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Use of stable water isotopes to assess sources and influences of slope groundwater on slope failure

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Abstract:

This study employs stable oxygen and hydrogen isotopes as natural tracers to assess the headwater of a landslide next to a drainage divide and the importance of the slope's headwater in the study area. The study is undertaken near Wu-She Township in the mountains of central Taiwan. Because a reservoir is located on the other side of the divide, this study evaluates the relationship between the reservoir water and headwater of the landslide as well. Over a 1-year period, water samples from September 2008 to September 2009, including local precipitation (LP), Wu-She Reservoir's water (WSRW), slope groundwater (SGW), upper-reach stream water (USTW), and down-reach stream water (DSTW), were analysed for deuterium (δD) and oxygen (δ^{18}O) stable isotopes. Results indicate that WSRW is the predominant component in SGW: approximately 70% of SGW originates from WSRW and 30% from LP based on a two end-member mass-balance mixing model for δ^{18}O. The similar two end-member mixing model is also employed to assess the contributions of USTW and SGW to DSTW. Model results indicate that SGW is the major source of DSTW with a contribution of about 67%. Accordingly, about 47% of DSTW sources from the WSRW. In short, owing to reservoir leakage, WSRW contributes the greater part of both SGW and DSTW. Plentiful WSRW in SGW threatens the stability of the slope in the divide area. To avoid subsequent continuous slope failure, necessary mitigation steps are required. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS stable water isotopes; slope groundwater source; slope failure; reservoir leakage; Taiwan

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INTRODUCTION

Structural geology, slope gradient, and water are three major factors contributing to landslides in landslide-prone regions (Easterbrook, 1999). Slopes with fractured geological structures are easily weathered by water or destroyed by unpredictable stresses (Lee and Dan, 2005). High gradient dip slopes are frequently associated with slope failure due to localized shear stress being greater than the resistance between strata (Akgun *et al*., 2008). Moreover, excessive water not only increases the mass weight on a slope but also provides extra pore water pressure to decrease slope stability (Iverson *et al*., 2000). Therefore, catastrophic slope failure is common during heavy rain. While weakened geological structures or high slope gradients are natural occurrences, often they can be made stable by appropriate engineering. One of the most difficult areas, however, in stabilizing a slope is the effect of water (Bogaard *et al*., 2007).

Several studies have indicated the importance of water other than local precipitation (LP) triggering landslides (Guglielmi *et al*., 2002; Bogaard *et al*., 2007; de Montety *et al*., 2007; Peng *et al*., 2007; Martins-Campina *et al*., 2008; Peng *et al*., 2010a). According to landslide studies on mountainous regions in Taiwan (Peng *et al*., 2007, 2010a), an island in the tropical–subtropical monsoon region of East Asia, slope groundwater (SGW) generally originates from LP and original slope groundwater (OSGW; Figure 1a). That is, LP and OSGW share the composition of SGW. OSGW can be regional groundwater derived from adjacent mountain catchments. The catchments gather infiltrated meteoric water from precipitation, forming the OSGW headwater. High amounts of OSGW have been implicated with a high probability of landslides because a high OSGW component may lead to SGW more readily exceeding the critical level of water needed to cause slope failure (Figure 1b). If the amount of OSGW on vulnerable slopes can be reduced, landslide risk will be lessened (Figure 1c). Thus, an appropriate assessment of recharge source and amount for OSGW is very important in slope stability studies.

Using stable oxygen and hydrogen isotopes as natural tracers to identify OSGW sources has proven to be very useful in landslide studies (Bogaard *et al*., 2007; Peng *et al*., 2007, 2010a). The advantages of this method are as follows: (1) the isotopic approach is not limited by questions of how, when, and where to add a tracer and retrieve a sample for verification that artificial

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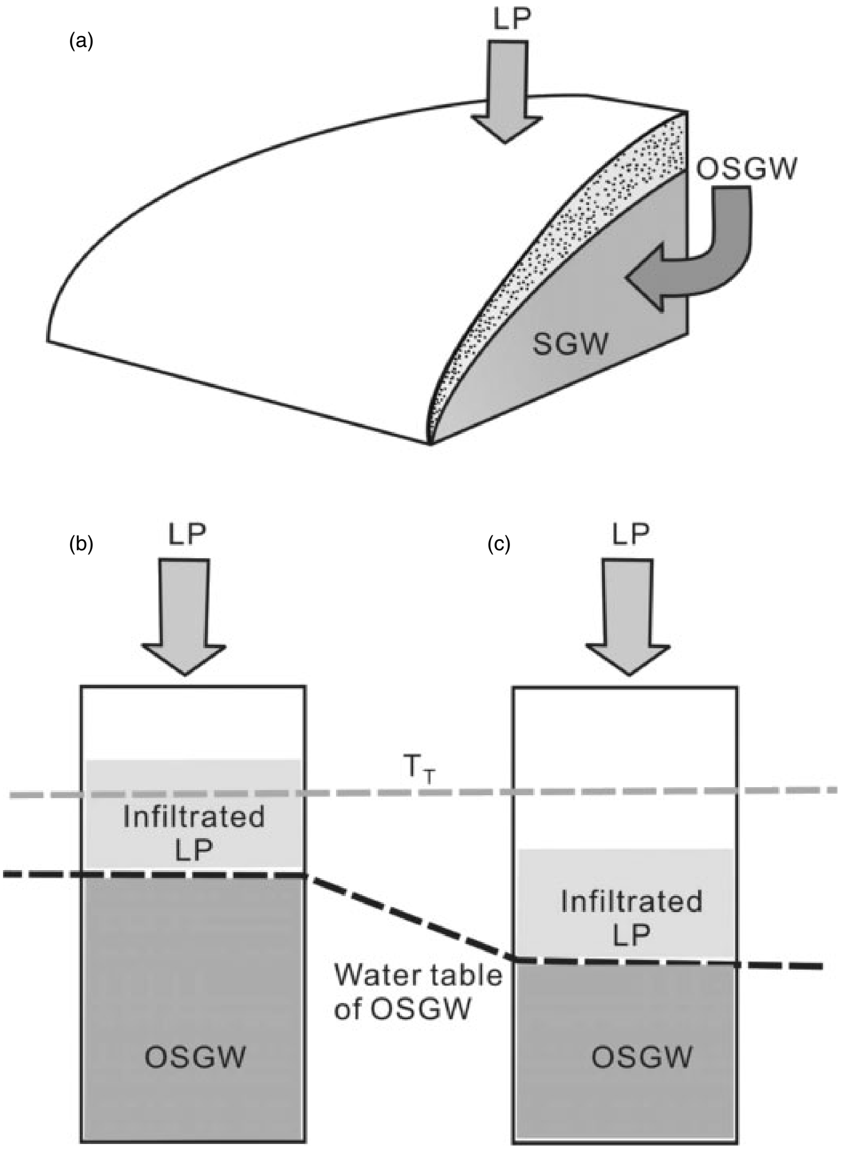

