior (Clark and Fritz, 1997; Criss, 1999). (2) Unique hydrogen and oxygen isotopic signatures can be differentiated from waters in various environments due to related isotopic fractionation effects (Dansgaard, 1964; Yurtsever and Gat, 1981; Criss, 1999). (3) Isotope compositions in water are conservative, they hardly affected by water–rock reaction under normal temperatures (Fritz, 1981; McCarthy et al., 1992). Moreover, the stable isotopic tracer approach is not limited by the questions of how, when, and where to put in the tracer and retrieve the sample for verification that an artificial tracer always encounters (IAEA, 1983).

The site of this case study is located along Da-Han Stream, northern Taiwan and is near a Yi-Xing hydropower plant (Fig. 1). Landslides occasionally takes place at the up slope region adjacent to the power plant after heavy raining events during summer, and the slope is identified as a creep slope with high-potential risk, threatening the power plant safety (CGS, 2008). According to the long-term meteorological records in the basin of Da-Han Stream (WRA, 2003), the annual mean rainfall is about 2,400 mm, of which 74% falls during the summer rainy season (May to October), and 26% to the winter dry season (November through April).

The altitude of the study region ranges 250 to 1,000 m (EL) approximately (Fig. 1a). The slope bedrock is composed of the Miocene Mushan Formation with a lithological character of alternated sandstone and shale layers (CGS, 1996). The survey results of Central Geological Survey (CGS, 2008) indicated that the slope consists of an ancient weathered slide body lying over the Miocene basement (Fig. 1c). The weathered slide body consists of fractured rocks overlaid with surface colluvial soil; its texture is permeable and poorly cohesive. The geological survey also reported that the hydraulic conductivity of the upper rock-fractured zone is approximately 10^{-5} to 10^{-7} m/s, which is higher than the values of $< 10^{-8}$ m/s of the underlying basement (CGS, 2008). Due to this high contrast in hydraulic conductivity, water in the slope tends to accumulate near the interface between the fractured zone and basement at about 40 to 50 m below ground (Fig. 1c); the interface can thus be regarded as a major slide plane for the mass movement.

While in service, the Yi-Xing hydropower plant takes stream water from a dam at the middle reaches of Da-Han Stream to its up-tank via a water-transporting tunnel (Fig. 1a). The up-tank water is then guided to a penstock, falling to a powerhouse to drive the turbine and generator (Fig. 1b). The tank is almost full of tunnel-sourced water during the plant's generating, but has little or no water when the hydropower plant is not in service. Due to high affinity between the conveying tunnel and creep region (Fig. 1c), there is a possibility that the mass movement has close connection with the tunnel water. If the tunnel water does leak somewhere, the leaking water may turn to the OSGW headwater for the studied slope.

The purposes of this study were to employ stable hydrogen and oxygen isotopes as natural tracers to (1) identify the relationship between the OSGW and conveying-tunnel water of the Yi-Xing hydropower plant and (2) evaluate the effects of the OSGW on the slope's mass movement adjacent to the hydropower plant.

2. Materials and methods

2-1 Samples

Water samples including precipitation, slope groundwater, and up-tank water were collected in 2008 for isotopic determination. The sampling locations are illustrated in Fig. 1b. Sampling details are as follows:

Local precipitation: rain samples were collected near the creep slope at an elevation of 500 m (EL) (Fig. 1b). Daily rainfall was recorded by a pluviograph.

Slope groundwater: slope groundwaters were taken from two monitoring wells of AH-7 and AH-3, located at 422 and 334 m (EL), respectively (Fig. 1c). Well screens are 50 m below ground, near the interface between the fractured zone and basement (Fig. 1c). Groundwater levels of the monitoring wells have been recording automatically per hour by the digital recorder.

Up-tank water: the up-tank, with an altitude of about 420 m (EL), transfers tunnel water to a penstock for generating electric power (Fig. 1c). The tunnel water came from a dam at the middle reaches of Da-Han Stream (Fig. 1a); the dam impounds water from upstream watershed with an elevation up to about 3,500 m (CGS, 2008). The up-tank keeps full of water from tunnel during electric-generating operation; however, it had little and stagnant water after June 2008 because the power plant had ceased operating for maintenance.

Water samples were taken monthly during the study period except for precipitation, which was collected on each rainy day. All samples were analyzed for stable oxygen and hydrogen isotope compositions. In addition, five of those samples, including precipitation, slope groundwater, and up-tank water collected in February/April 2008 were chosen to measure their tritium concentrations.

2-2 Isotope analyses

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 (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 $\delta^{18}O$. The average differences of duplicate analyses of water samples are ±1.5‰ for δD and ±0.11‰ for $\delta^{18}O$.

Tritium was measured in the dating laboratory of National Taiwan University using a liquid scintillation counter. Precisions of repeated analyses for samples and laboratory standards are 0.2 TU.

3. Results

3-1 Local precipitation (LP)

The stable isotope compositions of LP varied widely and exhibited distinct seasonal variations. The yearly weighted mean values are -6.6 ± 3.3‰ for $\delta^{18}O$ and -41 ± 29‰ for δD, and their CV (coefficient of variation) values are 51% for $\delta^{18}O$ and 71% for δD (Table 1). The mean $\delta^{18}O$ and δD for rainy season (May–October) are -8.8‰ and -59‰, respectively, and those for dry season (November–April) are -4.4‰ and -23‰, respectively. The feature that relatively heavier isotopic compositions are found in the winter dry season than those of the summer rainy season has been commonly observed in Taiwan (Peng et al., 2007; Peng and Wang, 2008). This seasonal isotopic discrepancy is primarily controlled by the prevailing monsoons with distinct isotope compositions; in addition, secondary evaporation effect such as raindrop evaporation or moisture recycling further enhances the isotopic discrepancy of precipitation between seasons (Peng et al., 2009).

