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Water Isotope framework for lake water balance monitoring and modelling in the Nam Co Basin, Tibetan Plateau

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ABSTRACT

Study region: The Nam Co, the second largest and highest saline lake in central Tibetan Plateau, China.

Study focus: Since the establishment of the Nam Co research station, a large number of water isotope measurements in the watershed was accumulated. There is a strong need to establish an isotope framework to benefit long-term monitoring and model development. Further discussions of the water balance of the lake and water yield of the basin are also possible under an isotope framework.

New hydrological insights: A water isotope framework for the Nam Co basin, including the Local Meteoric Water Line, limiting isotopic composition of evaporation and two hypothetical evaporation trajectories, is established. We further applied the isotope mass balance model to estimate the overall isotopic composition of input water to the Nam Co, the evaporation over inputs ratios (E/I) for three consecutive years, and the water yields (Wy, depth equivalent runoff) at a basin scale. Our results clearly suggest a positive water budget (i.e., $E/I < 1$), providing another line of evidence that the subsurface leakage from Nam Co is likely. The discrepancy between isotope-based water yields estimations and field-based runoff observations suggest that, compared to the well-studied Nyainqentanglha Mountains and southwestern mountains, the ridge-and-valley landscape in the western highlands and northwestern hogbacks are possibly low yields area, which should draw more research attentions in future hydrological investigations.

1. Introduction

Glacier retreat on the Tibetan Plateau (TP) (Bolch et al., 2012; Kang et al., 2010; Li et al., 2010; Yao et al., 2007), as a consequence of observed dramatic warming since the 20th century (IPCC, 2007), has become a serious concern on water resources management and flooding control in China and south Asia (Piao et al., 2010). The acceleration of glacier melting has significant impacts on hydrological cycles on the TP and downstream (Immerzeel et al., 2010; Zhang et al., 2013). Recently, increase in river discharges has been observed in the glacier-feed rivers (Yao et al., 2007). Expansions of glacier-fed-lakes have also been frequently

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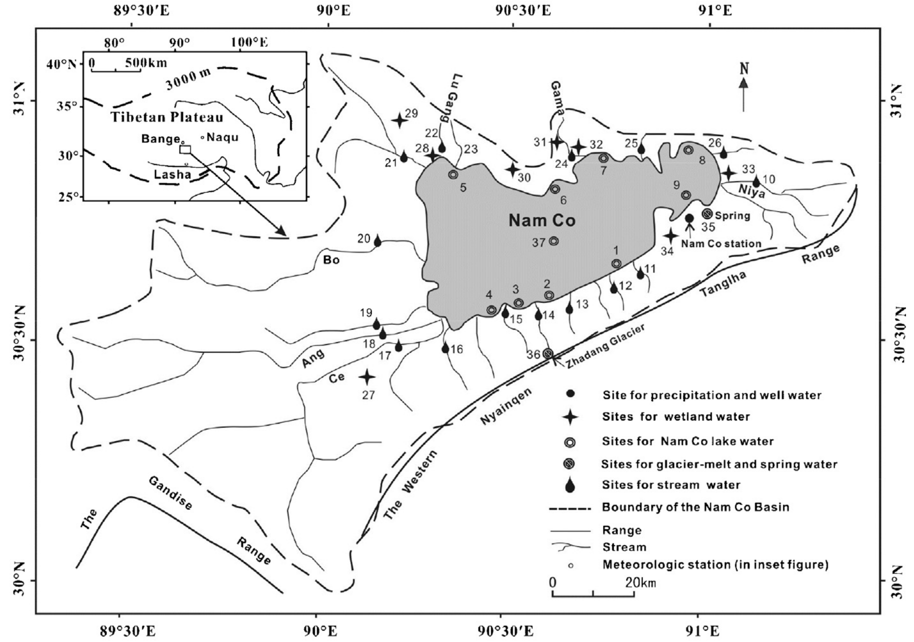

Fig 1. The Nam Co watershed. The surface area of the lake is grayed while the boundary of Nam Co basin is outlined with the long-dashed line. Locations of source water samples (precipitations, groundwater and glaciermelts) and samples from various surface water type (lake, streams and wetlands) are notes. The sampling locations for surficial and depth heterogeneity are also shown. The inset shows the geographic location of Na Co on the Tibetan Plateau and location of Bange where long-term climatic records are available.

reported on the TP (Lu et al., 2005; Wu and Zhu, 2008; Yao et al., 2007). These rapid-expansion lakes are structurally unstable, as such posed potential hazards on flooding villages, forest and high-quality pastures (Bian et al., 2006; Yamada and Sharma, 1992). Therefore, comprehending current hydrological changes on the TP at various spatial scales is an essential step toward understanding possible impacts of climate change in the region, which is also important to establish a scientific-informed strategy for the regional development and management.