Figure 1. (a) Schematic diagram illustrates that slope groundwater (SGW) generally is a mixture of local precipitation (LP) and original slope groundwater (OSGW). A slope with a high amount of OSGW (b) would more easily exceed the threshold of the water table (T_T) causing a slope failure than a slope possessing a low amount of OSGW (c), because LP and OSGW share in the composition of SGW

tracer studies always encounter [International Atomic Energy Agency (IAEA), 1983]. (2) Hydrogen and oxygen isotopes best approximate water behaviour because they are components of water molecules (Clark and Fritz, 1997; Criss, 1999). (3) Water's stable isotopic compositions are hardly affected by water-rock reactions under normal temperatures (Fritz, 1981; McCarthy *et al.*, 1992). (4) Waters in various environments can show distinct isotopic signatures because the related isotopic fractionation processes that they experienced are different (Dansgaard, 1964; Yurtsever and Gat, 1981). (5) The isotopic approach can provide additional new insights to routine exercises in hydrogeology of landslide studies, especially in defining catchment area (Guglielmi *et al.*, 2002; Bogaard *et al.*, 2007).

In addition to identifying the OSGW headwater, the stable isotopic approach can assess the relative importance between OSGW and LP in SGW in landslide studies by employing a conventional two end-member mass-balance equation (Peng *et al.*, 2007, 2010a). Previous mountain landslide studies, utilizing the isotopic approach for Taiwan (Peng *et al.*, 2007, 2010a), have indicated that OSGW's contribution to SGW can be up to ~85%, which is much greater than the contribution of 15% from LP. Therefore, although heavy LP may trigger a landslide, the amount and presence of OSGW, as a hidden factor, is critical to understand the underlying causes of landslides (Figure 1).

Conventionally, landslide amelioration requires the use of drainage facilities such as wells, pipes, and galleries to draw off SGW. The drainage method keeps water from exceeding soil's pore capacity, moderating groundwater pressure in a slope during rain events. However, an abundance of OSGW can result from human activity as well as natural infiltration of meteoric water. For example, Peng *et al.* (2007) used isotopes to demonstrate

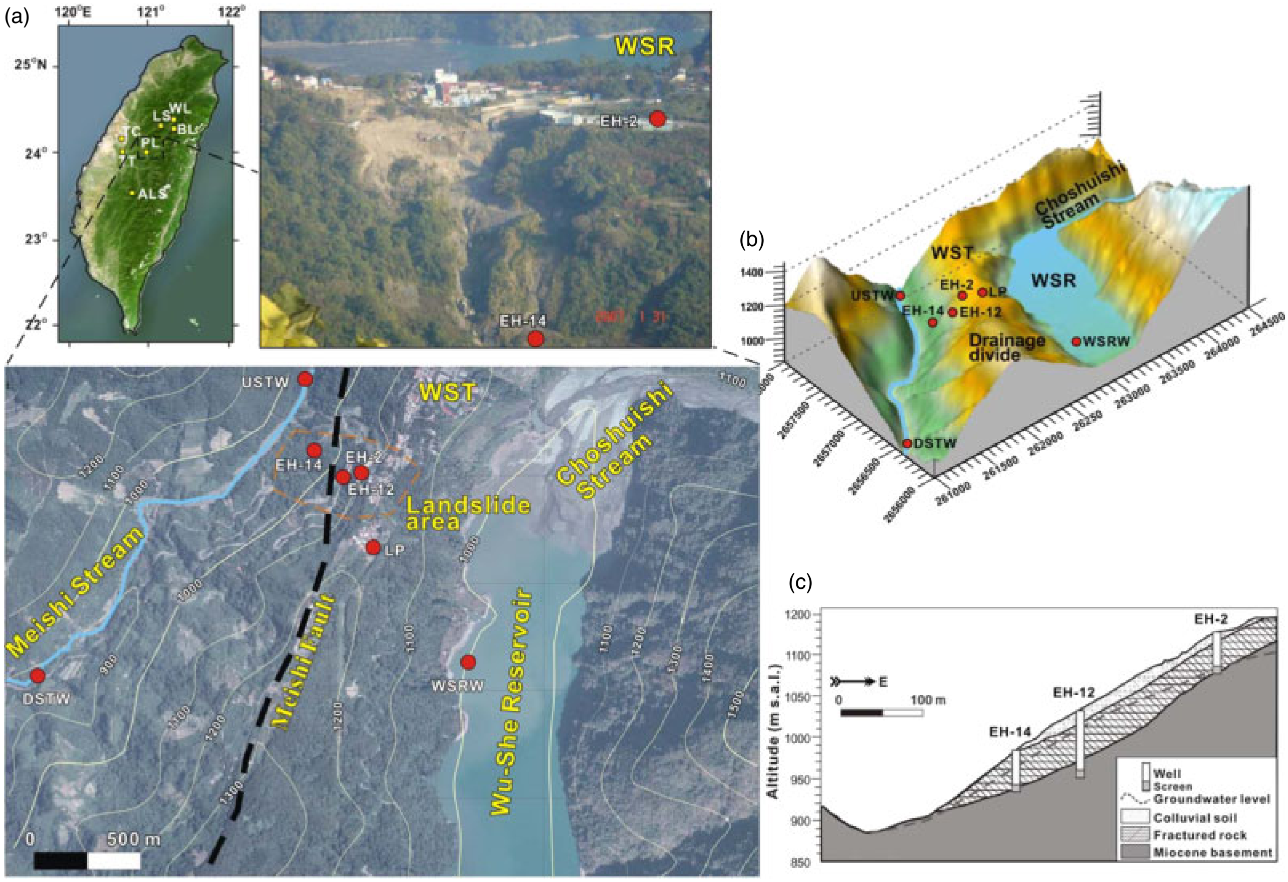

Figure 2. (a) Images of the study area and slope failure (SWCB, 2007; CGS, 2008). The sites denoted as TC, TT, PL, LS, WL, ALS, and BL are sampling locations for precipitation discussed in the text. The image also shows the water sampling locations of local precipitation (LP), upper-reach stream water (USTW), down-reach stream water (DSTW), Wu-She Reservoir's water (WSRW), and slope groundwaters (SGWs) of EH-2, EH-12, and EH-14. (b) Topographical landform of the studied region. (c) Geological profile of the studied slope

that irrigation water from a farm located directly above a studied landslide slope was the major source of OSGW. Using a similar isotopic approach, Peng *et al*. (2010a) indicated that leaking water from a water-transport tunnel of a hydropower plant was the OSGW headwater source for a creep slope threatening the safety of the power plant. To best address anthropogenic causes of landslides and bolster current drainage networks, alternate strategies must be carefully considered for the prevention of excessive human-activity sourced OSGW headwaters from flowing into landslide susceptible regions. Once such headwater recharge is significantly reduced and regulated, landslide risk will be substantially diminished.

