

# Assessing groundwater sources and their association with reservoir water using stable hydrogen and oxygen isotopes: a case study of the Taipei Basin, northern Taiwan

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Received: 30 December 2014 / Accepted: 8 March 2016 / Published online: 25 April 2016  
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**Abstract** The purpose of this isotopic study is to identify groundwater sources in Taipei Basin (TPB) and their association with water of the Feitsui Reservoir (FTR), northern Taiwan. To this end, water samples including precipitation, catchment surface water, TPB groundwater, FTR water, and catchment surface water of FTR were analyzed for stable hydrogen and oxygen isotope compositions ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ). Isotopic results support previous reports that Dahan Stream and Xindian Stream waters are the major recharge sources of TPB groundwater. These recharge regions are located along the southern border of the TPB. Further, isotopic evidence finds that water from the southern hills catchment area of the TPB also recharges TPB groundwater, and most importantly, indicates that TPB groundwater is highly related to FTR water. However, for caution's sake, future comprehensive study is needed to confirm hydrological connectivity between the FTR water and TPB groundwater.

**Keywords**  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  · Groundwater source · Feitsui Reservoir · Taipei Basin · Taiwan

## Introduction

Using stable hydrogen and oxygen isotopes ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) as natural tracers to identify groundwater sources is common in hydrological studies (Bogaard et al. 2007; Peng et al. 2007, 2010a; Zhang et al. 2010; Wassenaar et al. 2011). The isotopic approach is not constrained by some of the difficulties common to artificial tracers such as how, when, and where to add tracers and retrieve water samples for hydrological assessments (International Atomic Energy Agency 1983). Other advantages of using the natural isotopic tracers include: (1) their ability to better reflect natural water behavior (most artificial tracers are solutes dissolved in water) (Clark and Fritz 1997; Criss 1999); (2) the conservation of hydrogen and oxygen isotopes (water's  $\delta$  values are not greatly affected by water-rock reactions in normal low-temperature, low-circulation systems) (Fritz 1981; McCarthy et al. 1992); and (3) the uniqueness of  $\delta$  values to the origin of waters originating from different environments (due to isotopic fractionation effects) (Dansgaard 1964; Criss 1999; Yurtsever and Gat 1981). As a consequence, stable hydrogen and oxygen isotopes are commonly used in hydrological studies, especially in defining groundwater sources (e.g., Rozanski et al. 1993; Dafny et al. 2006; Peng et al. 2007, 2010a, 2012).

This case study is of the Taipei Basin (TPB) (Fig. 1a), located in northern Taiwan, and home to Taipei City, the biggest metropolitan center in Taiwan. According to Wang et al. (2008), the main groundwater recharge in the TPB depends predominantly on meteoric water infiltrating from the surrounding hills regions where aquifers have surface

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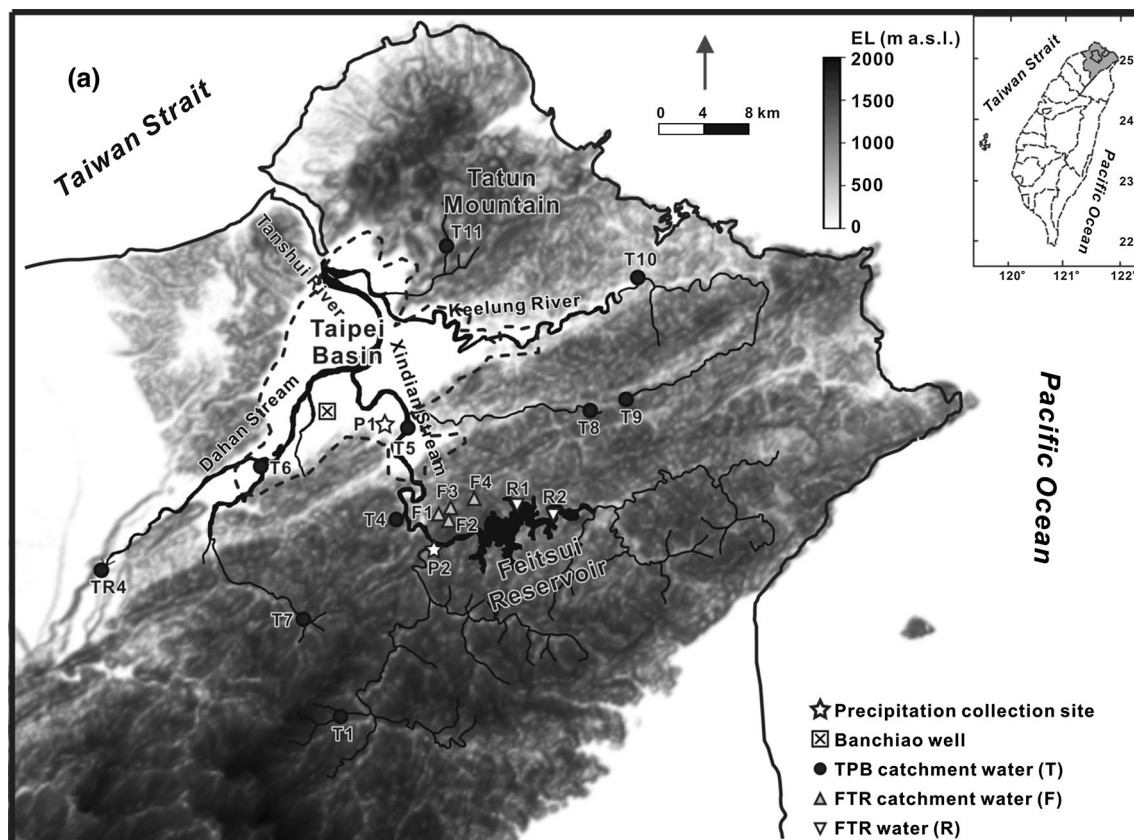
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outcrops. In the basin proper, however, meteoric water directly recharging the basin's aquifer is highly restricted due to rapid urbanization over the past 50 years. This means groundwater in the basin is highly sensitive to overdrawn and any reduction in recharge water accessing its aquifer. The sensitivity associated with the input and output of groundwater storage can be evidenced by long-term groundwater levels recorded at monitoring wells in the TPB. For example, as illustrated in Fig. 2, time series variations in groundwater levels at the Banchiao monitoring well (Fig. 1a) dropped to about  $-30$  meters above sea level (m a.s.l.) in the 1980s due to overdrawn of groundwater for civil and industrial needs (Water Resources Agency 2005). This drawdown not only caused land subsidence due to consolidation of the land strata (Hsu 1998), but also greatly elevated flood risk along river banks and Taipei Basin's low lying areas (Wang et al. 2004). From that period until recently, groundwater levels have manifestly recovered to a height of about  $-5$  m a.s.l. by the end of 2005. This achievement resulted from access to water impounded at the Feitsui Reservoir (FTR) after June 1987 and strict regulation of groundwater usage (Wang et al. 2008). The FTR is the second largest reservoir

(capacity of  $3.5 \times 10^8 \text{ m}^3$ ) on Taiwan with a catchment area of about  $303 \text{ km}^2$ . It is located about 30 km southeast of Taipei Basin (Fig. 1a). The supply of FTR water for public use in Taipei City has significantly reduced groundwater dependence.