Moreover, typhoons that prevail in summer often bring heavy rainfall with much lighter isotope compositions in the continent–ocean interface of East Asia (Araguás-Araguás et al., 1998; Peng et al., 2009). For example, in this study the mean stable isotope compositions of July's precipitation, mainly derived from typhoon rainfall, are significantly lighter than those of other months. These much depleted isotope values would result in the long-term mean value to be lighter than normal. If the distinct July's values are excluded, the mean isotope compositions of rainy season would be -7.7‰ for δ^{18}O and -50‰ for δD (Table 1), and the whole year's mean values would be -5.9‰ for δ^{18}O and -35‰ for δD, respectively.

In addition to the seasonal variation, stable isotope compositions vary with elevation due to altitude effect of precipitation (Dansgaard, 1964; Yurtsever and Gat, 1981) showing relatively lighter values in high-elevation region than those of low-elevation area. According to the isotope database of Taiwan's precipitation presented by Peng et al. (2009), the relationship between yearly isotope composition and elevation in terms of δ^{18}O value for six sites in mountainous region and northern Taiwan (altitudes from 110 to 2,410 m) is shown in Fig. 2. The mathematical regression between δ^{18}O value and elevation can be expressed as follows:

$$\delta^{18}O_Z = -5.18 - (1.6Z\times10^{-3}) \qquad (1)$$

where $\delta^{18}O_Z$ represents the oxygen isotope composition of precipitation at a given elevation Z, and Z is in meters (EL).

Since the LP samples of this study region were collected at about 500 m (EL), the expected $\delta^{18}O_Z$ value of yearly mean should be -6.0‰ by Eq. (1). The estimated -6.0‰ of $\delta^{18}O_Z$ value is identical to the yearly mean value of local precipitation if excluding the much depleted values of July's precipitation (-14.3‰; Table 1). The agreement between calculated and observed $\delta^{18}O_Z$ further supports the applicability of Eq. (1) to the estimation of source water in this work.

On the other hand, tritium concentration (TU) of the precipitation in February 2008 is 3.2 TU (Table 1). The tritium value is comparable with those of Taiwan's modern precipitation ranging between 1.5 and 3.2 TU (Peng et al., 2007; Peng and Wang, 2008).

3-2 Slope groundwater (SGW)

Yearly mean isotope compositions of up-slope groundwater (AH-7) are -9.4‰ and -65‰ for $\delta^{18}O$ and δD, respectively. By comparison, those of down-slope groundwater (AH-3) are relatively heavier and show values of -8.9‰ and -60‰ for $\delta^{18}O$ and δD, respectively (Table 1). Unlike precipitation, SGWs of both AH-7 and AH-3 exhibited minor isotope discrepancies between rainy and dry seasons, a typical feature in groundwater. The CV values of the yearly mean isotope compositions for the SGW are about 5% for $\delta^{18}O$ and 10% for δD (Table 1).

Tritium concentrations of AH-7 in February and April 2008 are 1.9 and 1.7 TU, respectively (Table 1). The values are comparable with those of modern precipitation as indicated above.

3-3 Up-tank water (UTW)

In comparison with LP and SGW, the UTW shows the lightest mean isotope compositions in this study. During the period from January to June while the plant was operating, mean stable isotope compositions are -10.2‰ for $\delta^{18}O$ (ranging from -10.4 to -9.9‰), and -69‰ for δD (ranging from -75 to -63‰), respectively (Table 1). After June, the Yi-Xing hydropower plant ceased operating and there was no fresh UTW for sampling. With limited six months data, the UTW isotope compositions showed insignificant variation between months as the CV values of its stable isotope compositions are only 2% for δ^{18}O and 6% for δD (Table 1).

The UTW was supplied from a dam at the middle reaches of Da-Han Stream via a tunnel (Fig. 1a). According to Eq. (1), the mean δ^{18}O value of -10.2‰ implied the source water was from an altitude of 3,100 m, which is compatible with the elevation range (up to about 3,500 m) of upstream watershed for impounding dam. In March 2009, both shallow and bottom dam waters were collected to verify the isotope relationship between UTW and dam water. The δ^{18}O values of shallow and bottom dam waters were -10.6‰ and -10.7‰, respectively, which are comparable to -10.2‰ of the UTW (Table 1). The similarity in δ^{18}O signal confirms the UTW shares the same source with dam water, and suffers little or no isotopic variation when transporting dam water to the up-tank.

Tritium concentrations of the UTW in February and April 2008 are 1.7 and 3.3 TU, respectively (Table 1), which are similar to those modern values mentioned above.

4. Discussion

4-1 Source for SGW

The plot of δD vs. δ^{18}O of LP in the study is showed in Fig. 3, and the regression line that represents the local meteoric water line (LMWL) is $\delta D = 8.39\ \delta^{18}O + 13.74$. In Fig. 3, isotope data of both SGW and UTW distribute along with the LMWL, indicating that the stable isotopes of those waters do not have effects of water–rock interaction or significant evaporation. Thus their isotopic characteristics behave conservatively.

Tritium is a radioactive isotope (half-life: 12.43 years) and commonly applied in identifying the presence of modern recharge. Tritium-free or low-level TU (< 0.8) groundwaters are considered older (prior to 1952) as compared to modern precipitation tritium values (Fritz et al., 1991; Krabbenhoft et al., 1994). The tritium concentrations of the SGW and LP in this study (Table 1) are compatible with those of Taiwan's modern precipitation (1.5 and 3.2 TU) (Peng et al., 2007; Peng and Wang, 2008). The affinity in tritium concentrations, as well as the distribute pattern along the LMWL (Fig. 3), demonstrates that the SGW mainly comes from contemporary meteoric water, and old groundwater from watershed can be excluded as likely source (Krabbenhoft et al., 1994; Peng et al., 2007; Peng and Wang, 2008).