This case study is conducted at Wu-She Township (WST), located in mountainous central Taiwan (Figure 2a). The WST is located at a drainage divide between the Meishi Stream and Choshuishi Stream (Figure 2b) and represents an important way-station along the only highway leading to eastern Taiwan. On the eastern side of WST, water of Choshuishi Stream has been captured by the Wu-She Reservoir (WSR); on the western side of WST, a deep valley has been cut by the Meishi Stream. The main issue of this case study is a landslide resulting from headward erosion on the western slope of WST (Figure 2a). The landslide presently imperils some town buildings and the important highway passing through the divide. Water impounded in the WSR is suspected of being involved in the landslide because reservoir water could be leaking out of dams via fractures or joints in the dam's banks (Turkmen *et al*., 2002; Peng and Wang, 2008). This leakage could be a source of OSGW contributing to the slope's failure. Although some engineering remediation efforts have been performed relating to the landslide at WST, assessments of the source and influence of OSGW on the slope failure are still lacking.

Consequently, the purpose of this study is to employ a stable water isotope approach to assess (1) the OSGW headwater source of the studied slope at WST, (2) the hydrological relationship between OSGW headwater and reservoir water, and (3) the role and importance of OSGW in the study area. Proper assessment of these aspects may lead to a better understanding of landslides in the study region.

MATERIALS AND METHODS

Study area

Geographically, WST is sited at a drainage divide at an altitude of ~1200 m above sea level (a.s.l.) between the Meishi Stream on the west and Choshuishi Stream on the east (Figure 2b). Stream water of the Choshuishi is impounded by the WSR, which has been used to provide hydropower since 1959. On the other hand, the Meishi Stream has cut a deep ravine on the western slope of WST.

Geomorphically, a variety of incised gullies are present along the western valley slope next to WST; the slope has a catchment area of ~200 ha. Of particular interest is a major landslide of ~10 ha resulting from headward erosion on the western slope [see photograph in Figure 2; Soil and Water Conservation Bureau (SWCB), 2007; Central Geological Survey (CGS), 2008]. The soil on the western slope is mainly of silt texture with a thickness of less than 0·5 m. The thin soil layer may be due to the steep gradients of the slope, which range about 35°–55°. In addition, shrubs are the major plant type on the studied slope.

Geologically, the bedrock of the drainage divide where WST is located comprises the Miocene Lushan Formation composed of alternating layers of argillite, phyllite, and slate (CGS, 2002). The geological structure of the studied slope (located to the west of WST) is considered fractured because of metamorphic cleavages; furthermore, the Meishi Fault is inferred across the slope region (Figure 2a). The Central Geological Survey reported that the studied slope consists of three main bodies (CGS, 2008): a surface colluvial layer, middle fractured rock, and the Miocene basement (Figure 2c). The colluvial layer is composed of permeable debris derived from slate, argillite, and fine clay, and its measured saturated hydraulic conductivity is 10^{-7} to 10^{-6} m/s approximately. The fractured rock underlying the colluvial layer consists of weathered slate with a saturated hydraulic conductivity of 10^{-6} to 10^{-5} m/s, which is significantly higher than that of typical unfractured rock of less than 10^{-10} m/s (Freeze and Cherry, 1979). The Miocene basement underlying the weathered fractured rock layer is of fresh slate, but it is lithologically characterized with well-developed cleavages. The hydraulic conductivity of the Miocene basement is 10^{-8} to 10^{-6} m/s approximately, which is somewhat smaller than that of the overlying fractured rock. In short, the drainage divide of the study is hydrogeologically permeable due to its structural character of well-developed cleavages and fractures.

Climatically, according to long-term meteorological records at WSR from 1993 to 2004 (CGS, 2008), the annual mean rainfall is about 2000 mm, of which 67% falls during the rainy months (May to August) and only 9% in the dry months (October to February). In addition, averaged monthly rainfall is about 234–461 mm during the rainy season and 37–235 mm in the dry season.

Water samples

Water samples including LP, SGW, WSR's water (WSRW), upper-reach stream water (USTW), and down-reach stream water (DSTW) were collected for isotopic determination. The sampling locations are illustrated in Figure 2. Sampling details are given below.

(1) LP: LP samples were collected near the study slope at an altitude of ~1200 m a.s.l. on each rainy day. Daily rainfall was recorded by a pluviograph. Sampling procedures for precipitation were in accordance with IAEA guidelines (IAEA, 1983); in short, the procedure is designed to avoid evaporation of precipitation samples.
(2) Stream water: USTW and DSTW were taken from the Meishi Stream adjoining the study slope. The sampling altitude of the streambed is ~900 m a.s.l. (Figure 2a), and Meishi Stream water comes from an upstream catchment at a minimum altitude of ~2000 m a.s.l. (CGS, 2008).
(3) WSRW: The WSR, with an altitude of ~1100 m a.s.l. (Figure 2a), impounds water of the Choshuishi Stream for the hydropower purposes. Choshuichi Stream water comes from an upstream catchment at a minimum altitude of ~2900 m a.s.l. (CGS, 2008).
(4) SGW: SGW samples were taken from three monitoring wells EH-2, EH-12, and EH-14 located at 1140, 1037, and 962 m a.s.l., respectively. The screen depth of each monitoring well was 50 m below ground surface (Figure 2c). Groundwater levels in the three monitoring wells were recorded hourly using a digital recorder.

Water samples were taken monthly from October 2008 to September 2009 except for LP, which was collected on each rainy day from September 2008 to August 2009. Additionally, USTW sample was available in February 2009. A 1-year period of all water samples except USTW was analysed for stable oxygen and hydrogen isotope compositions.