Besides the FTR helping to reduce overdrawn of the TPB aquifer directly by supplying Taipei City's water needs, it has been speculated that FTR water recharges TPB's groundwater by seeping from the reservoir into the TPB aquifer. This speculation has resulted from groundwater levels rising gradually since 1987 when the FTR began impounding water (Fig. 2). Impounded water leaking from the reservoir through fractures has been widely reported (Malkawi and Al-Sheriadeh 2000; Turkmen et al. 2002; Peng and Wang 2008; Peng et al. 2012). Additionally, the strata between TPB and FTR are highly folded and fractured because of tectonism associated with Taiwan's active orogeny, which has been occurring since the Pleistocene (Fig. 1b). It is possible that FTR water recharges TPB groundwater via these fractured strata. However, leakage from a reservoir is a complex phenomenon (Peng and Wang 2008) and understanding its extent is equally challenging. If it can be shown with certainty that FTR



**Fig. 1** a Map showing locations of Taipei Basin (TPB) and Feitsui Reservoir (FTR). Water collection sites excluding groundwater stations of TPB are indicated. b Geological map of the study regions.

Two profiles W–E and N–S illustrating hydrogeological characteristics of the TPB (Central Geological Survey 2011). Groundwater well-stations are denoted TG1 to TG9

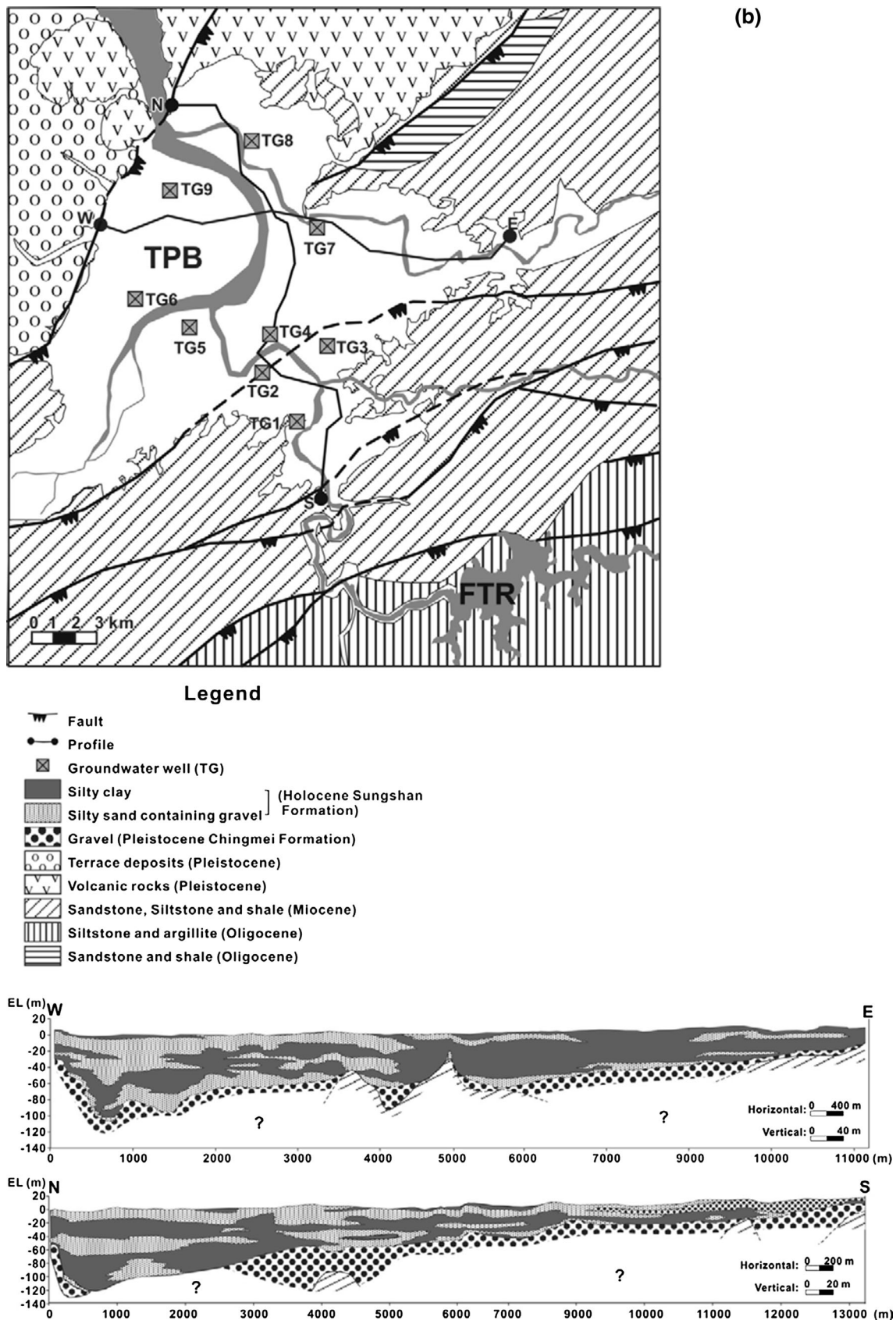
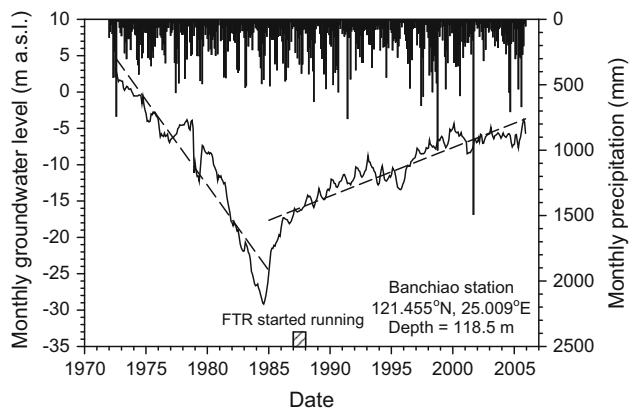


Fig. 1 continued



**Fig. 2** Monthly trends in groundwater levels at Banchiao monitoring well along with rainfall in the Taipei Basin from January 1972 to December, 2005. *Trend line* shows evolution of groundwater levels in the TBP. The FTR started operations in 1987. That remarkable GW levels started rebounding in 1984–1985 may be attributable to the strict regulation on groundwater pumping started in 1968. *Bar graph* shows monthly rainfall

water recharges TPB groundwater, this would greatly impact TPB groundwater management strategies.