According to daily records in 2008 (Fig. 4), groundwater levels of both up- and down-slope groundwaters fluctuated primarily with precipitation events higher than 100 mm/day, demonstrating the contribution from LP to SGW is confined to specific high rainfalls. The irregular variations in well AH-7 before March 2008 are attributed to well installation artifacts.

Regarding the little contribution of LP to SGW, isotope evidence is provided by the observation that $\delta^{18}O$ and δD values of SGW samples did not show significant isotope discrepancies between rainy and dry seasons as the LP did (Table 1). For example, the $\delta^{18}O$ and δD values of July's precipitation exhibited much depleted values (e.g., -14.3‰ for $\delta^{18}O$**,** Table 1); however, the light isotopic signal was not clearly observed in SGW samples after July. Similarly, the relative heavier $\delta^{18}O$ signal (-3.1‰) of March's precipitation did not occur in SGW samples as well. These features indicate that a considerable amount of OSGW exists in the slope and restricts the input from the LP due to a limited space for water capacity. Furthermore, groundwater level hydrographs show a constant base line during low or no rain periods (Fig. 4), demonstrating the high abundance of OSGW.

In short, SGW in the creep slope of this study is a mixture of the two components of LP and OSGW based on the evidence of isotopic characteristics and groundwater level records. Since isotopic signals indicate that the SGW is primarily from modern meteoric water, OSGW should have the same modern source as of SGW. Because OSGW may provide considerable water to the studied slope and serve as a prospective factor on the slope's mass movement, its source and importance must be first clarified.

4-2 Source and significance of OSGW

Since OSGW and LP are two major sources contributing to SGW, the relative contributions between OSGW and LP can be estimated by a regular two-end member mass-balance equation (Criss, 1999; Criss et al., 2001; Peng et al., 2007). The equation in terms of $\delta^{18}O$ values can be expressed as follows:

$$\delta^{18}O_{SGW} = X\ \delta^{18}O_{LP} + (1-X)\ \delta^{18}O_{OSGW} \qquad (2)$$

where X and (1-X) are the fractions of LP and OSGW in SGW, respectively. The application of Eq. (2) is assuming that SGW is a well mixture of LP and OSGW (Krabbenhoft et al., 1990; Clark and Fritz, 1997; Hunt et al., 1998), as evidenced by the relative low CV values of SGW isotope compositions (Table 1). In Eq. (2), $\delta^{18}O$ values of both LP and SGW were readily identified (Table 1); however, the OSGW part still needs a further confirmation.

The yearly $\delta^{18}O_{SGW}$ values for AH-7 and AH-3 are -9.4‰ and -8.9‰, respectively, which are much depleted than the -5.9‰ of $\delta^{18}O_{LP}$ (Table 1). Therefore, $\delta^{18}O_{OSGW}$ value must be lighter than those of $\delta^{18}O_{SGW}$ and $\delta^{18}O_{LP}$, because $\delta^{18}O_{OSGW}$ serves as the end member with depleted isotope composition as contrast to the enriched end of $\delta^{18}O_{LP}$ based on Eq. (2). As stated above, modern tritium evidence has ruled out the possible source of the SGW from old groundwater. The most likely source of OSGW is the meteoric water derived from a higher watershed relative to LP based on Eq. (1). In this study, two prospective sources for the OSGW are the UTW and headwater from precipitation at the adjacent watershed.

With respect to the headwater from precipitation at the adjacent watershed, its elevation can be inferred from Eq. (1). Assuming a zero LP contribution to the SGW, $\delta^{18}O_{OSGW}$ is then equal to the $\delta^{18}O_{SGW}$ in Eq. (2), consequently, the inferred elevation by Eq. (1) would be the lowest estimation for adjacent watershed. If the relative enriched $\delta^{18}O_{LP}$ term is introduced in Eq. (2) with a specified $\delta^{18}O_{SGW}$, $\delta^{18}O_{OSGW}$ would become depleted and the derived elevation of the watershed turns to a higher elevation. From Table 1, $\delta^{18}O_{SGW}$ ranges from -9.9 to -8.3 ‰, the lowest elevation of the adjacent watershed calculated from Eq. (1) would be about 1,900 to 2,900 m (Fig. 2). In reality, the elevation of the adjacent slope is up to 1,000 m at most (Fig. 1) and cannot provide water to support the lighter $\delta^{18}O_{OSGW}$. Therefore, the OSGW source from the adjacent up-slope watershed is very unlikely.

On the other hand, mean $\delta^{18}O$ value of UTW is -10.2 ‰ (Table 1), which is relatively depleted than $\delta^{18}O$ values of LP and SGW. In the δD vs. $\delta^{18}O$ plot of Fig. 5, AH-7 and AH-3 distribute along the mixing line between the two ends of the UTW and LP, implying that UTW would be a very likely candidate for lighter isotope end-member. It is this concluded that the OSGW source carries the same isotope composition or source as the UTW. Because no other water with similar depleted isotope composition as UTW can be found in the studied region, it is suggested that the water-transporting line of Yi-Xing hydropower plant is leaking somewhere in the tunnel or the up-tank region. The leaking water flows into the creep slope and becomes the OSGW thereafter.