The Nam Co Basin, a *meso*-scale watershed on the central TP (Fig. 1), is particularly suitable for studying the impacts of climate change on hydrological processes and water resources on the plateau. First of all, the Nam Co Basin is a paradigm-type hydrologic system including most of the common hydrologic components and characteristic terrains on the TP (Kang et al., 2011). Lake Nam Co, the second largest lake in Tibet has been expanding 72.6 km^2 since the 1970s due to the dramatic retreating of glaciers in the western Nyainqentanglha Range and increasing in precipitation (Chen et al., 2009; Wu and Zhu, 2008). Water balance observation and calculation imply that there might be a water seepage for Nam Co but the hypothesis is subject to serious debates (Zhou et al., 2013). Clearly, the basin is experiencing significant hydrological changes, while mechanism and consequence of these changes are not clear yet. The establishment of Nam Co Station for Multisphere Observation and Research (Nam Co station) by Chinese Academy of Sciences since 2005 makes it possible to observe and investigate the long-term impact of climate change on water cycles on the TP. Various field and model techniques including: precipitation sampling (Li et al., 2007; Xu et al., 2011; You et al., 2007), observation of glaciers (Kang et al., 2009; Kang et al., 2008), measurements of runoff (Gao et al., 2009 Keil et al., 2010; Zhou et al., 2010), simulation of hydrological processes (Gao et al., 2011; Krause et al., 2010; Zhang et al., 2016) and monitoring lake level (Bolch et al., 2010; Zhou et al., 2006) have been employed since 2005, historical samples of hydrological components can be easily accessible and a multi-dimensional picture of the hydrological system in the basin is on the edge of emerging with the interaction of *trans*-disciplinary investigations (Krause et al., 2010).

Physically-based hydrologic modelling method is common in evaluating hydrology status in alpine regions (Abbaspour et al., 2007; Grayson et al., 1992; Singh and Woolhiser, 2002). These investigations generally estimated hydrological processes and water balances of catchments with inputs of high-resolution digital terrain and elevation models, land use, soil type, climate, chemical tracers, and geographic information and so on. However, there are limitations in transferring the similar methodology into TP studies, mainly due to the lack of high-resolution climate data (Krause et al., 2010). In addition, information about land use, soil type, and field observations for cross-validation are also rare due to remoteness and harsh environment on the TP. All these restrictions make conventional hydrological modelling difficult, if not impossible. On the other hand, an isotope-based hydrological approach has been successfully developed for remote areas in the northern Canada (Gibson and Edwards, 2002; Yi et al., 2008; Brock et al., 2009; Gibson and Reid, 2010; Turner et al., 2014; Gibson et al., 2016). Water isotope investigations in other regions of the world including the TP were also proven to be useful in understanding water balance and hydrological processes (Tian et al., 2008; Longinelli et al., 2008; Henderson and Shuman 2009; Jones and Imbers, 2010; Wu et al., 2015; Yang et al., 2016). This approach usually requires a snapshot sampling of lake water for isotopic analysis and basic hydro-climatic measurement (such as water temperature and relative humidity) for a first order approximation of lake water balance, which hold the great advantage for lake systems on the TP context. As a result, we carried out a stable water isotope ($\delta^{18}O$ and $\delta^{2}H$) investigation during 2005–2008 to systematically document and study isotopic signatures in the Nam Co Basin.

In this paper, we report water isotope ($\delta^{18}O$ and $\delta^{2}H$) measurements in local precipitation, lake water, streams, glacier-melts, groundwater and wetland storage collected in the Namco Basin. The systematic observations of isotopic signatures in various types of waters in the watershed lead to the establishment of the first water isotope framework for the basin and further discussion of the water balance of the lake. The overall objectives of the paper are: 1) to present isotopic characteristics of different hydrological components in the Namco Basin; 2) to establish a water isotope framework for evaluating current hydrological status of the lake from an isotope perspective; 3) to provide isotopic evidence discussing the water balance of the lake and water yield of the basin. The establishment of an isotopic framework is the very first step toward the long-term monitoring and modelling the hydrology and ecology of the basin with the stable water isotopes.

2. Study area

The Nam Co (30° N, 90° E, 4718 m a.s.l.) is the second largest saline lake on the TP. It is an endorheic lake system experiencing significant changes in hydrology, ecology, and physical characteristics (Chen et al., 2009; Keil et al. 2010; Zhang et al., 2011, 2013). The lake itself covers an area of 2018.25 km^2 measured in 2009 (Zhang et al., 2013), with a maximum depth over 90 m (Wang et al., 2009). The drainage area for the lake is about 10,680 km^2 bounded by the Gandise Range in the southwest, the western Nyainqentanglha Range in the southeast, and rolling hills in the north (Fig. 1) (Kang et al., 2011; Wang and Dou, 1998). A large number of glaciers (~166 km^2 in total area) are developed in the Nyainqentanglha Range, which feeds numerous streams running into the lake (Chen et al., 2009). It was suggested that streams originated from the glaciered area in the western Nyainqentanglha Range are the most important contributors to Nam Co (Krause et al., 2010).

The geomorphological characters of the Nam Co drainage are diverse. Keil et al. (2010) suggests seven units for the entire basin. Among these units, western highlands, Nyainqentanglha mountains, and southwestern mountains are of the most areally significant, accounting for 32%, 30% and 21% of basin area respectively (Keil et al., 2010). Steep slopes, which promote rapid hydrological responses, are one of the main characteristics of Nyainqentanglha Mountains, southwestern mountains and northern highlands. In a contrast, western highlands and northwestern hogbacks are ridge-and-valley landscapes, where slopes are relatively gentle and fluvial and periglacial processes are evident. Primary dune fields and sand sheets are common in the eastern highlands, implying strong vertical hydrological connectivity in the area. Wetland is also an important landscape feature in the watershed, mainly distribute around the lake (i.e., the lakeshore unit) and in western highlands and northwestern hogbacks where delta-like fluvial deposits interfinger with lacustrine deposits in flat plains. According to a relief map (1:100,000 in scale), we estimated that the surface areas of wetland are more than 600 km^2, including ~200 km^2 along the lakeshore.

The Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITP-CAS), operates Nam Co Station at the eastern end of the lake. Observations and documentations of weather, glacier, lake level and stream runoff were started since 2005 (Kang et al., 2011). Fig. 1 illustrates the drainage boundary, the lake surface area and sampling locations for hydrological and weather observations. From 2005 to 2008, the annual maximum difference of lake level during the thaw season is less than 0.8 m (Krause et al., 2010; Zhou et al., 2013), which is subtle comparing to the maximum depth of the lake, however a decadal trend of increasing in lake level is also evident according to long-term studies (Zhang et al., 2011; Wu et al., 2014). The drainage basin area features semi-arid subarctic plateau climate with strong seasonality, mainly due to the interaction of Westerlies, the winter monsoon, the South West Asian monsoon and the East Asian monsoon (Krause et al., 2010). The monsoon season (June to September), is characterized by relative warm and wet conditions; while during non-monsoon months (October to May), the westerly predominate the region with cold and dry air mass (Keil et al., 2010; Li et al., 2007). According to the weather observations at Nam Co station, the mean annual air temperature is ~ −0.6 °C; mean annual relative humidity is ~53.6%. Mean annual precipitation is ~414.6 mm, with more than 330 mm (~80%) as rainfall during monsoon season, while less than 83 mm as snowfall during the non-monsoon season (Kang et al., 2011). It is also important for the hydrological investigations that the lake generally remain open water conditions during May to October, slightly longer than the monsoon season. In the rest of a year, the lake surface was cover by thick ice prevention evaporation and atmospheric interaction.

3. Methodology

3.1. Sample collection

During our sampling campaign between 2005 and 2008 in the Nam Co basin, various source water including precipitation (rainfall and snowfall), glaciermelts, groundwater, and samples of surface water types including the Nam Co, streams and wetlands were collected. Fig. 1 illustrates samples locations for various water samples.

Precipitation was collected by an automated precipitation collector at Nam Co station (near site No. 35, Fig. 1). The collector has two buckets for collecting wet and dry deposition with a barrelhead, which can switch automatically with regard to weather condition. During precipitation events, the barrelhead switches to cover the dry deposition barrel so that precipitation can be sampled in a HDPE plastic bag placed within the wet deposition barrel. Glacier meltwater was collected from the tone of Zhadang Glacier (30°28′N, 90°39′E; 5500 m a.s.l., site No. 36, Fig. 1) on the Western Nyainqentanglha Range, whenever field team visited the glacier for fieldwork between May and October 2008.

Groundwater are represented by samples from a well and a natural spring in the basin. Well water was collected from a well (7 m in depth) at Nam Co station (near site No. 35, Fig. 1) with biweekly sampling frequency from August 2005 to June 2006; and weekly between May 2007 and October 2008. A natural spring near the Nam Co Station (site No.35, Fig. 1) was also founded and sampled weekly from September 2007 to September 2008.

Seventeen streams were sampled near the mouth (sites No.10 to No.26, Fig. 1) during summers from 2005 and 2008. It was usually one snapshot sample for individual stream in each summer. Niyaqu (site No.10, Fig. 1), originated from non-glaciated area, was sampled more frequent (weekly when it is possible) between June and October 2008 to make observations of temporal changes in stream discharge. Wetland samples were collected from eight wetlands along the lakeshore (sites No.27 to No. 34, Fig. 1), when field visits were made in September-2005 and May-2006.

Lake water of Nam Co were sampled regularly (approximately weekly) at a near shore location (site No. 9, Fig. 1) from August 2005 to November 2006 and from July 2007 to October 2008. Spatial survey of surface heterogeneity were also conducted twice (September 2005 and May 2006) for nine locations (sites No.1 to No.9, Fig. 1) in Nam Co. Additionally, 17 samples of a depth profile for Nam Co (site No.37, Fig. 1) were taken in 5 m intervals on September 19th, 2006. All water samples were collected in 15 ml sealed HDPE bottles and kept frozen before analysis.

3.2. Isotopic analysis

The majority water samples were submitted to the Max-Planck-Institute for Biogeochemistry Isotope Laboratory, Jena, Germany for $\delta^{18}O$ and $\delta^{2}H$ analysis. The lab use a modified thermal conversion/elemental analyzer system connected to an isotope ratio mass spectrometer (TC/EA-IRMS) for isotopic analysis (Gehre et al., 2004). The samples of spatial survey and depth profiling were analyzed for $\delta^{18}O$ only at the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Results are reported in δ notation relative to Vienna Standard Mean Ocean Water (VSMOW). The average standard deviation (σ) was 0.5‰ for $\delta^{2}H$ and 0.2‰ for $\delta^{18}O$.

3.3. Meteorology data

Air temperature and relative humidity data were recorded at Nam Co station (2006–2008) and Bange meteorological station (1979–2008) (31°23′N, 90°01′E, 47, 000 m a.s.l), which is 15 km north of the Nam Co Basin (Fig. 1). Data from Bange station are used to derive long-term (~ 30 years) climate normal, while data from Nam Co station are used for year specific evaluations. Fortunately, evaporation measured by standard cylinder-shaped E601-B evaporation dish (60 cm height, 62 cm diameter) are available at both stations for the period of 2007–2008 (Zhou et al., 2013; Ma et al., 2015). Evaporations were recorded daily every 12 h at 8:00am and 8:00pm during the observation period. To better represent meteorological conditions when evaporation was occurring, monthly evaporation rates were used as weights to calculate evaporation-flux-weighted meteorological conditions including relative humidity and temperature for the framework developments.