The main purpose of this study, therefore, is to identify the sources of groundwater in the Taipei Basin with special attention given to hydrological connectivity between TPB groundwater and FTR water using stable hydrogen and oxygen isotopes.

## Materials and methods

### Study area

This case study includes the TPB and its surrounding catchments. The TPB has a sub-tropical climate with an average annual precipitation of about 2170 mm (Wang et al. 2008), of which 52 % falls during the rainy season of June to September, and 26 % in the dry months (November to March).

Surrounding catchments of the TPB consist of hills and mountains about 300–1000 m a.s.l. (Fig. 1a). These catchments feed three major rivers, the Keelung, Xindian, and Dahan Streams, which arise in the eastern, southeastern, and southern catchments, respectively. The three rivers are tributaries of the Tanshui River and converge in the middle of the TPB and flow northwesterly toward the Taiwan Strait (Water Resources Agency 2005). The Feitsui Reservoir (FTR) is in the southeastern catchment of the Xindian Stream (Fig. 1a).

Geologically, bedrock of the basin's surrounding catchment areas is comprised primarily of Tertiary sedimentary strata, except for the northern Tatun Mountain

area, which is of Pleistocene volcanic rock (Fig. 1b; Central Geological Survey 1988, 1996, 1998, 2000). Tertiary sedimentary strata are lithologically described as thick-bedded or massive sandstone, or alternating sandstone and shale layers. Furthermore, Holocene terrace and alluvium deposits can also be seen in the riverbanks and TPB (Fig. 1b). In addition, due to Taiwan's active orogeny and related tectonism since the Pleistocene (Ministry of Economic Affairs 1982), strata in the study regions are highly folded and fractured with at least five major thrust faults being indicated (Fig. 1b).

There is no significant boundary between aquifer and aquitard in the TPB (Central Geological Survey 2011; Fig. 1b). The sediments underlying the TPB are characterized by shallow Holocene lake deposits (the Sungshan Formation) comprising mostly semi- to impermeable silt/mud layers. Underlying these Holocene lake deposits is a major aquifer comprised of Pleistocene alluvium deposits (the Chingmei Formation), mainly permeable sands or gravels (Huang 2006). Generally, both the Sungshan and Chingmei Formations are thin at the southern and eastern corners of the TPB, and simultaneously increase in thickness toward the basin's northern and western corners (Fig. 1b). According to hydrogeological investigations reported by the Water Resources Planning Commission (1995), groundwater of the TPB derives its water from Xindian and Dahan Streams with recharge regions being at approximately the southern corner of the TPB (Wang-Lee et al. 1978).

### Water samples

To identify groundwater sources in the Taipei Basin with special attention given to hydrological connectivity between TPB groundwater and FTR water, this study first characterizes the stable hydrogen and oxygen isotopic compositions of related waters. They include precipitation and groundwater in the TPB, surface water in possible recharge regions of the TPB, and water in the FTR region. Next, isotopic hydrological relations are interpreted for TPB groundwater and possible recharge water sources to better understand where TPB groundwater is sourced.

To this end, water samples from three areas were collected for isotopic study: (1) in the TPB, (2) in the hill catchments surrounding the TPB, and (3) in the FTR area. Summer samples were taken between June to September and winter samples from November to March. The sampling locations of all studied waters except groundwater are given in Fig. 1a and listed in Table 1. The sampling locations of groundwater samples are given in Fig. 1b and listed in Table 2. Sampling details are as follows:

**Table 1** Stable isotopic compositions of studied waters in the regions of Taipei Basin (TPB) and Feitsui Reservoir (FTR)

Water type	Sampling elevation (m a.s.l.)	Summer (June–September)		Winter (November–March)		Yearly mean	
		$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
<b>1. Precipitation</b>							
TPB (P1)	21	$-7.2 \pm 2.3$	$-50.3 \pm 18.5$	$7 \pm 2$	$-3.0 \pm 12.5$	$18 \pm 6$	$-22.6 \pm 26.4$
FTR (P2) <sup>a</sup>	65	$-6.7 \pm 1.5$	$-44.9 \pm 12.0$	$8 \pm 1$	$-6.1 \pm 15.9$	$16 \pm 3$	$-20.7 \pm 21.9$
<b>2. Stream catchments of TPB</b>							
<b>(1) Dahan Stream</b>							
TR4	80	-8.2	-55.1	11	-42.0	11	-48.6
T6	17	-7.8	-55.5	7	-24.1	16	-39.8
T7	259	-7.0	-41.7	14	-36.9	12	-39.3
Average		$-7.7 \pm 0.7$	$-50.8 \pm 7.9$	$11 \pm 3$	$-34.3 \pm 9.2$	$13 \pm 3$	$-42.6 \pm 11.8$
<b>(2) Xindian Stream</b>							
T1	369	-7.3	-45.2	13	-43.7	13	-44.5
T4	55	-7.0	-43.1	13	-36.2	14	-39.7
T5	4	-5.6	-36.9	8	-29.5	12	-33.2
Average		$-6.6 \pm 0.9$	$-41.7 \pm 4.32$	$11 \pm 3$	$-36.5 \pm 7.1$	$13 \pm 1$	$-39.1 \pm 6.0$
<b>(3) Keelung Stream</b>							
T8	193	-5.2	-28.5	13	-24.9	13	-26.7
T9	226	-5.3	-29.0	14	-20.4	17	-24.7
T10	27	-5.5	-36.5	8	-12.4	16	-24.5
T11	151	-5.7	-31.7	14	-26.6	13	-29.2
Average		$-5.5 \pm 0.2$	$-31.4 \pm 3.7$	$12 \pm 3$	$-21.1 \pm 6.3$	$15 \pm 2$	$-26.3 \pm 7.3$
<b>3. FTR region</b>							
<b>(1) Creek water in FTR catchments</b>							
F1	308	$-6.9 \pm 0.3$	$-38.7 \pm 3.0$	$16 \pm 1$	$-37.0 \pm 3.6$	$17 \pm 2$	$-37.2 \pm 3.8$
F2	477	$-6.9 \pm 0.4$	$-37.2 \pm 3.9$	$18 \pm 1$	$-36.0 \pm 3.5$	$18 \pm 2$	$-36.1 \pm 3.9$
F3	276	$-6.9 \pm 0.3$	$-38.1 \pm 2.3$	$17 \pm 1$	$-36.8 \pm 3.1$	$17 \pm 2$	$-37.1 \pm 3.0$
F4	226	$-7.1 \pm 0.2$	$-40.0 \pm 1.9$	$17 \pm 1$	$-38.3 \pm 3.0$	$17 \pm 2$	$-38.6 \pm 2.7$
Average		$-6.9 \pm 0.3$	$-38.5 \pm 2.9$	$17 \pm 1$	$-37.0 \pm 3.3$	$17 \pm 2$	$-37.2 \pm 3.4$
<b>(2) Reservoir water</b>							
R1		$-5.9 \pm 0.4$	$-33.5 \pm 3.0$	$14 \pm 1$	$-35.0 \pm 1.6$	$15 \pm 2$	$-33.9 \pm 2.8$
R2		$-6.0 \pm 0.4$	$-33.2 \pm 3.4$	$15 \pm 2$	$-34.5 \pm 2.0$	$16 \pm 1$	$-33.3 \pm 3.3$
Average		$-6.0 \pm 0.4$	$-33.4 \pm 3.1$	$14 \pm 2$	$-34.7 \pm 1.8$	$15 \pm 1$	$-33.6 \pm 3.0$