Assumed OSGW is solely derived from the leaking water, the effect of the leaking water (as represented by the UTW) on SGW in terms of the $\delta^{18}O$ is evaluated by Eq. (2) and listed in Table 2. The estimation of leaking water fraction in SGW is mainly based on the yearly $\delta^{18}O$ means of related waters because the time span of precipitation travelling to groundwater is hard to assess precisely (Hunt et al., 2005). Therefore, it is more reasonable to take yearly $\delta^{18}O$ values than monthly mean data to calculate the leaking water fraction. As shown in Table 2, fractions of leaking water in AH-7 and AH-3 are about 81% and 70%, respectively. The leaking fraction decreases with the LP component increases from up to down slope. The results clearly indicate that the leaking water is the predominant part in SGW.

To evaluate the fractions in respective rainy or dry seasons may be less precise because the UTW has only 6-month data from January to June. Again, the CV value of UTW $\delta^{18}O$ is only 2% (Table 1), indicating the difference of isotope compositions between rainy and dry seasons is very small. Nonetheless, provided the $\delta^{18}O_{OSGW}$ values of rainy and dry seasons are similar to those of $\delta^{18}O_{UTW}$, the leaking water fractions in AH-7 are about 68% and 88% for rainy and dry seasons, respectively; and in AH-3 are 44% and 78% for rainy and dry seasons, respectively (Table 2). Obviously, the leaking amount in SGW is higher in dry season than in rainy season, and greater in the up-slope groundwater than in down-slope site.

5. Conclusions and suggestions

Isotope results of water samples show that local precipitation (LP) and original slope groundwater (OSGW) are two endmembers for slope groundwater

(SGW) of the studied creep slope. The isotopic evidence also indicates that the OSGW source is derived from the leaking of the water-transporting system at the up slope of the Yi-Xing hydropower plant. The leaking fraction in SGW ranges about 70–80%; in addition, the leaking fraction is higher in dry season than in rainy season, and greater in the up-slope region than in down-slope site. Since the leaking water contributes considerable amount to slope groundwater than local precipitation, it is regarded as a crucial factor for the mass movement of the creep slope.

The existence of abundant leaking water in the SGW is a potential threat to the creep slope safety because the perpetual leaking plus the excessive LP would easily exceed the critical threshold of slope in a heavy raining event. If heavy precipitation in the area triggers a landslide, the leaking water in the slope poses a hidden and higher risk factor for landslides. Therefore, the most important measure for the subsequent remedial project is to perform a comprehensive check and repair the leak of the water-transporting system, in order to prevent the leaking flowing into slope and reduce the landslide hazard for the hydropower plant.

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Figure captions

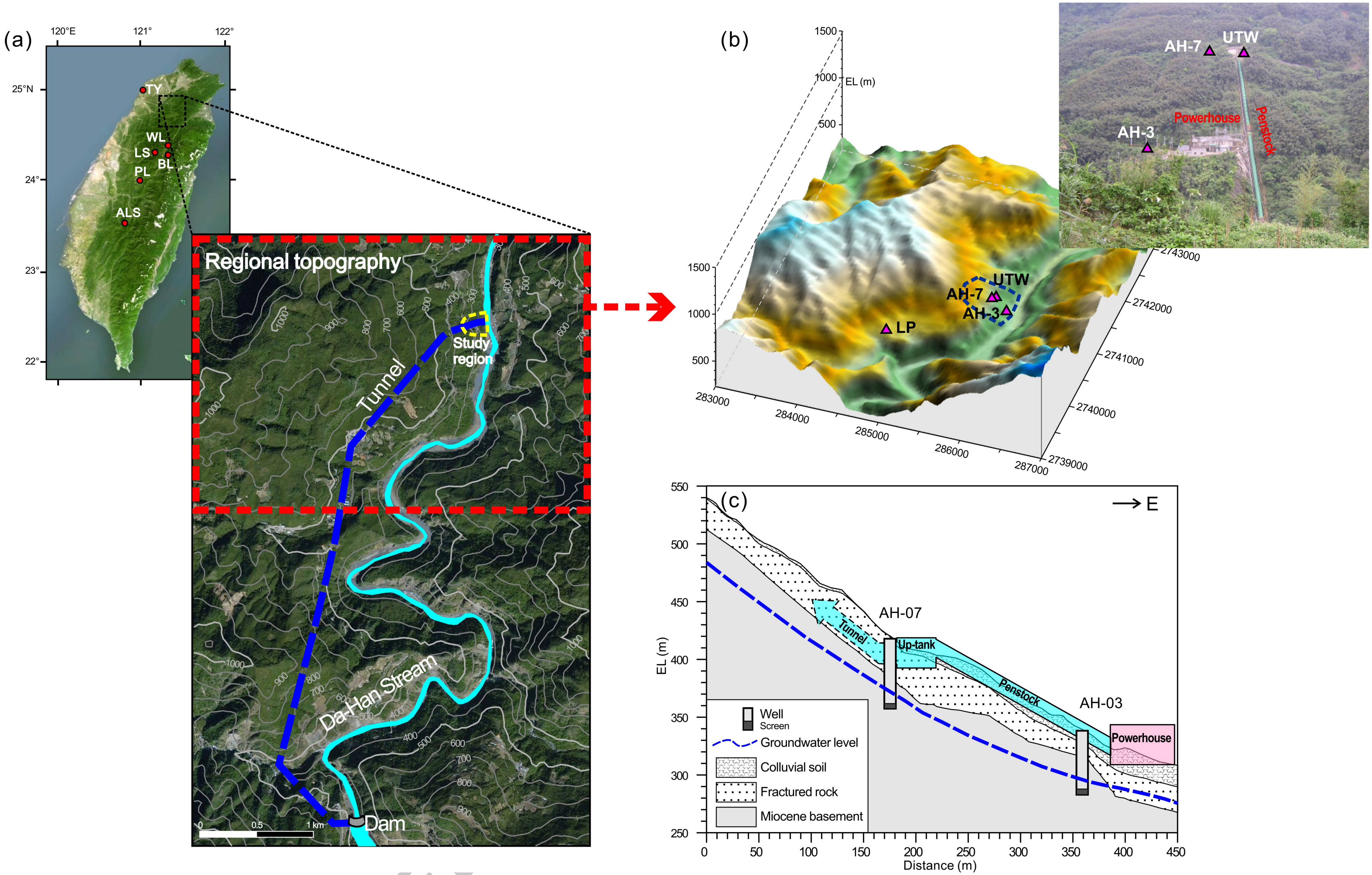
Fig. 1. (a) Images of study area. The sites denoted as TY, PL, LS, WL, ALS, and BL are sampling locations for precipitation discussing in text. (b) Sampling locations of local precipitation (LP), up-tank water (UTW), and slope groundwaters (SGW) of AH-7 and AH-3. (c) Geological profile of the studied creep slope adjacent to Yi-Xing hydropower plant.