Isotope analyses

Stable oxygen isotopic compositions were determined by analysing samples prepared by a carbon dioxide (CO_2)-water (H_2O) equilibration method (Epstein and Mayeda, 1953; Brenninkmeijer and Morrison, 1987). The equilibrated CO_2 gas was measured by an isotope ratio mass spectrometer (IRMS, SIRA 10, VG Isotopes, United Kingdom). The hydrogen isotopic compositions were determined on an IRMS (MM602D, VG Isotopes, United Kingdom) after reduction of water to hydrogen gas (H_2) using zinc shots (Coleman *et al*., 1982).

All isotopic ratio results are reported as δ-notation (‰) relative to the international Vienna Standard Mean Ocean Water standard and normalized on a scale whereby the δ^{18}O and δD of Standard Light Antarctic Precipitation are −55·5 and −428‰, respectively (Gonfiantini, 1978). The analytical precision is expressed as 1 standard deviation (σ) for the laboratory standards are within 1·3‰ for δD and 0·08‰ for δ^{18}O, respectively. The average differences in duplicate analyses of water samples are ±1·5‰ for δD and ±0·11‰ for δ^{18}O, respectively.

Two end-member isotope-mixing model for partitioning water sources

Given water M2 is a mixture of S1 and S2, the proportions of S1 and S2 in M2 can be evaluated by a conventional two end-member mass-balance equation in terms of δ^{18}O values (Clark and Fritz, 1997; Peng *et al.*, 2007, 2010a):

$$\delta^{18}O_{M2} = \delta^{18}O_{S1} \times R_{S1} + \delta^{18}O_{S2} \times R_{S2} \quad (1a)$$

$$1 = R_{S1} + R_{S2} \quad (1b)$$

The solutions for Equations (1a) and (1b) are

$$R_{S1} = (\delta^{18}O_{M2} - \delta^{18}O_{S2})/(\delta^{18}O_{S1} - \delta^{18}O_{S2}) \quad (2a)$$

$$R_{S2} = (\delta^{18}O_{M2} - \delta^{18}O_{S1})/(\delta^{18}O_{S2} - \delta^{18}O_{S1}) \quad (2b)$$

In Equations (1) and (2), δ^{18}O represents oxygen isotope composition; R_{S1} and R_{S2} are the fractions of S1 and S2 in M2, respectively. Equation (1) is applicable if M2 comprises well-mixed S1 and S2 (Clark and Fritz, 1997; Peng *et al.*, 2010a). The uncertainty with 95% confidence interval for each derived fraction of Equations (2a) and (2b) can be estimated using the appropriate equations reported by Phillips and Gregg (2001a,b).

RESULTS

Local precipitation

Stable isotopic compositions of LP varied widely and exhibited distinct seasonal variability (Figure 3). The yearly precipitation-weighted mean value for δ^{18}O is −8·3‰ with a coefficient of variation (CV) value of 37% and that for δD is −56‰ with a CV value of 49% (Table I). The plot of δD *versus* δ^{18}O for LP in the study is displayed in Figure 4a; the local meteoric water line (LMWL) established by LP samples is $\delta D = 8{\cdot}3\ \delta^{18}O + 14{\cdot}2$. Since the slope value of the LMWL is not lower than 8, it is indicated that the precipitation samples analysed in this study experienced little evaporation (Clark and Fritz, 1997; Peng *et al.*, 2010b).

In general, the stable isotope compositions of summer's precipitation are more depleted than those of winter's precipitation (Figure 3). This is typical of the East Asian monsoon region, where summer and winter seasons are, respectively, controlled by two different prevailing monsoons with respective distinct isotopic compositions (Peng *et al.*, 2010b). However, typhoons often bring heavy rainfall of much lighter isotopic compositions to the East Asian monsoon region (Araguás-Araguás *et al.*, 1998). In this study, due to typhoons, the isotopic compositions of precipitations in September and October 2008 and August 2009 are significantly lighter than those of other months (Figure 3). These much depleted isotopic values would result in the long-term mean value being lighter than normal due to their relatively big contribution (Peng *et al.*, 2010a).

For example, because of the altitude effect in precipitation, isotopic compositions vary with altitude and show relatively depleted values in high-altitude regions over those of low-altitude regions (Dansgaard, 1964; Yurtsever and Gat, 1981). Figure 5 shows the relationship between yearly isotope composition and altitude in terms of δ^{18}O values for seven sites in Central Taiwan (altitudes from 34 to 2410 m a.s.l.) based on the isotope database of Taiwan's precipitation reported by Peng *et al.* (2010b). The mathematical regression between δ^{18}O values and altitudes can be expressed as follows:

$$\delta^{18}O_Z = -4{\cdot}78 - (1{\cdot}84Z \times 10^{-3}) \quad (3)$$

where $\delta^{18}O_Z$ represents the oxygen isotope composition of precipitation at a given altitude Z (in m a.s.l.). Since LP samples of this study region were collected at ∼1200 m a.s.l., the calculated $\delta^{18}O_Z$ value should be around −7·0‰ by Equation (3) (Figure 5). However, the estimated value is heavier than the yearly mean measured value −8·3‰ of LP (Table I). On the other hand, if the distinct values of typhoon precipitations in September and October 2008 and August 2009 are excluded, the yearly mean δ^{18}O value for the LP is −6·5‰ (Table I), which is similar to the calculated $\delta^{18}O_Z$ value.

The more depleted yearly mean isotope values of precipitation in this study due to typhoons may be attributed to a La Niña episode during the study period. According to the 5-month weighted mean of the southern oscillation index (SOI) from the Bureau of Meteorology, Australia (2010), continuous positive SOI values for the period April 2008 to May 2009 represented a La Niña episode. During La Niña episodes, the warmer ocean water (resulting in typhoons) is typically located in the western Pacific region, as compared to normal circumstances or El Niño episodes when the warm ocean water is located around the central or eastern equatorial Pacific (Yu *et al.*, 1998). Warmer ocean water near East Asia during La Niña events would generate more typhoons in the western Pacific, which have a higher probability of invading Taiwan than those generated in the central or eastern Pacific. During this study from September 2008 to August 2009, five typhoons invaded Taiwan and noticeably increased the rainfall in the study region (Figure 6). The high count of visiting typhoons during the study period is greater than the average frequency of typhoon invasions for Taiwan, which is three times per year (long-term meteorological records of Taiwan, Central Weather Bureau, 2009).