<sup>a</sup> Data from Chuang (2006)

**Table 2** Stable isotopic compositions of groundwater in Taipei Basin

Well station	Groundwater	Screen depth (m b.l.g.)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$d^{\text{E}}$ (‰)	Group	Sampled date
TG1	TG1-S	20–47	−6.2	−38.8	11	Low- $d^{\text{E}}$	October 2004
TG2	TG2-S	6–18	−6.0	−36.9	11	Low- $d^{\text{E}}$	October 2004
	TG2-D	41–53	−6.6	−38.0	15	High- $d^{\text{E}}$	October 2004
TG3	TG3-S	16–22	−6.3	−39.2	11	Low- $d^{\text{E}}$	November 2004
	TG3-D	42–48	−6.3	−36.6	13	High- $d^{\text{E}}$	November 2004
TG4	TG4-D	55–70	−6.5	−38.0	14	High- $d^{\text{E}}$	November 2004
TG5	TG5-S	6–15	−6.8	−44.9	10	Low- $d^{\text{E}}$	October 2004
	TG5-D	55–73	−6.3	−40.7	10	Low- $d^{\text{E}}$	October 2004
TG6	TG6-S	74–101	−6.6	−37.7	14	High- $d^{\text{E}}$	November 2004
	TG6-D	150–168	−5.7	−34.2	11	Low- $d^{\text{E}}$	November 2004
TG7	TG7-D	60–65	−6.1	−43.0	7	Low- $d^{\text{E}}$	November 2004
TG8	TG8-S	7–19	−4.3	−22.9	11	–	October 2004
	TG8-D	47–56	−6.1	−34.6	15	High- $d^{\text{E}}$	October 2004
TG9	TG9-S	9–15	−6.6	−42.9	10	Low- $d^{\text{E}}$	November 2004
	TG9-D	90–120	−6.0	−36.8	11	Low- $d^{\text{E}}$	November 2004

*b.l.g.* below ground

1. For samples of the TPB:

- (a) Precipitation: a total of 149 precipitation samples were collected at one site P1 (121.51°E, 24.98°N, altitude 21 m a.s.l.) on each rainy day from April 2004 to March 2006. This was done to avoid evaporation of precipitation samples. Sampling procedures were in line with International Atomic Energy Agency guidelines (International Atomic Energy Agency 1983).
- (b) Groundwater: groundwater samples were taken from 15 newly constructed wells belonging to 9 stations (TG1–TG9) in 2004 or 2006. Geographically, stations TG1 to TG4 are along the Xindian Stream; TG5 and TG6, Dahan Stream; and TG7 and TG8, Keelung Stream. Station TG9 is near the Tanshui River. Each station has two wells of different screen depths except for TG1, TG4, and TG7, which are equipped with only one well. Note shallow station-groundwaters are labeled “S” while deep-station groundwaters are labeled “D” (Table 2). This classification is derived from the depth of well screens (Table 2). Two hydrogeological profiles are shown in Fig. 1b. Generally, shallow groundwaters are contained in the Holocene Sungshan Formation while deep groundwaters are of the Pleistocene Chingmei Formation (Fig. 1b).

2. For samples of hill catchments surrounding the TPB:

Sampling of catchment waters was carried out in the respective watersheds of the Xindian, Dahan, and Keelung Streams.

- (a) Xindian stream watershed: water sampling was conducted at sites denoted T1, T4, and T5.
- (b) Dahan stream watershed: water sampling was conducted at sites denoted TR4, T6, and T7.
- (c) Keelung stream watershed: water sampling was conducted at sites denoted T8, T9, and T10. Two sampling campaigns were carried out for stream water—one in March 2004, and the other in July 2004. A total of 20 catchment samples were taken.

3. For samples at the Feitsui Reservoir:

- (a) Precipitation: archived daily precipitation stable isotopic data from April 2004 to March 2005 at the FTR (P2 in Fig. 1a; 121.55°E, 24.90°N, altitude 65 m a.s.l.) listed in Chuang (2006) were employed in this study.
- (b) Reservoir water: the FTR impounds upstream water of the Xindian Stream. Surface reservoir water samples were taken at two sites: R1 and R2.
- (c) Catchment water: four catchment surface waters, denoted F1 to F4, were taken in catchment regions of the FTR. Reservoir and catchment surface water samples were collected monthly from August 2009 to June 2011.

### Isotope analysis

All water samples were analyzed for stable oxygen and hydrogen isotope composition.  $^2\text{H}/^1\text{H}$  and  $^{18}\text{O}/^{16}\text{O}$  ratios for Taipei Basin water samples and its surrounding catchments, which were collected and analyzed before 2007, were determined by isotope ratio mass spectrometry (IRMS). The  $^2\text{H}/^1\text{H}$  ratios were analyzed with a VG MM602D IRMS after reduction of water to  $\text{H}_2$  gas using zinc shots (Coleman et al. 1982), and  $^{18}\text{O}/^{16}\text{O}$  ratios were analyzed by a  $\text{CO}_2\text{-H}_2\text{O}$  equilibration method (Epstein and Mayeda 1953). After equilibration,  $\text{CO}_2$  gas was introduced to a VG SIRA 10 IRMS.

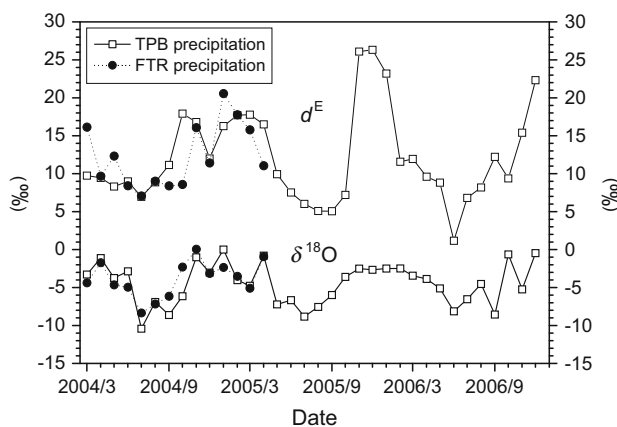
After 2010, our laboratory employed a Liquid–Water Isotope Analyzer (LWIA) produced by Los Gatos Research, USA to perform stable isotopic analyses on the hydrogen and oxygen isotopic compositions of waters in the Feitsui Reservoir regions. LWIA is based on off-axis integrated cavity output spectroscopy (OA-ICOS) lasers connected to a CTC LC-PAL liquid auto-sampler (LAS) to measure both  $^2\text{H}/^1\text{H}$  and  $^{18}\text{O}/^{16}\text{O}$  ratios of water molecules directly and concurrently in a single run (Lis et al. 2008).