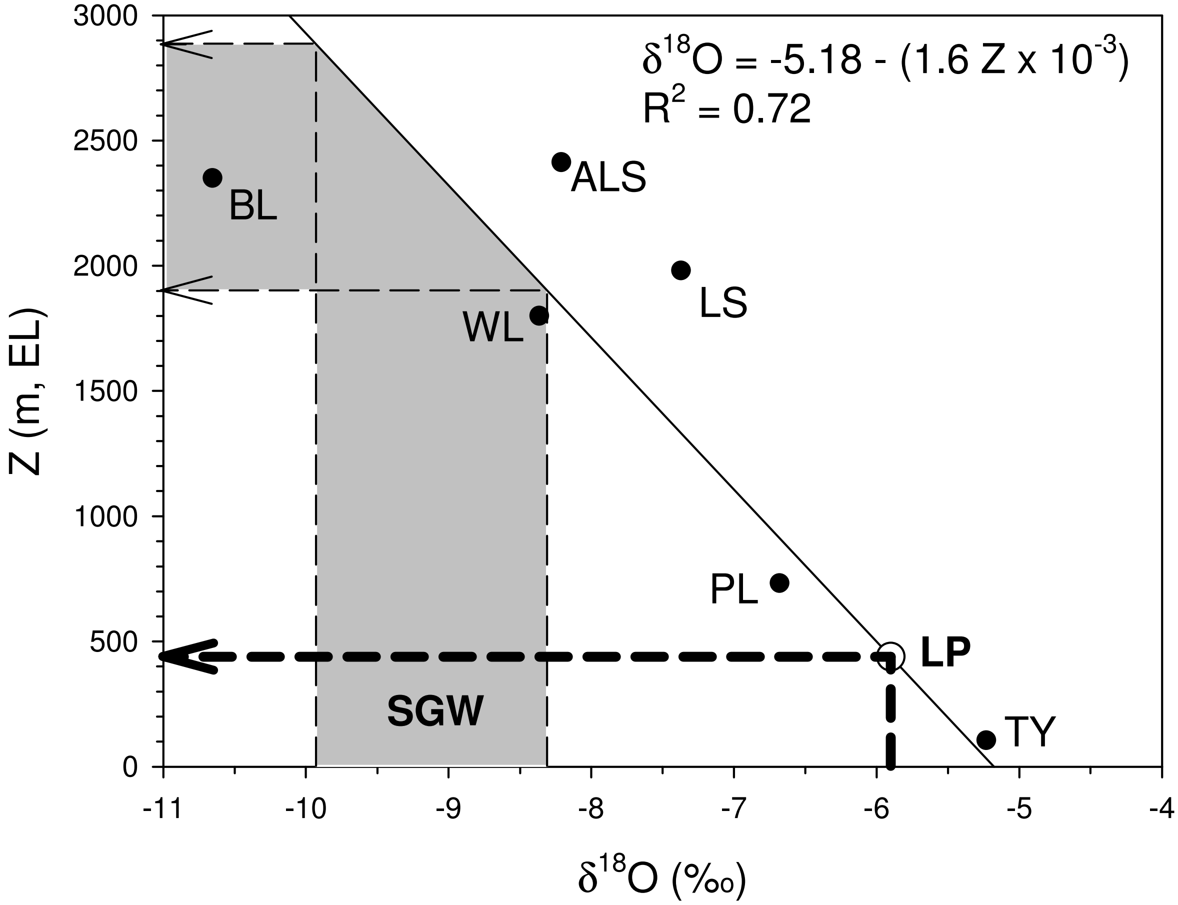
Fig. 2. The relationship between yearly δ^{18}O value of precipitation vs. elevation of six locations, TY, PL, LS, WL, ALS, and BL, in mountainous region and northern Taiwan (Fig. 1a). δ^{18}O values and elevations of the six locations are excerpted from Peng et al. (2009). In the figure, the mathematical regression is $\delta^{18}O = -5.18 - (1.6Z\times10^{-3})$, and LP denotes local precipitation of this study.

Fig. 3. Plot of δD vs. δ^{18}O of precipitation (LP), up-tank water (UTW), and slope groundwater samples (SGWs AH-7 AH-3) in the slope region. The local meteoric water line (LMWL) is established as $\delta D = 8.39\ \delta^{18}O + 13.74$ by data of local precipitation.

Fig.4. Hydrographs with hourly records of precipitation and groundwater table in (a) up, (b) down slope groundwater.