Stream water (DSTW and USTW)

Monthly variability of stable isotopic composition of DSTW next to the study slope is illustrated in Figure 3. The yearly mean isotope values of DSTW are −10·7‰ with a CV value of 6% for δ^{18}O and −70‰ with a CV value of 6% for δD (Table I). Low isotopic CV values indicate that the seasonal variations of isotopic compositions are insignificant for DSTW. The isotopic values of USTW sampled in February 2009 are −11·1‰ for δ^{18}O and −71‰ for δD. The values are similar to those of stream water (−11·3‰ for δ^{18}O and −75‰ for δD) derived from the same upstream catchment that reported by Peng *et al.* (2007). The δ^{18}O and δD values of both DSTW and USTW are more depleted than those of LP (Table I), suggesting that the sampled stream

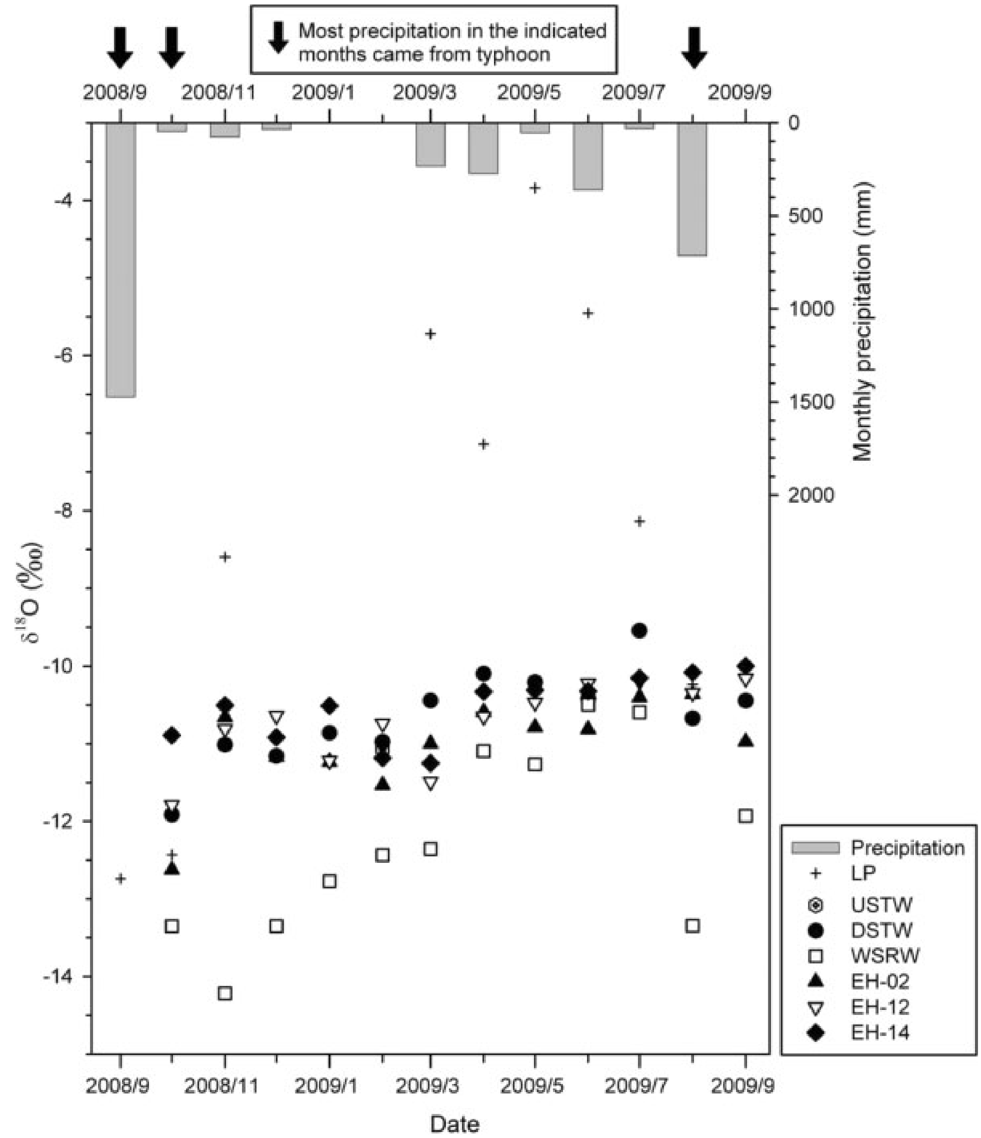

Figure 3. Temporal monthly $\delta^{18}O$ variations of LP, DSTW, WSRW, and SGWs of EH-2, EH-12, and EH-14 during the study period. USTW has only 1 month of data shown in February 2009

water derives from catchments higher than the altitude (~1200 m a.s.l.) of the LP sampling site.

Wu-She Reservoir's water

In comparison with waters from LP, DSTW, and USTW, WSRW shows relatively depleted isotopic compositions (Figure 3). The yearly mean isotopic compositions of WSRW are −12·3‰ for $\delta^{18}O$ and −83‰ for δD, respectively (Table I). The CV values of the stable isotopic compositions are 10% for $\delta^{18}O$ and 12% for δD.

The mean $\delta^{18}O$ and δD values of WSRW are more depleted than those of both LP by 4·0 and 27‰, respectively, and DSTW by 1·6 and 13‰, respectively (Table I). This depleted isotopic feature agrees well with water from the WSR as its water is sourced from the Choshuishi Stream that derives water from catchments of altitude ~2900 m a.s.l., which is higher than the altitudes of the catchments for the DSTW and the LP sampling site.

Slope groundwater

Annual mean isotopic compositions of SGW get heavier with decreasing altitude. The mean $\delta^{18}O$ and δD values of up-SGW (EH-2) are −11·0 and −75‰, respectively (Table I); by comparison, those of down-SGW (EH-14) are −10·5 and −69‰, respectively. The isotopic values of mid-SGW (EH-12) are −10·7‰ for $\delta^{18}O$ and −71‰for δD, which are between the values of EH-2 and of EH-14.

Similar to DSTW, all SGWs show minor isotopic discrepancies between months (Figure 3), a typical feature in groundwater. The CV values of the yearly mean isotopic compositions for the SGWs are lower than 6% for $\delta^{18}O$ and 7% for δD (Table I).