All  $^2\text{H}/^1\text{H}$  and  $^{18}\text{O}/^{16}\text{O}$  results determined by IRMS or LWIA are reported in  $\delta$ -notation (‰) relative to the international Vienna Standard Mean Ocean Water (VSMOW) index in which the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  of Standard Light Antarctic Precipitation (SLAP) are given as  $-55.5$  and  $-428$  ‰, respectively. The analytical precision (1 sigma) of isotopic IRMS analyses (basin samples) are  $\pm 1.5$  ‰ for  $\delta^2\text{H}$  and  $\pm 0.12$  ‰ for  $\delta^{18}\text{O}$ , and those by LWIA (reservoir samples) are  $\pm 0.7$  ‰ for  $\delta^2\text{H}$  and  $\pm 0.3$  ‰ for  $\delta^{18}\text{O}$ , resulting in an uncertainty of about 3 ‰ for deuterium excess (defined as  $d^E = \delta^2\text{H} - 8\delta^{18}\text{O}$ , Dansgaard 1964).

## Results

### Precipitation in TPB

During April 2004 to March 2006,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of 149 precipitation samples in the TPB were analyzed. Yearly weighted mean  $\delta$  values of the TPB's precipitation samples are  $-4.4 \pm 2.8$  and  $-23 \pm 26$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Table 1), respectively. Additionally, precipitation's  $\delta$  values vary widely and display discrete seasonal variations with relatively lower values in summer samples (June–September) and higher  $\delta$  values in winter samples (November–March) (Fig. 3). The weighted mean  $\delta$  values of winter precipitation are  $-2.6$  and  $-3$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Table 1), respectively, while those of summer precipitation are  $-7.2$  and  $-50$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ,



**Fig. 3** Monthly  $\delta^{18}\text{O}$  and  $d^E$  variations in precipitation samples of Taipei Basin (TPB) and Feitsui Reservoir (FTR)

respectively. Moreover, weighted mean  $d^E$  values are about 18 and 7 ‰ for winter and summer precipitation, respectively (Table 1).

### Stream water in catchments of TPB

Summer, winter, and yearly averaged  $\delta$  values of catchment stream water for the Xindian, Dahan, and Keelung Streams are listed in Table 1. Generally, the  $\delta$  values of catchment stream waters of the Dahan and Xindian Streams are lower than those of the Keelung Stream. For example, the yearly mean  $\delta^{18}\text{O}$  values of catchment stream waters of the Dahan and Xindian Streams range from  $-7.4$  to  $-5.4$  ‰ compared to about  $-5.3$  to  $-4.6$  ‰ for the Keelung Stream (Table 1).

Another common but salient feature in catchment stream waters at the three streams is that  $\delta$  and  $d^E$  values are lower in summer water than in winter water (Table 1). For example, the  $\delta^{18}\text{O}$  values of summer catchment stream waters of the Dahan, Xindian, and Keelung Streams are  $-7.7$ ,  $-6.6$ , and  $-5.5$  ‰, respectively, compared to  $-5.9$ ,  $-6.2$ , and  $-4.5$  ‰ of winter catchment stream waters for the three streams. Moreover, the  $d^E$  values of summer catchment stream waters of the Dahan, Xindian, and Keelung Streams are 11, 11, and 12 ‰, respectively, compared to 13, 13, and 15 ‰ for winter catchment stream waters.

### TPB groundwater

The mean  $\delta$  values of all TPB groundwaters except TG8-S are  $-6.2$  ‰ for  $\delta^{18}\text{O}$  (ranging from  $-6.8$  to  $-5.7$  ‰) and  $-40$  ‰ (ranging from  $-45$  to  $-34$  ‰) for  $\delta^2\text{H}$  (Table 2). TG8-S has values of  $-4.3$  ‰ for  $\delta^{18}\text{O}$  and  $-23$  ‰ for  $\delta^2\text{H}$  (Table 2), which are higher than those of any other TPB groundwaters.

Additionally, excluding TG8-S, TPB groundwaters can be divided into high- $d^E$  and low- $d^E$  value groups (Table 2). The low- $d^E$  group includes nine groundwater samples denoted: TG1-S, TG2-S, TG3-S, TG5-S, RG5-D, TG6-D, TG7-D, TG9-S, and TG9-D. These samples have relatively low  $d^E$  values of about 10 ‰ while samples of high- $d^E$  group have values of about 14 ‰. This group includes five groundwater samples: TG2-D, TG3-D, TG4-D, TG6-S, and TG8-D. The mean  $\delta$  values of the high- $d^E$  group are  $-6.4$  ‰ (ranging from  $-6.6$  to  $-6.1$  ‰) for  $\delta^{18}\text{O}$  and  $-37$  ‰ (ranging from  $-38$  to  $-35$  ‰) for  $\delta^2\text{H}$  (Table 2). On the other hand, the mean  $\delta$  values of low- $d^E$  group are  $-6.2$  ‰ (ranging from  $-6.8$  to  $-5.7$  ‰) for  $\delta^{18}\text{O}$  and  $-40$  ‰ (ranging from  $-45$  to  $-34$  ‰) for  $\delta^2\text{H}$ .

### Precipitation at the FTR

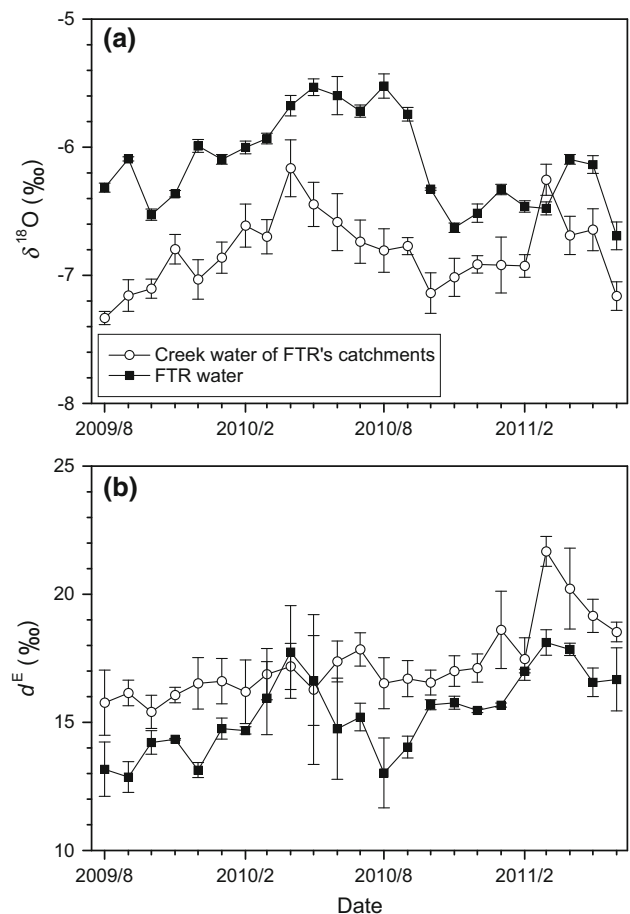
Archived daily precipitation stable isotopic data from April 2004 to March 2005 at the FTR (Chuang 2006) were employed for comparison purposes. Similar to TPB's precipitation,  $\delta$  and  $d^E$  values of winter precipitation at FTR are much higher than those of summer precipitation (Fig. 3). Yearly weighted mean  $\delta$  values of precipitation samples at the FTR are  $-4.1 \pm 2.4$  and  $-21 \pm 22$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Table 1), respectively. The weighted mean  $\delta$  values of winter precipitation are  $-2.8$  and  $-6$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Table 1), respectively, while those of summer precipitation are  $-6.7$  and  $-45$  ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ , respectively. Moreover, weighted mean  $d^E$  values are about 16 and 8 ‰ for winter and summer precipitation, respectively (Table 1). The average  $\delta$  and  $d^E$  values of FTR precipitation are similar to those of TPB precipitation in respective summer and winter seasons (Table 1).