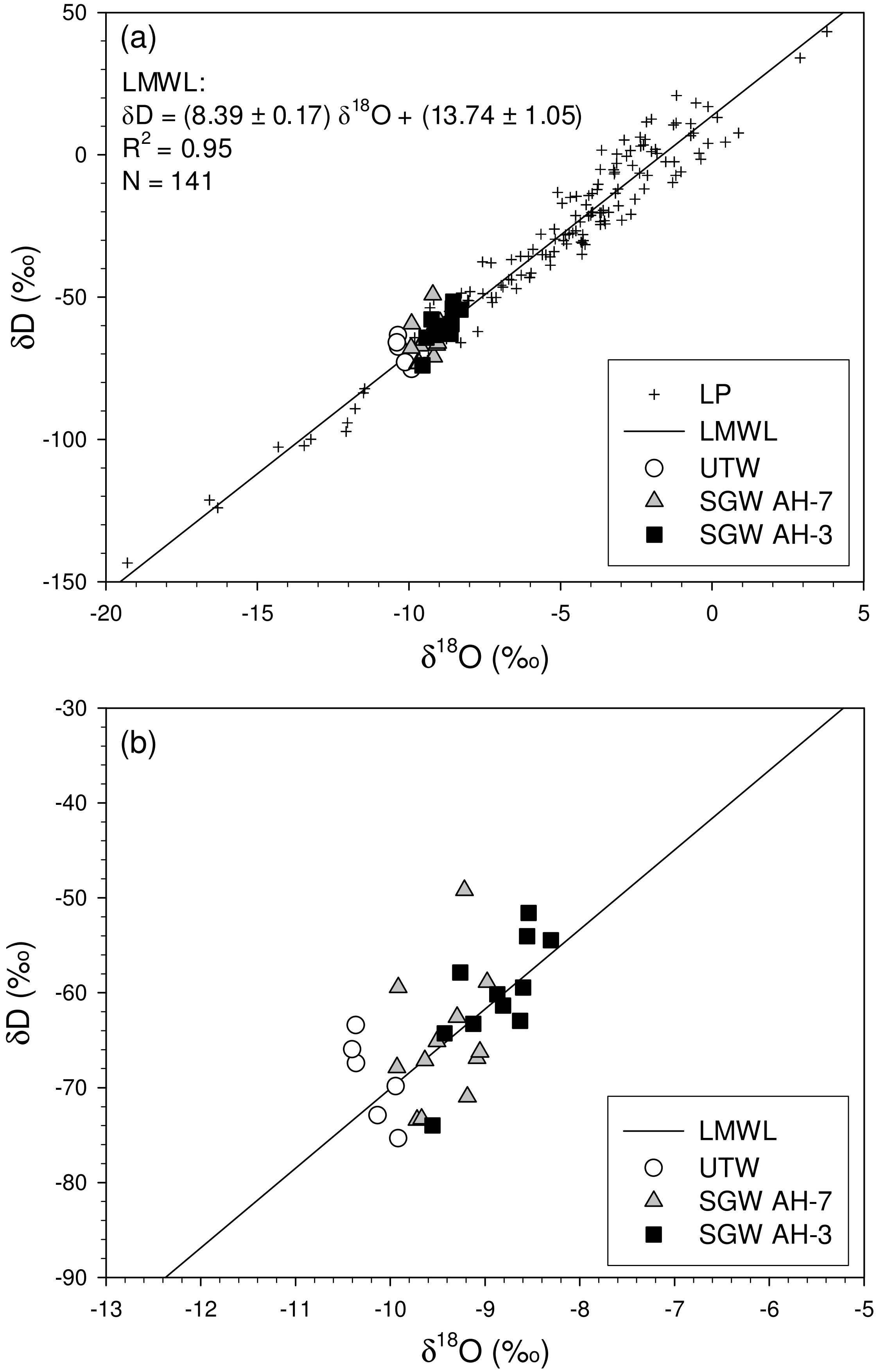
Fig. 5. Slope groundwater samples of AH-7 and AH-3 distributed along the mixing line between the yearly mean values of up-tank water (UTW) and local precipitation (LP).


(a)
120°E
121°
122°
25°N
24°
23°
22°
TY
WL
LS
BL
PL
ALS
Regional topography
Study region
Tunnel
Da-Han Stream
Dam
0
0.5
1 km
1000
900
800
700
600
500
400
300
(b)
1500
1000
500
EL (m)
283000
284000
285000
286000
287000
2739000
2740000
2741000
2742000
2743000
UTW
AH-7
AH-3
LP
Powerhouse
Penstock
(c)
→ E
550
500
450
400
350
300
250
EL (m)
0
50
100
150
200
250
300
350
400
450
Distance (m)
AH-07
AH-03
Tunnel
Up-tank
Penstock
Powerhouse
Well
Screen
Groundwater level
Colluvial soil
Fractured rock
Miocene basement



$\delta^{18}O = -5.18 - (1.6\ Z \times 10^{-3})$
$R^2 = 0.72$
BL
ALS
LS
WL
PL
LP
TY
SGW
Z (m, EL)
3000
2500
2000
1500
1000
500
0
-11
-10
-9
-8
-7
-6
-5
-4
δ18O (‰)

Fig. 2


(a)
LMWL:
$\delta D = (8.39 \pm 0.17)\ \delta^{18}O + (13.74 \pm 1.05)$
$R^2 = 0.95$
N = 141
δD (‰)
50
0
-50
-100
-150
-20
-15
-10
-5
0
5
$\delta^{18}O$ (‰)
LP
LMWL
UTW
SGW AH-7
SGW AH-3
(b)
δD (‰)
-30
-40
-50
-60
-70
-80
-90
-13
-12
-11
-10
-9
-8
-7
-6
-5
$\delta^{18}O$ (‰)
LMWL
UTW
SGW AH-7
SGW AH-3