The isotopic data of DSTW, USTW, WSRW, and SGW samples distribute along with the LMWL (Figure 4a), indicating that those waters originate from meteoric water and their isotopic compositions do not experience significant fractionations such as evaporation or isotopic

Table I. Yearly mean stable oxygen and hydrogen isotopic compositions of precipitation, stream water, reservoir water, and slope groundwater in the study area

Samples	Mean δ values (CV%)
Oxygen isotope (δ^{18}O, unit in ‰)	
Precipitation[a] (LP)	$-8{\cdot}26 \pm 3{\cdot}09$ (37%)
	$-6{\cdot}48 \pm 1{\cdot}81$[b]
Down-reach stream water (DSTW)	$-10{\cdot}65 \pm 0{\cdot}60$ (6%)
Upper-reach stream water (USTW)	$-11{\cdot}09$[c]
Wu-She Reservoir's water (WSRW)	$-12{\cdot}27 \pm 1{\cdot}21$ (10%)
Slope groundwater (SGW)	
EH-2	$-11{\cdot}01 \pm 0{\cdot}61$ (6%)
EH-12	$-10{\cdot}73 \pm 0{\cdot}53$ (5%)
EH-14	$-10{\cdot}54 \pm 0{\cdot}42$ (4%)
Hydrogen isotope (δD, unit in ‰)	
Precipitation[a] (LP)	$-56{\cdot}0 \pm 27{\cdot}4$ (49%)
	$-40{\cdot}2 \pm 16{\cdot}7$[b]
DSTW	$-70{\cdot}3 \pm 4{\cdot}6$ (6%)
USTW	$-70{\cdot}7$[c]
WSRW	$-82{\cdot}7 \pm 9{\cdot}8$ (12%)
SGW	
EH-2	$-74{\cdot}5 \pm 5{\cdot}0$ (7%)
EH-12	$-71{\cdot}2 \pm 3{\cdot}1$ (4%)
EH-14	$-69{\cdot}2 \pm 3{\cdot}1$ (5%)

[a] Precipitation-weighted mean value.
[b] Mean isotopic compositions of precipitation exclude the depleted mean values of the typhoon precipitations in months of September and October 2008 and August 2009. Refer the text for details.
[c] USTW sample was available only in February 2009.

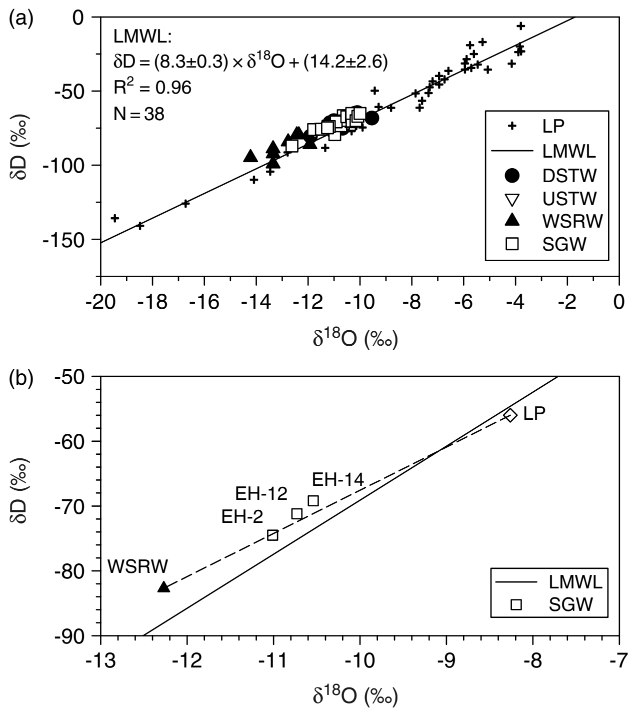

Figure 4. (a) Plot of δD *versus* δ^{18}O of precipitation (LP), down-reach stream water (DSTW), upper-reach stream water (USTW), Wu-She Reservoir's water (WSRW), and slope groundwater samples (SGW) of EH-2, EH-12, and EH-14 in the slope region. The local meteoric water line (LMWL) is established as $\delta D = 8{\cdot}3\ \delta^{18}O + 14{\cdot}2$ by LP data. (b) SGWs of EH-2, EH-12, and EH-14 distributed along the isotopic mixing line between the yearly mean values of WSRW and LP

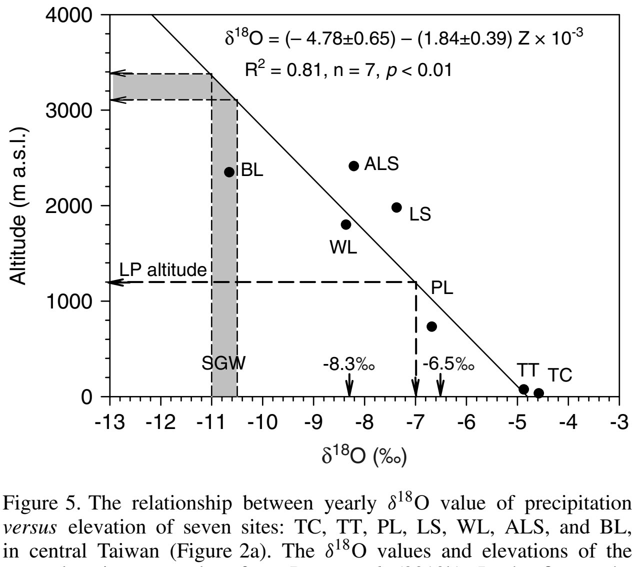

Figure 5. The relationship between yearly δ^{18}O value of precipitation *versus* elevation of seven sites: TC, TT, PL, LS, WL, ALS, and BL, in central Taiwan (Figure 2a). The δ^{18}O values and elevations of the seven locations are taken from Peng *et al.* (2010b). In the figure, the mathematical regression is $\delta^{18}O_Z = -4{\cdot}78 - (1{\cdot}84Z \times 10^{-3})$, and LP denotes local precipitation discussed in this study. The indicated value $-8{\cdot}3$‰ is yearly mean of all LP samples; $-6{\cdot}5$‰, the mean value excludes the typhoon samples in September and October 2008 and August 2009 (for details, see text)

exchange. Had these fractionations occurred, those data points shown in Figure 4a would significantly diverge from the LMWL (Clark and Fritz, 1997). Thus, their isotopic compositions can be regarded as conservative (Criss, 1999).

DISCUSSION

Headwater of OSGW

As mentioned in the Section on Introduction, for landslide studies on mountainous regions in Taiwan, LP and OSGW are two major components for SGW (Figure 1). According to daily records during the study period (Figure 6), groundwater levels of both up- and down-SGWs (EH-2 and EH-14) fluctuated primarily with precipitation events higher than 100 mm/day, but the fluctuation threshold for mid-SGW (EH-12) is about 50 mm/day. This indicates that the contribution from LP to SGW is small and confined to the mid-slope area. One notable feature is that groundwater levels do not fluctuate greatly with rainfall, indicating that a great amount of OSGW exists in the slope (Martins-Campina *et al.*, 2008). This restricts any contribution from LP because of limited space in the soil's pore capacity (Peng *et al.*, 2010a).