### Catchment surface water of the FTR

Monthly variability of stable isotopic compositions for  $\delta^{18}\text{O}$  and  $d^E$  values of catchment surface waters of the FTR including F1 to F4 sampling sites are illustrated in Fig. 4. Seasonal variations of  $\delta$  and  $d^E$  values for these waters are very minor (Table 1), and the differences in  $\delta$  or  $d^E$  values among the 4 sampling sites are small. The mean values for  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , and  $d^E$  are about  $-6.8$ ,  $-37$ , and 17 ‰, respectively (Table 1).

### FTR water

Monthly variability of  $\delta^{18}\text{O}$  and  $d^E$  values of reservoir surface waters of the FTR at sampling sites R1 and R2 are illustrated in Fig. 4. As indicated in Table 1,  $\delta$  and  $d^E$  values of the two sampling sites are almost identical.



**Fig. 4** Monthly variability of  $\delta^{18}\text{O}$  (a) and  $d^E$  (b) values of creek waters (F1–F4) in the FTR catchments and the Feitsui Reservoir water (R1–R2). Error bars in the plots refer to 1 sigma

Similar to the FTR's catchment stream water (F1 to F4 sampling sites), the differences in  $\delta$  and  $d^E$  values between summer and winter reservoir waters are very minor (Table 1). The yearly mean values for  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , and  $d^E$  are about  $-6.1$ ,  $-34$ , and 15 ‰, respectively (Table 1).

One may argue the reservoir surface waters which we analyzed cannot represent the whole reservoir because  $\delta$  values of reservoir water could differ depending on where water was sampled (i.e., surface water vs. mid-depth or bottom waters). According to monthly isotopic data for reservoir water during March 2004 to March 2005 reported by Chuang (2006), no differences in  $\delta^{18}\text{O}$  values exist among reservoir water at various depths. This finding was based on five sampling sites in the FTR. According to Chuang's data, the yearly mean  $\delta^{18}\text{O}$  value is  $-5.7$  ‰ for surface reservoir water, and  $-5.8$  and  $-5.9$  ‰ for middle and bottom reservoir waters, respectively; in addition, the average  $\delta^{18}\text{O}$  value of all reservoir water is about  $-5.8$  ‰. This averaged value is close to the  $-6.1$  ‰ of our data (Table 1).



## Discussion

### Seasonal variation and altitude effect on meteoric water

As indicated in Table 1, the isotopic feature that gives  $\delta$  and  $d^E$  values of winter precipitation much higher than those of summer precipitation in the TPB and FTR principally results from prevailing monsoons, which have different isotopic compositions in summer and winter (Peng et al. 2010b). According to Peng et al. (2010b), stable isotopic composition of Taiwan's precipitation is mainly controlled by three different air masses with different isotopic signatures. These are the two summer prevailing monsoon air masses, which supply summer precipitation of relatively low  $\delta$  and  $d^E$  values, and one winter prevailing monsoon air mass, which contributes relatively high  $\delta$  and  $d^E$  values to winter precipitation.

Furthermore, the differences in  $\delta$  values among various catchment waters reflect isotopic altitude effect whereby the source altitude of catchment stream waters differs from watershed to watershed (Kendall and Coplen 2001; Dutton et al. 2005). For example, the yearly mean  $\delta^{18}\text{O}$  values of catchment stream waters of the Dahan and Xindian Streams range from  $-7.4$  to  $-5.4$  ‰ compared to about  $-5.3$  to  $-4.6$  ‰ of the Keelung Stream (Table 1). This isotopic feature also echoes the fact that stream waters of Dahan Stream and Xindian Stream originate from mountain/hill regions at elevations of about 3100 and 750 m a.s.l., respectively, while the Keelung Stream derives its water from the northern and eastern hill catchment regions of the TPB at elevations lower than 500 m a.s.l. (Fig. 1a).

How altitude effect influences the results of this study can be confirmed by use of mathematical regression between  $\delta^{18}\text{O}$  value and elevation in northern Taiwan (altitude from 110 to 2410 m a.s.l.) as reported by Peng et al. (2010a):

$$\delta^{18}\text{O}_Z = -5.18 - (1.6Z \times 10^{-3}) \quad (1)$$

where  $\delta^{18}\text{O}_Z$  represents the oxygen isotope composition of precipitation at a given elevation  $Z$ , and  $Z$  is in m a.s.l. In this study, the yearly mean  $\delta^{18}\text{O}$  values of catchment stream waters of the Dahan Stream range from  $-7.4$  to  $-6.4$  ‰ (Table 1), which correspond to ground elevations ranging from 830 to 1390 m a.s.l. to receive precipitation [Eq. (1)]. Similarly, the derived source elevations for precipitation in catchment stream waters are 140 to 1250 m a.s.l. for Xindian Stream, and no higher than 100 m a.s.l. for Keelung Stream.

### Base-flow contribution process of stream

As indicated in “Stream water in catchments of TPB”,  $\delta$  values for stream waters in catchments of the TPB, similar to those of precipitation, are lower in summer water than in winter water, demonstrating that catchment stream waters are affected by concurrent precipitation. However, the seasonal  $\delta$  differences for catchment stream waters of the three streams are not as large as those for precipitation. For example, the difference in average  $\delta^{18}\text{O}$  values between summer and winter precipitation in the TPB and FTR areas are about 4.6 and 3.8 ‰ (Table 1), respectively. By comparison, the seasonal differences are, respectively, about 0.4, 1.8, and 1.0 ‰ for catchment stream waters of the Xindian, Dahan, and Keelung Streams.