3.4. Isotope mass balance model

With isotopic and climatic observations in the watershed, an isotopic framework is established. The framework follows the isotope mass balance as reviewed by Gibson et al. (2016). LMWL (local meteoric water line), range and mean isotopic values of rainfall (δ_R), snow (δ_S), groundwater (δ_{GW}) and glaciermelt (δ_{GM}) are summarized based upon local observations. Precipitation-flux-weighted isotopic composition for precipitation (δ_p^{fw}), limiting isotopic composition of evaporated water (δ^*) and isotopic composition of ambient moisture (δ_A) are calculated (Gibson et al., 2016) and proposed for a long-term regional isotope framework especially for the Nam Co basin. Within the context of the isotopic framework, the observations of isotopic compositions in the surface water including Nam Co (δ_L), wetland (δ_{WL}), glacier-fed streams ($\delta_{str}{}^{glacier}$) and non-glacier-fed streams ($\delta_{str}{}^{non-glacier}$) are embraced by projected local evaporation trajectories with hypothetical input scenarios. Following well-established methods of coupling $\delta^{18}O$ and $\delta^{2}H$ signatures for water balance estimations (Yi et al., 2008; Brock et al., 2009), isotopic composition of input water for Nam Co Lake (δ_I), evaporation over input ratios (E/I ratio) and water yield (Wy) for the Nam Co Basin are further estimated for specific year when it is feasible. Mathematic details on the isotope mass balance model and subsequent estimations of the isotopic composition of input water (δ_I), evaporation over input ratios (E/I ratio) and water yield (Wy) are provided in the supplementary materials.

4. Results

4.1. Isotopic signatures in water

In this study, we obtained hundreds of individual isotopic measurements. Flux-weighted averages are used to report mean isotopic signatures in rainfall, snow, and glaciermelts because amounts of relevant flux (such as precipitation and glaciermelts) are available. The calculation equations are provided in the supplementary materials. The usages of flux-weighted averages are common in isotope studies (Bowen and Revenaugh, 2003) and are expected to better reflect signatures from major events. As for groundwater, streams, wetlands and the lake, where the flux weights are not available, simple arithmetic averages are reported.

4.1.1. Rainfall (δ_R), snow (δ_S) and precipitation-flux-weighted mean (δ_p^{fw})

During the campaign, almost all precipitation events were sampled at the Nam Co station. In total, 284 precipitation events were

Table 1
Summary of isotopic composition of water resources and surface water in the Nam Co Basin.

		Mean		Min		Max		#
		$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	
Water Resources	Rainfall[a]	−19.7	−145.3	−32.6	−243.5	−2.8	−1.3	202
	Snowfall[a]	−11.6	−71	−34.4	−253.2	2.2	31.7	82
	Groundwater	−17.5	−133.1	−18	−136.9	−16.3	−120.6	136
	Glaciermelt[a]	−16.3	−119	−19.3	−142.8	−12.7	−87.2	13
Surface Water	Nam Co	−6.98	−70.9	−12.51	−103.2	−6.18	−63.5	78
	Wetland	−12.76	−104.1	−16.8	−136.2	−8.1	−68	8
	Glacier-fed stream	−15.25	−107.46	−18	−130.6	−11.2	−77.3	15
	non-Glacier-fed stream	−16.73	−125.66	−19	−144	−13.6	−98.9	62

[a] The amount-weighted averages are used as mean values.

sampled over the 4-year period. Most of rainfall occurred between the middle of June and the end of September, while snowfall happened in the rest of a year. As summarized in Table 1, the isotopic compositions of snow range from −34.4‰ to 2.2‰ for $\delta^{18}O$ (−253.2‰–31.7‰ for $\delta^{2}H$), whereas the isotopic compositions of rainfall range from −32.6‰ to −2.8‰ for $\delta^{18}O$ (−243.5‰–−1.3‰ for $\delta^{2}H$). This extremely broad isotopic variations (> 30‰ in $\delta^{18}O$ and > 240‰ in $\delta^{2}H$) in both rain and snow, with an overlapping range, reflect the dynamic nature of the weather in the region. The interactions of Westerlies, the winter monsoon, the South West monsoon and the East Asian monsoon make the weather condition, consequently the moisture source and precipitation, extremely dynamic and highly variable on an event basis.

At a monthly scale, however, a seasonal pattern appears. In Fig. 2, both the precipitation amounts and $\delta^{18}O$ compositions are summarized into monthly means, and error bars indicate one standard deviation. The monthly mean $\delta^{18}O$ are precipitation-flux-weighted averages. In spite of the wide variability (as indicated by error bars in Fig. 2 and individual samples in Fig. 3a), The monsoon season (from June to September) is presented by low mean $\delta^{18}O$ values and high precipitation amount; in contrast the non-monsoon season (dominated by Westerlies between Oct and May) is marked by higher mean $\delta^{18}O$ values with very low precipitation amount. This strong seasonal pattern in monthly mean isotopic signatures is consistent with previous observations in the region (Tian et al., 2007; Keil et al., 2010), and higher $\delta^{18}O$ values in snow, such as May in Fig. 2 are generally attributed to more isotopically enriched moisture brought by Westerly (Tian et al., 2007).