The small contribution of LP to SGW is also evidenced by stable isotopic values of SGW samples that do not show significant isotopic discrepancies between months. An example of how LP contributes to SGW can be seen for the month of May (Figure 3). In May, the δ^{18}O and δD values for precipitation exhibited greatly enriched values (e.g. $-3{\cdot}8$‰ for δ^{18}O, Figure 3); however, the heavy

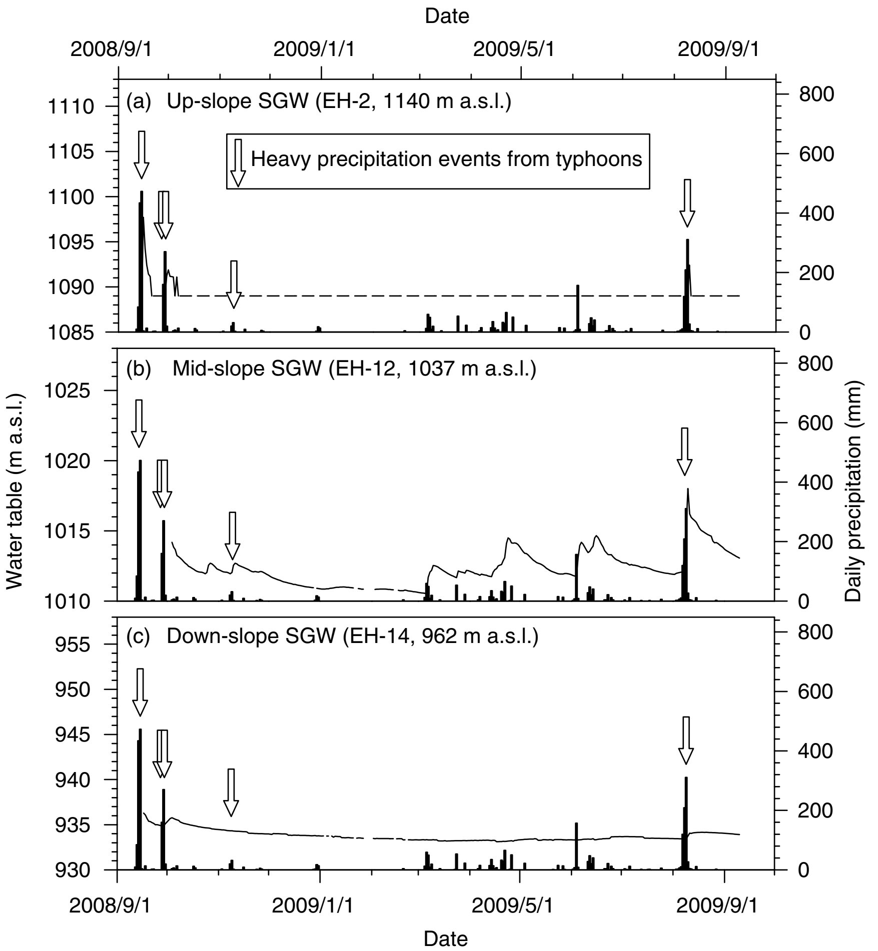

Figure 6. Hydrographs with daily records of precipitation and groundwater table in (a) up-, (b) mid-, and (c) down-slope groundwater

isotopic signal is not clearly observed in SGW samples after May. Furthermore, groundwater level hydrographs show a constant baseline during low or no rain periods (Figure 6), demonstrating dominant OSGW signal over LP in SGW. Even typhoons that brought heavy rainfall during the studied period resulted in little infiltration of SGW. This evidence suggests that although SGW is a mixture of the two components of LP and OSGW, LP's contribution to SGW is limited and OSGW contributes considerable amounts of water to the studied slope, serving as a potential factor in landslide events. Therefore, the source and importance of OSGW must be first clarified.

The relative contributions to SGW between OSGW and LP can be estimated using equation similar to Equation (1):

$$\delta^{18}O_{SGW} = \delta^{18}O_{LP} \times R_{LP} + \delta^{18}O_{OSGW} \times R_{OSGW} \quad (4)$$

The $\delta^{18}O$ values of both LP and SGW for Equation (4) were readily identified (Table I); however, the OSGW component still needs further confirmation.

Since the lightest mean $\delta^{18}O_{SGW}$ value is $-11{\cdot}0$‰ of EH-2 and the $\delta^{18}O_{LP}$ value is $-6{\cdot}5$‰ (or $-8{\cdot}3$‰ if the values of typhoon precipitations are considered) (Table I), then $\delta^{18}O_{OSGW}$ should possess a value lighter than $-11{\cdot}0$‰. This is because the OSGW serves as the end-member with depleted isotopic composition in contrast to the enriched side of $\delta^{18}O_{LP}$ based on Equation (4). That is, OSGW should derive from a catchment altitude higher than that of the study region.

According to the topography of the studied region (Figure 2), three prospective sources for the OSGW are (1) WSRW, (2) groundwater deriving from adjacent catchments higher than the studied divide of WST, and (3) precipitation infiltrating at the divide (WST). If the OSGW originates from precipitation infiltrating at the divide (~1200 m a.s.l.), the $\delta^{18}O_{OSGW}$ value would be $-7{\cdot}0$‰ approximately based on Equation (3). This value $-7{\cdot}0$‰, however, does not agree with the requirement that the $\delta^{18}O_{OSGW}$ should be lighter than $-11{\cdot}0$‰.

With respect to groundwater recharge arriving from an adjacent region higher than the study area, the recharge altitude of OSGW headwater can be inferred from Equation (3). If LP contribution is negligible to the SGW, $\delta^{18}O_{OSGW}$ is then equal to the $\delta^{18}O_{SGW}$ in Equation (4) and the inferred altitude by Equation (3) would be the lowest estimation for an adjacent watershed. Since the mean $\delta^{18}O_{SGW}$ values of the three SGWs range from $-11{\cdot}0$ to $-10{\cdot}5$‰, the lowest altitude for the recharge region calculated from Equation (3) would be 3100 m approximately (Figure 5). In reality, the altitude of the adjacent divide is lower than 2000 m (Figure 2)

Table II. Fractions of respective end sources contributed to SGWs and DSTW of this study using a two end-member isotope-mixing model in terms of yearly mean $\delta^{18}O$ values[a]