The smaller seasonal  $\delta$  differences of catchment stream waters than those of precipitation are due to the  $\delta$  values of winter stream waters being closer to those of summer precipitation than winter precipitation (Table 1). For examples, in summer the averaged  $\delta^{18}\text{O}$  values of catchment stream waters of the Xindian Stream, Dahan Stream, and Keelung Stream range from  $-7.7$  to  $-5.5$  ‰, close to about the  $-7.0$  ‰ of summer precipitation in the TBP or FTR areas (Table 1). This isotopic similarity indicates that local summer precipitation is the most important contributor of summer stream water. By comparison, in winter the averaged  $\delta^{18}\text{O}$  values of catchment stream waters of the three streams range from  $-6.2$  to  $-4.5$  ‰, notably lower than the  $-2.7$  ‰ of the winter precipitation in the TBP or FTR areas (Table 1). This isotopic diversity implies that except for winter local precipitation, water originating from summer precipitation is another important source recharging the three studied streams in winter. That summer precipitation occurs in winter catchment stream water means excess summer precipitation is being stored as groundwater during summer and released in winter in the form of base flow. Base-flow contributing to stream water is common in hill/mountain regions and conspicuous in low-rainfall seasons (Walker and Krabbenhoft 1998; Dutton et al. 2005; Peng et al. 2014, 2015).

In other words, in summer, catchment stream waters of the TPB are mainly sourced from concurrent precipitation; in winter, catchment stream waters are mainly sourced from concurrent winter precipitation and base flow, which is mainly sourced from excess summer precipitation. Nevertheless, to properly quantify base flow requires many hydrological data and hydrograph-separation studies integrating isotopic and hydrological data including meteoric water and groundwater in catchments.

### Moisture-recycling effect on waters in the FTR area

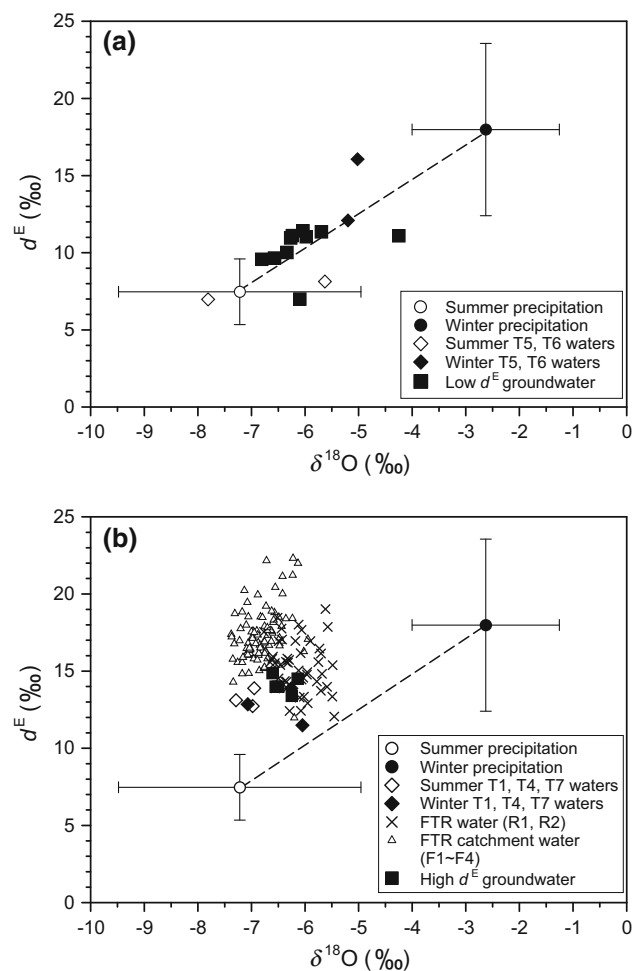
In the FTR region, reservoir water and catchment stream water both exhibit relatively lower  $\delta$  values similar to those of summer precipitation, but have relatively higher  $d^E$  values similar to winter precipitation (Fig. 4 and Table 1). This can be accounted for by isotopic fractionation due to the effect of secondary moisture recycling on waters of the FTR region (Salati et al. 1979; Froehlich et al. 2008).

According to Salati et al. (1979) and Froehlich et al. (2008), surface water incorporated in convective rain, i.e., precipitation containing recycled moisture, should display high  $d^E$  values. Generally, convection brings additional re-evaporated moisture from local surface water to the prevailing air mass. Once moisture recycling occurs,  $\text{HD}^{16}\text{O}$  molecules may preferentially contribute to water vapor, resulting in higher  $d^E$  but similar  $\delta^{18}\text{O}$  values in succeeding precipitation (Clark and Fritz 1997; Ingraham 1998). Consequently, it is believed that the relatively lower  $\delta$  and higher  $d^E$  values of the winter reservoir-region waters (compared to winter precipitation) are caused by summer precipitation containing recycled moisture. This scenario suggests a portion of summer precipitation containing recycled moisture infiltrating and being stored as groundwater in catchments during summer, and like the base-flow process indicated in “Base-flow contribution process of stream”, the stored water sourced from summer precipitation is released in winter while effective precipitation is insignificant.

However, while reservoir water and catchment stream waters (sampled during 2009–2011) both exhibit relatively higher  $d^E$  values in summer, summer precipitation at the FTR (sampled during 2004–2006) displays low  $d^E$  values (Table 1). It seems that summer precipitation at FTR (discussed in this study) is not affected by recycled moisture. One possible reason is that isotopic differences in precipitation occurred between the periods of 2004–2006 and 2009–2011. Another explanation may be that there are isotopic differences between precipitation at FTR and precipitation in its catchments. Precipitation at the FTR, similar to TPB precipitation, is not affected by recycled moisture as it exhibits relatively low  $d^E$  values (Table 1). In contrast, precipitation in FTR catchments is affected by recycled moisture, resulting in high  $d^E$  values in creek water which recharges the FTR. These explanations whilst credible remain unsubstantiated due to insufficient isotopic data on precipitation.

### Assessment of groundwater sources of TPB

Except for groundwater TG8-S, TPB groundwaters have  $\delta$  and  $d^E$  values similar to the catchment waters of the T1, T4, T5, T6, T7 sampling sites (Fig. 5a, b), which are



**Fig. 5** Plot of  $\delta^{18}\text{O}$  vs.  $d^E$  values of TPB groundwaters. **(a)** Groundwaters with relatively low  $d^E$  values (smaller than 14 ‰). **(b)** Groundwaters with relatively high  $d^E$  values (greater than 14 ‰). Error bars in the plots refer to 1 sigma

catchments for the Xindian and Dahan Streams distributed along the southern region of the Taipei Basin (Fig. 1a). The similar isotopic compositions between groundwater and catchment water of this study re-stress contentions reported by the Water Resources Planning Commission (1995) that most TPB groundwater is derived from stream waters of the Xindian and Dahan Streams. Groundwater TG8-S has values of  $-4.3$  ‰ for  $\delta^{18}\text{O}$  and  $-23$  ‰ for  $\delta^2\text{H}$  (Table 2), which are similar to those of catchment water (e.g. T10) of the Keelung Stream that flows along the northern part of the Taipei Basin (Table 1 and Fig. 1). This isotopic similarity implies that the source of groundwater TG8-S is related with catchment water of the Keelung Stream.