Weighted by precipitation amounts, we calculated the mean values of −19.7‰ ($\delta^{18}O$) and −145.3‰ ($\delta^{2}H$) for rainfall (δ_R), and the mean values of −11.6‰ ($\delta^{18}O$) and −71.0‰ ($\delta^{2}H$) to represent snowfall (δ_S). Clearly, δ_R is significantly depleted than δ_S, which is unique when comparing to isotopic signatures in precipitation in high latitude regions with strong climate seasonality (Rozanski et al., 1993; Edwards et al., 2004). This is generally attributed to the changes of moisture sources (Tian et al., 2007). Summer rainfalls origin from southwest monsoon, while winter snows are brought by westerly winds. The apparently different δ_R and δ_S highlight the potentials to label and trace rainfall and snow at an integrated time scale. More specific for the water balance modelling in the latter

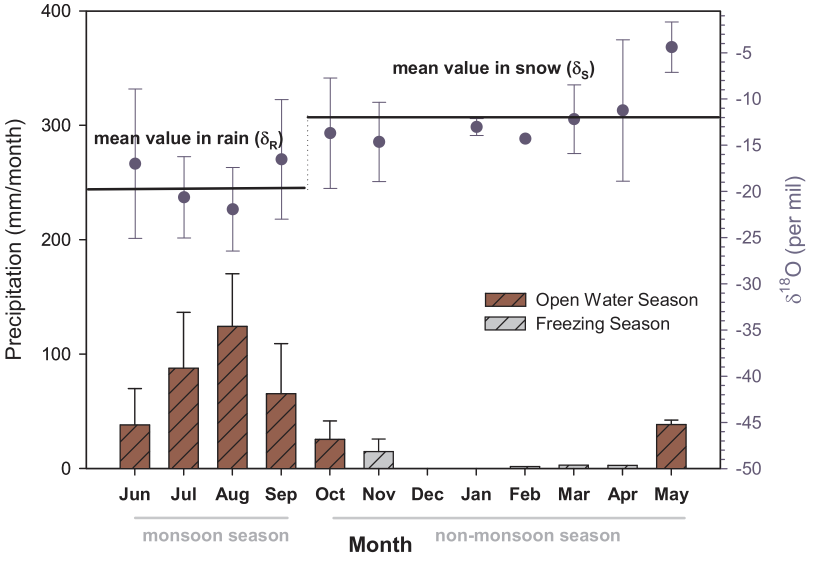

Fig. 2. A summary of monthly precipitation amount and monthly mean $\delta^{18}O$ in precipitation. This is based on local observations at Nam Co Station between 2005 and 2008. The error bars indicate one standard deviation. The black solid lines presented estimated mean values for rainfall (δ_R) and snow (δ_S) respectively. Months for open water season, freezing season, monsoon season and non-monsoon season are indicated.

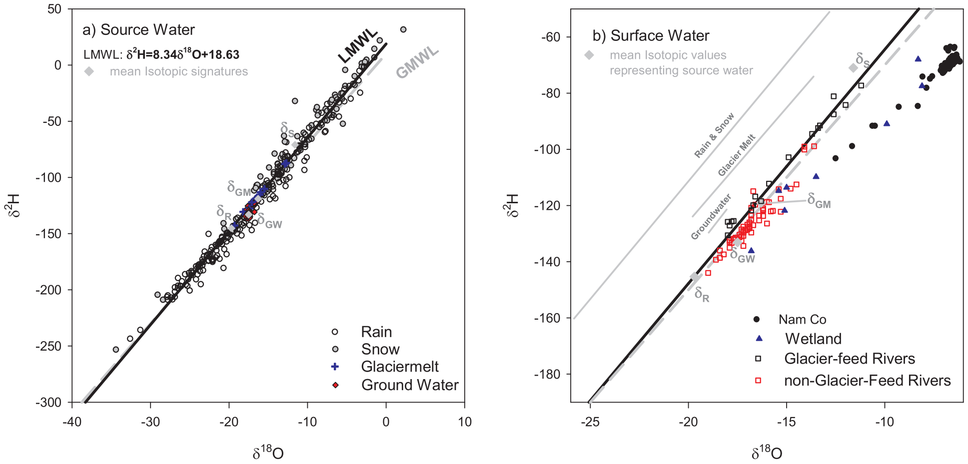

Fig. 3. $\delta^{18}O$-δ^2H plot of isotopic signatures in the Nam Co basin. a) isotopic observations representing source water are presented in different symbols. δ_R, δ_S, δ_{GW} and δ_{GM} denote mean values of rainfall, snow, groundwater and glaciermelts respectively. Local Meteoric Water Line (LMWL) is developed based upon the regression of rainfall and snow results. b) isotopic signatures in various surface water types, including Nam Co Lake, wetland, glacier-fed streams and non-glacier-fed streams. For the purpose of comparison, the range and mean values of δ_R, δ_S, δ_{GW} and δ_{GM} in a) are also presented.

section, we also estimate the amount-weighted mean isotopic compositions in precipitation during open water season (May–October). The resulting precipitation-flux-weighted isotopic composition ($\delta_P{}^{fw}$) is calculated to be −16.1‰ ($\delta^{18}O$) and −113.6‰ (δ^2H) respectively. $\delta_P{}^{fw}$ is somewhere in between δ_S and δ_R, likely representing a mixture of rainfall and snowfall. The $\delta_P{}^{fw}$, therefore, will be used to estimate representative moisture conditions (δ_A) during open water evaporation and will be referred as an important long-term parameter for the isotope framework in the following section.

Based on the multiple years observations (2005–2008) in precipitation (rainfall and snow), a Local Meteoric Water Line (LMWL) for the Nam Co Basin is also developed via a linear regression in $\delta^{18}O$-δ^2H space ($\delta^2H = 8.34 \times \delta^{18}O + 18.63$, r = 0.99, Fig. 3a). This proposed LMWL is very similar to LMWL determined based upon single year observations ($\delta^2H = 8.2 \times \delta^{18}O + 22.3$, reported by Keil et al., 2010). The slope of 8.34 is slightly higher than the slope of Global Meteoric Water Line (GMWL), and the intercept (18.63) is also higher than that of the GMWL. The consistently higher slope and intercept of LMWL than GMWL is also reported in nearby high Himalaya region (Pande et al., 2000; Hren et al., 2009)