Mixed water	Two end sources	Relative contributing fraction
Slope groundwater (SGW)		
SGW (EH-2, −11·0 ± 0·6‰)	(1) Wu-She Reservoir's water (WSRW, −12·3 ± 1·2‰)	EH-2 = (78 ± 6%) WSRW + (22 ± 6%) LP
SGW (EH-12, −10·7 ± 0·5‰)	(2) Local precipitation (LP, −6·5 ± 1·8‰[b])	EH-12 = (72 ± 5%) WSRW + (28 ± 5%) LP
SGW (EH-14, −10·5 ± 0·4‰)		EH-14 = (70 ± 5%) WSRW + (30 ± 5%) LP
Stream water (STW)		
Down-reach STW (DSTW, −10·7 ± 0·6‰)*	(1) SGW (EH-14, −10·5 ± 0·4‰)	DSTW = (67 ± 32%) SGW + (33 ± 32%) USTW
	(2) Upper-reach STW (USTW, −11·1‰)	

[a] The yearly mean $\delta^{18}O$ values of waters shown in this table are listed in Table I.
[b] $\delta^{18}O$ values of precipitation excluded the depleted mean values of the typhoon precipitations in months of September and October 2008 and August 2009. Refer to the text for details.

and cannot provide water to support such lighter $\delta^{18}O_{OSGW}$ values as −10·5‰. Therefore, an OSGW source from the adjacent up-slope divide is very unlikely.

The mean $\delta^{18}O$ value of WSRW is −12·3‰ (Table I), which fits the requirement that the $\delta^{18}O_{OSGW}$ value should be relatively more depleted than the $\delta^{18}O$ values of LP and SGW. Additionally, in the δD *versus* $\delta^{18}O$ plot of Figure 4b, averaged SGW data distribute along the mixing line between the two ends of the WSRW and LP, strongly implying that WSRW is a very likely candidate for the lighter isotope end-member. Because no other water with a similarly depleted isotopic composition as WSRW can be found in the study region, it is suggested that WSRW is responsible for the headwater of the OSGW. That is, WSRW penetrates the drainage divide via fractured strata supplying the OSGW (Figure 2). Other researchers have also shown how fractured strata can drive groundwater flow to a slope and trigger landslides (Bogaard *et al*., 2007; de Montety *et al*., 2007).

Assuming OSGW is solely derived from WSRW, the effect of the WSRW on SGW in terms of $\delta^{18}O$ can be evaluated by Equation (4). To estimate the WSRW fraction in SGW, it is more reasonable to take yearly mean $\delta^{18}O$ values than monthly or seasonal mean data (Peng *et al*., 2010a) because precipitation infiltration rates in groundwater are hard to assess (Hunt *et al*., 2005). It also ensures the assumption for Equation (4) that OSGW and LP are well mixed in SGW.

Table I shows that the SGW yearly mean $\delta^{18}O$ values for EH-2, EH-12, and EH-14 are −11·0, −10·7, and −10·5‰, respectively. The yearly mean $\delta^{18}O_{LP}$ value is −6·5‰, representing the heavy-isotope end-member in Equation (4). The light-isotope end-member $\delta^{18}O_{OSGW}$ is represented by $\delta^{18}O_{WSRW}$ with a yearly mean value of −12·3‰. The WSRW fractions in EH-2, EH-12, and EH-14 are 78, 72, and 70%, respectively, and the LP fractions in EH-2, EH-12, and EH-14 are 22, 28, and 30%, respectively (Table II). From the top of the slope downward, WSRW fractions decrease, while the LP component increases (Table II and Figure 2).

WSRW is the predominant component of SGW at 70% (minimum; Table II). The prevalence of reservoir water in the SGW may result from hydraulic pressure at the reservoir coupled with highly permeable fractured strata in the divide.

Role and importance of OSGW in study area

SGW can serve as a major contributor to stream water. Typically, stream water at the down-stream reaches (DSTW) has three contributors: LP, stream water from upper reaches (USTW), and baseflow from subsurface water (Kendall and Coplen, 2001; Yuan and Miyamoto, 2008). The baseflow component corresponds to the SGW of this study. Although LP is a source of water in the DSTW of the study region, it is also a common source for USTW and SGW. That is, the isotopic compositions of DSTW, USTW, and SGW all have signals from LP. Since LP is a common source for DSTW, USTW, and SGW, its individual importance in DSTW is hard to evaluate.

Consequently, in this study, DSTW is regarded as a mixture of USTW and SGW (Figure 2), and the relative importance of the two contributions to DSTW is assessed by a similar equation to Equation (4):

$$\delta^{18}O_{DSTW} = \delta^{18}O_{USTW} \times R_{USTW} + \delta^{18}O_{SGW} \times R_{SGW} \quad (5)$$

The yearly mean $\delta^{18}O$ values of DSTW, USTW, and SGW (represented by down-slope SGW EH-14) employed in Equation (5) are listed in Table I, and the respective fractions of 33 and 67% for R_{USTW} and R_{SGW} are accordingly obtained (Table II). The higher value of R_{SGW} relative to R_{USTW} clearly indicates that SGW is the major source of DSTW.

The R_{SGW} (contribution of SGW to DSTW) corresponds to the so-called baseflow fraction of a stream's discharge (Kendall and Coplen, 2001; Yuan and Miyamoto, 2008). According to an investigation reported by Water Resources Agency (2003), the average percentage ratios of natural groundwater flow to river runoff of mountainous streams in Taiwan are mostly lower than 40% and not greater than 50%; those estimated ratios are lower than the value 67% obtained by this study. This high SGW (baseflow) component in the studied stream is believed to be associated with the fractured geological structure of the drainage divide and increased water pressure from the reservoir next to the divide.

In light of the calculated fractions obtained via Equations (4) and (5), WSRW contributes the predominant part of SGW, making up at least 70%. Since the contribution of DSTW from SGW is about 67%, WSRW contributes about 47% of DSTW. Thus, WSRW plays an important role in the study region. WSRW, which is sourced from the Choshuishi Stream, flows through the studied slope via weak structures in the drainage divide and seeps into the Meishi Stream (Figure 2).

IMPLICATIONS AND CONCLUSIONS

In summary, substantial water pressure from the WSR and local geological characteristics (weakened strata and fracture zones) have led to SGW being a potential threat to the stability of the slope in the divide area. The study raises the following concerns: First, the critical threshold needed for slope failure could easily be met by heavy rain (Figure 1) given the large amounts of reservoir water that have leaked into the moving slope zone. Second, if frequent slope failures occur, then headward erosion on the slope along the divide will continue, leading to an eventual crossing of the divide. In this case, the Meishi Stream would capture reservoir water or Choshuishi Stream water because the streambed's altitude of Choshuishi Stream is higher than that of Meishi Stream (Figure 2). Therefore, any subsequent remedial project should be aimed at avoiding landslides or headward erosion along the studied slope.

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