Furthermore, in a plot of  $\delta^{18}\text{O}$  vs.  $d^E$  for TPB groundwater (Fig. 5a), groundwaters of the low- $d^E$  group, including TG1-S, TG2-S, TG3-S, TG5-S, RG5-D, TG6-D, TG7-D, TG9-S, and TG9-D (Table 2), have  $\delta$  and  $d^E$  values similar to the catchment waters of T5 and T6 located at

the southern margin of the Taipei Basin (Fig. 1). This similarity in isotopic composition re-emphasizes that most TPB groundwaters are derived from catchment waters of the Xindian Stream and Dahan Stream (Water Resources Planning Commission 1995), and confirms that groundwater recharge regions are mostly at the southern margins of the basin (Wang-Lee et al. 1978).

On the other hand, those groundwaters with relatively high  $d^E$  values, including TG2-D, TG3-D, TG4-D, TG6-S, and TG8-D (Table 2), correspond to surface waters at T1, T4, T7, and reservoir-region waters (Fig. 5b). Those corresponding surface waters are all located in the southern hill-catchments of the TPB (Fig. 1a). This likeness in isotopic compositions demonstrates that water from southern hill-catchments is an important source of recharge water for TPB groundwater in addition to stream water from the southern margins of TPB. Further, as displayed in Fig. 5b, the high- $d^E$  group groundwaters have isotopic compositional ranges identical to FTR water. This isotopic similarity indicates that that TPB groundwater is highly related to FTR water, implying that FTR water recharges TPB groundwater.

Additionally, the low- $d^E$  group groundwaters can be further grouped into two sub-groups based on screen depths; i.e., shallow and deep groundwaters (Table 2). The low- $d^E$  group shallow groundwaters (TG1-S, TG2-S, TG3-S, TG5-S, and TG9-S) have screen depths ranging from about 6 to 47 m below ground (b.l.g.) while the low- $d^E$  group deep groundwaters (TG5-D, TG6-D, TG7-D, and TG9-D) have screen depths greater than 55 m b.l.g. On the other hand, the high- $d^E$  group groundwaters (TG2-D, TG3-D, TG4-D, TG6-S, and TG8-D) have screen depths ranging from about 41 to 70 m b.l.g. All groundwaters above or below this depth have clearly low  $d^E$  values. This  $d^E$  value distribution implies that high- $d^E$  FTR water has a flow route different to that of low- $d^E$  water in the southern margin of the Taipei Basin, recharging TPB groundwater at the middle depth.

That waters from southern hill-catchments including FTR water recharge TPB groundwater is a new finding in local hydrological studies. The catchment water of the hills probably recharges TPB groundwater through the highly fractured strata between TPB and its southern catchment areas (Fig. 1b) reported in related geological surveys (Central Geological Survey 1988, 1996, 1998, 2000).

It is reasonable to consider the possibility of seasonal variations in  $\delta$  values for TPB groundwater and only looking at groundwater sampling data from one period may not properly represent seasonal isotopic variations. In this study, seasonal variations in  $\delta$  (and  $d^E$ ) values of the studied groundwater are assumed minor and are attributed to isotopic homogenization occurring when recharge water passes through the unsaturated zone into the saturated zone

(Clark and Fritz 1997). According to Table 2, the screen depths of the studied shallow groundwater range from approximately 15 to 101 m b.l.g., and those for deep groundwater range from approximately 48 to 168 m b.l.g. Additionally, due to rapid urbanization of the TPB, meteoric water directly recharging the basin's aquifer is highly restricted (Wang et al. 2008), reducing the possibility of quick infiltration. Consequently, we think flow-path lengths are enough for isotopic homogenization to occur and assume that the  $\delta$  and  $d^E$  values of groundwater are similar whenever they were collected.

## Summary and conclusion

This study employed stable hydrogen and oxygen isotopes to identify the groundwater sources of the Taipei Basin (TPB) and assess whether reservoir water of the Feitsui Reservoir (FTR) recharges TPB groundwater. To this end, water samples including precipitation, catchment surface water, and TPB groundwater as well as reservoir water and catchment surface water of the FTR were analyzed.

Because of monsoon effect, stable isotopic compositions of TPB precipitation display discrete seasonal variations with relatively high  $\delta$  and  $d^E$  values in winter precipitation compared to summer precipitation. Furthermore, the stable isotopic evidence implies that summer precipitation is an important water source for catchment stream water of the TPB regardless of the season. In summer, catchment stream waters of the TPB are mainly sourced from concurrent precipitation; in winter, catchment stream waters are mainly sourced from concurrent winter precipitation and base flow, which is mainly sourced from excess summer precipitation.

In the FTR region, similar to precipitation in TPB, precipitation displays higher  $\delta$  and  $d^E$  values in winter than in summer. However, reservoir water and its catchment water have relatively low  $\delta$  values like summer precipitation but have relatively high  $d^E$  values like winter precipitation. The isotopic signatures indicate that those waters in the FTR region are affected by summer precipitation containing recycled moisture. The feature that reservoir water and its catchment water (sampled during 2009–2011) exhibit relatively higher  $d^E$  values in summer but summer precipitation at FTR (sampled during 2004–2006) displays low  $d^E$  values may be the result of isotopic differences in precipitation occurring between the periods 2004–2006 and 2009–2011, or isotopic differences between precipitation at FTR and precipitation in its catchments. Which of these two explanations is the most valid description of isotopic differences in evaluated water samples cannot be decided until more isotopic precipitation data is attained.

Comparing the isotopic characteristics between TPB groundwater and waters in the catchments of the TPB, this study isotopically evidences previous reports that the major sources of TPB groundwater are waters of the Dahan Stream and Xindian Stream sourced from recharge regions located along the southern border of the TPB. Further, our isotopic evidence finds that waters from the southern hills-catchments of the TPB including FTR water and its catchments are recharge sources of TPB groundwater. The possibility that waters from southern hill-catchments including those of the FTR recharge TPB groundwater is a new finding in local hydrological studies. Because of the discrepancy in sampling periods between surface water in FTR region (2009–2011) and the other regions (2004–2006), future comprehensive study is needed to confirm the mechanism by which FTR water recharges TPB groundwater.

**Acknowledgments** The authors are very grateful to anonymous reviewers for their constructive comments, which greatly improved our manuscript. Work on this paper is divided into two parts. That focusing on the Taipei Basin is financially supported by the Central Geological Survey, Ministry of Economic Affairs, Taiwan (5926901000-02-93-02), and that regarding the Feitsui Reservoir is financially supported by the National Science Council, Taiwan (NSC 98-2116-M-005-001).

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