4.1.2. *Glaciermelt (δ_{GM}) and groundwater (δ_{GW})*

The isotopic compositions for glaciermelts (δ_{GM}) range from −19.3‰ to −12.7‰ for $\delta^{18}O$ (−142.8‰ to −87.2‰ for δ^2H, Table 1). The variations in glaciermelt are much constrained comparing to precipitation. Weighted by the synchronous runoff of Zhadang glacier (Gao et al., 2009), we estimated that the mean compositions of −16.3‰ ($\delta^{18}O$) and −119.0‰ (δ^2H) to represent δ_{GM}. From May to June, the $\delta^{18}O$ values of melt water varied between −12.0‰ and −16.0‰, usually slightly enriched than mean δ_{GM}, likely reflecting the addition of fresh snow (characterized by enriched δ_S) to the melting of glacier ice. From June to August, with a sharp increase in air temperature and precipitation, $\delta^{18}O$ values of melt water become lower than the proposed mean δ_{GM}, varying between −16.0‰ and −20.0‰. This likely reflects the mixing with local rainfalls, because δ_R is usually more depleted as presented in our source water summary. As the melting season approach to the end in September and October, the $\delta^{18}O$ values of melt water become similar to the mean δ_{GM}, varying between −16.0‰ and −18.0‰.

Groundwater are represented by water samples collected from a local well at 7 m below the ground surface and a natural spring found near the Nam Co Station (Fig. 1). Samples were collected year round (including winter) in both locations. The results suggest an extremely narrow range of variations for the groundwater in the region. $\delta^{18}O$ signatures vary between −18.0‰ and −16.3‰ (between −136.9‰ and −120.6‰ in δ^2H) without clear seasonal trend (Table 1). The average $\delta^{18}O$ and δ^2H values of δ_{GW} are calculated to be −17.5‰ (σ = 0.1‰) and −133.1‰ (σ = 1.8‰), respectively. Note that σ represents the standard deviation of $\delta_{GW,}$ and σ values are comparable to the analytical uncertainty of isotopic results. Isotopically, groundwater could be considered as a water resource with near-constant signatures. The representative δ_{GW} values (−17.5‰ and −133.1‰) are slightly depleted than the mean δ_{GM} (−16.3‰ and −119.0‰), and somewhere in between mean δ_S and δ_R, indicating the long-term averages for the mixing of snow and rainfall.

Fig. 3a plots glaciermelts (δ_{GM}) and groundwater (δ_{GW}) in $\delta^{18}O$-δ^2H space along with the results of precipitation (δ_S and δ_R). In contrast to the broad range of rainfall and snow, glaciermelts and groundwater are more constrained in isotopic compositions. More importantly, both groundwater and glaciermelts show strong evidence of meteoric origin. The glaciermelts tightly vary along the LMWL, which heavily overlap with the range for rainfalls, but show the enrichment effect of snow in the month of May and June. On the other hand, the groundwater cluster around the mean values with minimum variations, reflecting the long-term averaging of precipitation in groundwater.

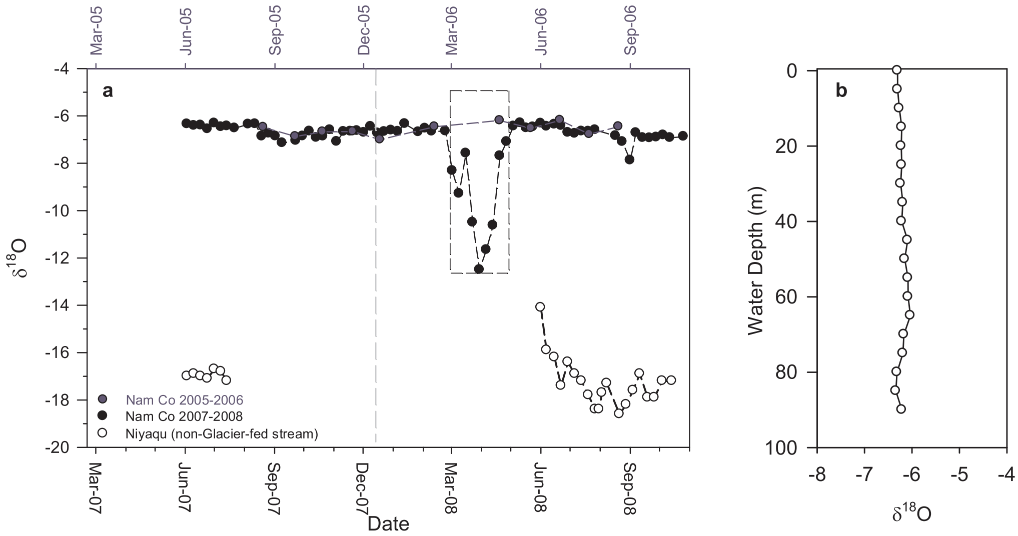

Fig. 4. Temporal and spatial variation of isotopic signatures in surface water in the basin. a) Temporal series of $\delta^{18}O$ signatures in the lake (Nam Co) and a stream (Niyaqu) between 2007 and 2008. The temporal records of Nam Co between 2005 and 2006 are also plotted based upon matching Julian days. The negative excursion occurred in March/April 2008 is highlighted by the dashed-line box. b) the depth profile (from the surface to > 90 m depth) of $\delta^{18}O$ signatures in Nam Co sampled at site No. 37.