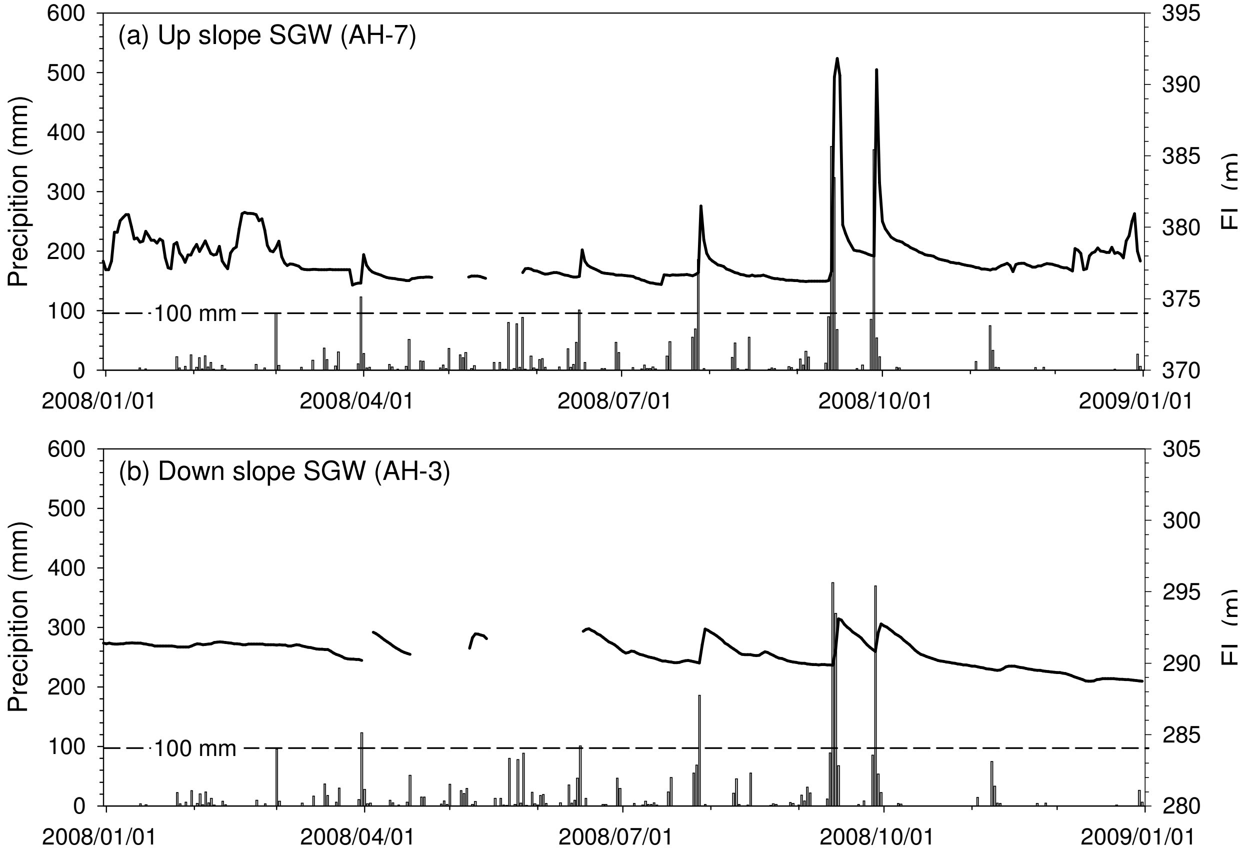

(a) Up slope SGW (AH-7)
Precipition (mm)
Fl (m)
600
500
400
300
200
100
0
395
390
385
380
375
370
100 mm
2008/01/01
2008/04/01
2008/07/01
2008/10/01
2009/01/01
(b) Down slope SGW (AH-3)
Precipition (mm)
Fl (m)
600
500
400
300
200
100
0
305
300
295
290
285
280
100 mm
2008/01/01
2008/04/01
2008/07/01
2008/10/01
2009/01/01