4.1.3. Streams ($\delta_{str}^{glacier}$ & $\delta_{str}^{non-glacier}$) and wetlands ($\delta_{WL}$)

There are more than one hundred of streams running into Nam Co (Wang and Dou, 1998). Seventeen of them, including the major tributaries Cequ, Angqu and Niyaqu, were sampled for water isotope analysis. According to the headwater characteristics, sampled streams are categorized into two types: glacier-fed streams and non-glacier-fed streams. The isotopic compositions of glacier-fed streams varied from −18.0‰ to −11.2‰ in $\delta^{18}O$ and −130.6‰ to −77.3‰ in $\delta^{2}H$, with average values of −15.25‰ ($\delta^{18}O$) and −107.46‰ ($\delta^{2}H$) representing $\delta_{str}^{glacier}$. $\delta_{str}^{glacier}$ values reasonably agree with δ_{GM} in mean values and the range of variations (Table 1). The isotopic signatures of non-glacier-fed stream varied from −19.0‰ to −13.6‰ in $\delta^{18}O$ and −144.0‰ to −124.0‰ in $\delta^{2}H$, with the average compositions of −16.73‰ ($\delta^{18}O$) and −121.45‰ ($\delta^{2}H$) for $\delta_{str}^{non-glacier}$ (Table 1). Although glacier-fed streams and non-glacier-fed streams are very similar in mean $\delta^{18}O$ values and overall isotopic range, dual-isotope signatures (both $\delta^{18}O$ and $\delta^{2}H$) provide evidence of distinctions between the two types of streams. In the $\delta^{18}O$-$\delta^{2}H$ plot, glacier-fed streams closely vary along the LMWL(Fig. 3b); in a contrast, the majority of non-glacier-fed streams plot below the LMWL, showing subtle deviation from LMWL, likely caused by evaporation. While it is not clear yet that if the evaporative deviations in non-glacier-fed streams reflect longer residence time of streamflow or simply because of contribution of evaporative surface runoff to the stream, the differences between glacier-fed streams and non-glacier-fed streams highlights the importance of measuring both $\delta^{18}O$ and $\delta^{2}H$ signatures.

Niyaqu (a major tributary without glacier distribution within the catchment) was sampled regularly in 2007 & 2008, but attempts of sampling baseflow under the ice were not successful. Fig. 4a presents the temporal series of $\delta^{18}O$ in NiyaQu discharge during open water seasons. With the very limited number of samples, not many variations were observed during 2007. While in 2008, the stream discharge was significantly enriched at the beginning of the open water season (−14.1‰ in $\delta^{18}O$ and −100.0‰ in $\delta^{2}H$ on June-1 2008). As the monsoon season progress, the isotopic compositions of discharge gradually changed and stabilized around −18.0‰ in $\delta^{18}O$ (Fig. 4a). A temporal trend of isotopic depletion in stream discharge was also reported for Qugaqie (a glacier-fed stream) in 2006 (Zhou et al., 2014). The enriched isotopic signatures in Niyaqu discharge at the beginning of the open water season are plotted close to LMWL, suggesting the meteoric origin of the water. Therefore, the observation of enriched signature in an early open water season in Niyaqu is likely due to contributions of isotopically enriched source water such as melting snow.

Wetland is another important landscape feature in the Nam Co basin. Only eight wetland samples were collected in this study. A broad range of isotopic variation was found, varying from −16.8‰ to −8.1‰ in $\delta^{18}O$ and −136.2‰ to −68.0‰ in $\delta^{2}H$, with average values of −12.76‰ ($\delta^{18}O$) and −104.1‰ ($\delta^{2}H$) for δ_{WL}. In the $\delta^{18}O$ − $\delta^{2}H$ plot, δ_{WL} values deviate significantly from LMWL (Fig. 3b), showing clear effects of evaporation. This makes the wetland water isotopically distinct from stream waters ($\delta_{str}^{non-glacier}$ and $\delta_{str}^{glacier}$) as well as various meteoric origin resource water (δ_{R},δ_{S}, δ_{GW} and δ_{GM}).

4.1.4. Nam Co lake (δ_{L})

Due to the large surface area and large volume of water in the lake, spatial surveying and depth profiling of lake water were performed in the early phase of the sampling campaign to assess the heterogeneity of isotopic signatures within the waterbody, and only $\delta^{18}O$ values were analyzed. Two spatial surveys were conducted at nine locations (sites No.1–No.9, Fig. 1) around the lake. Results of the September 2005 survey report a σ value (one standard deviation) of 0.50‰ in $\delta^{18}O$, ranging from −6.9‰ to −8.2‰. In the May-2006 campaign, $\delta^{18}O$ variations in Nam Co surface water are characterized by the σ value of 0.69‰ (change between −6.6‰ and −8.2‰). Depth profiling of the lake in September 2006 (Fig. 4b) even presents much smaller variations from the surface to 90 m depth, with the σ value of 0.09‰ (the $\delta^{18}O$ range between −6.03‰ and −6.34‰). For the reference, the σ value due to the analytical uncertainty in this study is 0.2‰ for $\delta^{18}O$. Although thermocline has been observed in the water column of Nam Co, hydrochemical properties (such as pH, conductivity and O_2 content) are demonstrated to be generally constant through the water column (Keil et al., 2010). Our isotopic surveys further demonstrate that the Nam Co can be treated as an isotopically well-mixed lake with very limited heterogeneity. In following sections, isotopic measurements of the lake surface water collected at Site No. 9 (Fig. 1) were presented and discussed to represent the isotopic composition of Nam Co.