Fig. 4

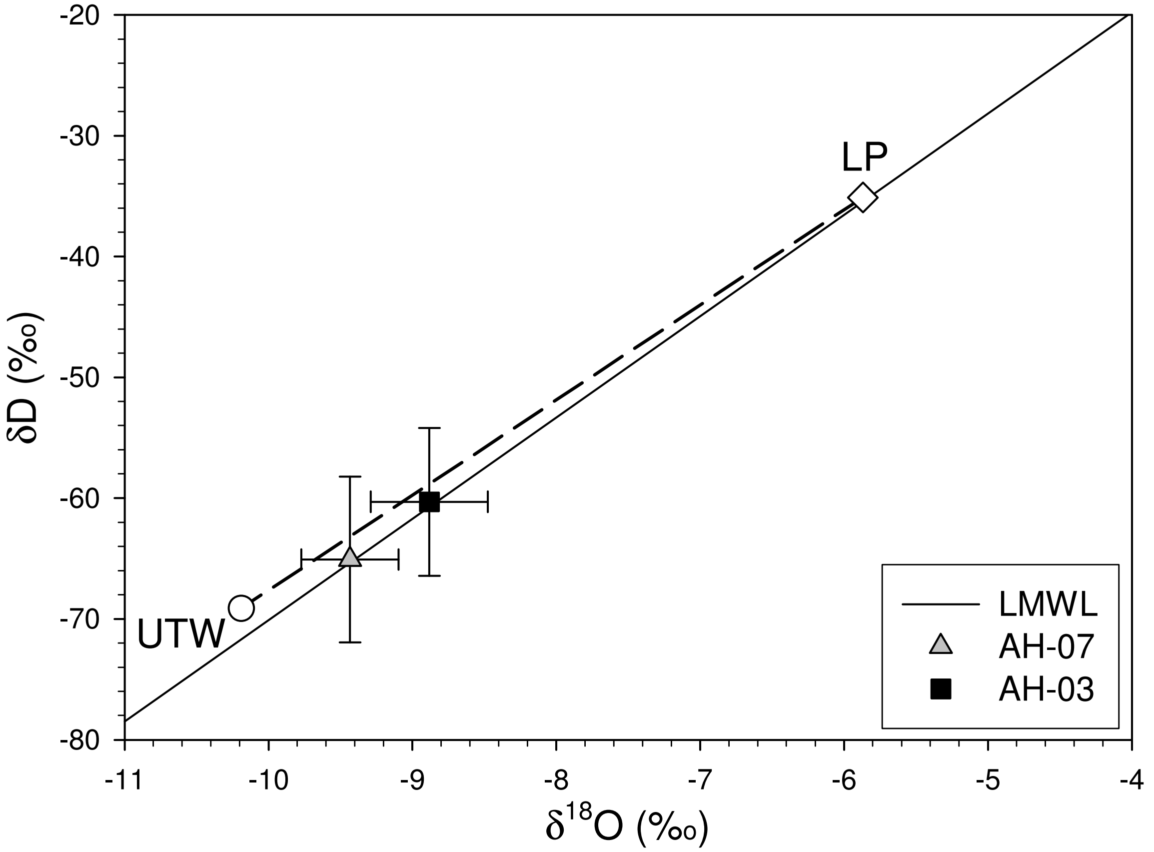


Fig. 5

Table 1. Monthly mean stable oxygen and hydrogen isotopic compositions for precipitation, up-tank water, and slope groundwater in study area, with some tritium determinations.

Samples	2008												Rainy season (May–October)	Dry season (November–April)	Mean (CV%)
	January	February	March	April	May	June	July	August	September	October	November	December			
(1) Oxygen isotope (unit in ‰)															
Precipitation* (LP)	-5.85	-5.07	-3.11	-3.88	-4.06	-9.39	**-14.31**	-6.84	-9.88	-8.10	-3.75	-4.60	-8.76 (-7.66)**	-4.38	-6.57±3.32 (51%) (-5.87)**
		[3.2TU]***													
Up-tank water (UTW)	-9.94	-10.37	-10.36	-10.40	-9.92	-10.14	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	—	—	-10.19±0.22 (2%)
		[1.7TU]		[3.3TU]											
Slope groundwater (SGW)															
AH-7	-9.64	-9.92	-9.93	-9.22	-8.98	-9.19	-9.09	-9.51	-9.72	-9.67	-9.30	-9.06	-9.36	-9.51	-9.43±0.34 (4%)
		[1.9TU]		[1.7TU]											
AH-3	-9.13	-9.43	-9.26	-8.54	-9.55	-8.87	-8.81	-8.56	-8.63	-8.60	-8.31	—	-8.84	-8.93	-8.88±0.41 (5%)
(2) Hydrogen isotope (unit in ‰)															
Precipitation (LP)	-39.7	-27.7	1.7	-19.8	-17.1	-61.6	-105.1	-40.6	-73.6	-56.6	-23.8	-27.5	-59.1 (-49.9)**	-22.8	-40.9±29.1 (71%) (-35.1)**
Up-tank water (UTW)	-69.9	-63.4	-67.4	-66.0	-75.3	-72.9	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	—	—	-69.1±4.4 (6%)
Slope groundwater (SGW)															
AH-7	-67.1	-59.4	-67.9	-49.2	-58.9	-71.0	-66.9	-65.2	-73.4	-73.3	-62.6	-66.2	-68.1	-62.1	-65.1±6.9 (11%)
AH-3	-63.3	-64.3	-57.9	-51.6	-74.0	-60.2	-61.3	-54.0	-62.9	-59.5	-54.5	—	-62.0	-58.3	-60.3±6.1 (10%)

NA: the samples are not available after June because the power plant ceased operating

*: weighted mean value.

**: mean isotope compositions of precipitation exclude the extreme depleted mean value of July's precipitation.

***: tritium concentrations.

Table 2. Fractions of respective end sources contributed to slope groundwater in the studied creep slope.

End-source	Slope groundwater	Relative contributing fraction
Yearly		
Local precipitation (LP, -5.9‰)*	AH-7 (-9.4‰)	AH-7 = (81±9%) LK + (19±2%) LP
Leaking water (LK, -10.2‰)**	AH-3 (-8.9‰)	AH-3 = (70±8%) LK + (30±3%) LP
Rainy season		
Local precipitation (LP, -7.7‰)*	AH-7 (-9.4‰)	AH-7 = (68±6%) LK + (32±3%) LP
Leaking water (LK, -10.2‰)**	AH-3 (-8.8‰)	AH-3 = (44±4%) LK + (56±5%) LP
Dry season		
Local precipitation (LP, -4.4‰)	AH-7 (-9.5‰)	AH-7 = (88±12%) LK + (12±1%) LP
Leaking water (LK, -10.2‰)**	AH-3 (-8.9‰)	AH-3 = (78±10%) LK + (22±2%) LP

*: Mean δ^{18}O values of precipitation exclude the extreme value of July's precipitation.

**: Mean δ^{18}O values of leaking water represent the mean values for yearly, rainy, and dry seasons, respectively. Please refer the text for details.