From August 2005 to November 2008, the $\delta^{18}O$ and $\delta^{2}H$ values of Nam Co lake water range from −12.5‰ to −6.0‰ and −103.2‰ to −63.5‰, respectively (Table 1). Apparently, the lake water signatures (δ_L) are more enriched than signatures in other surface water ($\delta_{WL,}$ $\delta_{str}^{non-glacier}$ and $\delta_{str}^{glacier}$) in the basin. In $\delta^{18}O$-$\delta^{2}H$ space, all δ_L values deviate from LMWL, showing the apparent effect of evaporation (Fig. 3b). The majority of lake water samples clustered around the multi-year average (δ_L: −6.98‰ for $\delta^{18}O$ and −70.9‰ for $\delta^{2}H$), while only a few samples show depleted signatures pointing toward the cluster of streams ($\delta_{str}^{non-glacier}$ and $\delta_{str}^{glacier}$). It is also important to note that the trajectory of δ_L variations in the $\delta^{18}O$-$\delta^{2}H$ plot appears to be coherent with the variation of δ_{WL} in a linear manner, as both lake and wetland experience open water evaporation under similar atmospheric conditions. The regression of lake water only produces a linear line of $\delta^{2}H = 5.93 \times \delta^{18}O - 29.47$ ($R^2 = 0.9294$), which intersects with LWML at values of −19.7‰ and −145.8‰ for $\delta^{18}O$ and $\delta^{2}H$ respectively.

$\delta^{18}O$ time series of lake water compositions in 2007/2008 (Fig. 4a) further reveal that isotopic compositions of Nam Co are stable for the most time of a year, while the depletions in isotopic signatures related to the period of March/April 2008, when the lake was still under the cover of ice. In Fig. 4a, we overlaid 2005/2006 results with 2007/2008 results by matching Julian days. Under-ice results for 2005/2006, however, did not show the same negative excursion as results from 2007/2008. It is unfortunate that the winter season of 2005/2006 was not sampled as frequent as that of 2007/2008. The contrast between 2005/2006 and 2007/2008 could not rule out the possibility of systematic occurrence of isotopic depletion in δ_L. We also believe that the negative excursion in δ_L is not likely caused by sampling (i.e., contamination of snow) because δ_S is likely to be relatively enriched according to our isotopic summary (Table 1). The intersection of lake water regression and LMWL further suggest that the negative excursion likely reflects the impact of water resources characterized by −19.7‰ in $\delta^{18}O$ and −145.8‰ in $\delta^{2}H$, which are more depleted than mean snow, groundwater and stream signatures for the season but still within variation ranges of these water resources. All in all, the isotopic depletion of lake water under the ice in March/April 2008 may capture an episode of shallow inputs (groundwater or stream water) in early spring. Similar to the temporal observation in the Niyaqu, the temporal variations in Nam Co are not fully understood yet. More observations, especially under ice conditions, and further investigations are warranted.

With the observation of δ_L over multiple years (2005–2008), we conclude that the isotopic compositions of Nam Co maintain fairly stable from year to year. The average isotopic compositions of open water season were calculated for individual years: −6.7‰ ($\delta^{18}O$) and −67.2‰ ($\delta^{2}H$) for 2005; −6.5‰ ($\delta^{18}O$) and −67.3‰ ($\delta^{2}H$) for 2006; −6.7‰ ($\delta^{18}O$) and −68.7‰ ($\delta^{2}H$) for 2007, and −6.7‰ ($\delta^{18}O$) and −70.2‰ ($\delta^{2}H$) for 2007.

4.2. Stable water isotope framework for the Nam Co basin

Isotopic labeling of hydrological processes is typically manifested by the existence of patterns, and key references for both $\delta^{18}O$ and $\delta^{2}H$ signatures, such as LMWL for local precipitations and Local Evaporation Lines (LEL) for evaporation trajectories in the $\delta^{18}O$-$\delta^{2}H$ plot (Edwards et al., 2004). Visually illustrating isotopic trajectories and incorporating important references into the $\delta^{18}O$-$\delta^{2}H$ space as an isotopic framework are essential to utilize stable isotope techniques to understand, assess and quantify hydrological processes within the context of natural variability (Brock et al., 2009; Edwards et al., 2004; Gibson and Edwards, 2002; Wolfe et al., 2007). Providing the enormous efforts at Nam Co station to collect and summarize isotopic signatures from source water and surface water (as presented in section 4.1), it is the appropriate opportunity to establish the first regional isotope framework on the TP for the benefit of future monitoring and modelling.

Long-term climate records for the region is obtained from the nearest meteorological station (1979–2008, Bange Meteorological Station, see in Fig. 1). The precipitation-flux-weighted isotopic signatures (δ_P^{fw}) for the open water season are also calculated based on a large number of observations. Due to the difficulties in directly measuring the isotopic composition of ambient moisture (δ_A), δ_A is estimated based on isotopic equilibrium with precipitations during the open water season (δ_P^{fw}). These long-term reference conditions for open water season are summarized in Table 2. δ_A is estimated to be −26.7‰ in $\delta^{18}O$, which is very close to the average $\delta^{18}O$ value of −24.77‰ (range of −16.24‰–−32.44‰) in observations of atmospheric moisture at a nearby location (Yu et al., 2005). According to the Craig-Gordon model for evaporation, regardless of water resources sustaining a lake, the isotopic composition of surface water converge toward a value, as it approached completed desiccation (Craig and Gordon, 1965; Gonfantini,

Table 2
Long term hydroclimatic and isotopic references used to set up the framework in the Nam Co Basin.

Paremters	Values	Notes
h (%)	58	Bange Meteorological station (evaporation-flux-weighted mean, 1979–2008)
T (°C)	8	
δ_P^{fw} (‰)	(−16.1; −113.6)	Nam Co Station (precipitation-flux-weighted mean, 2006–2008)
δ_A (‰)	(−26.7; −190.6)	
δ^* (‰)	(2.2; −37.8)	this study
LMWL	$\delta^{2}H = 8.34\delta^{18}O + 18.63$	this study

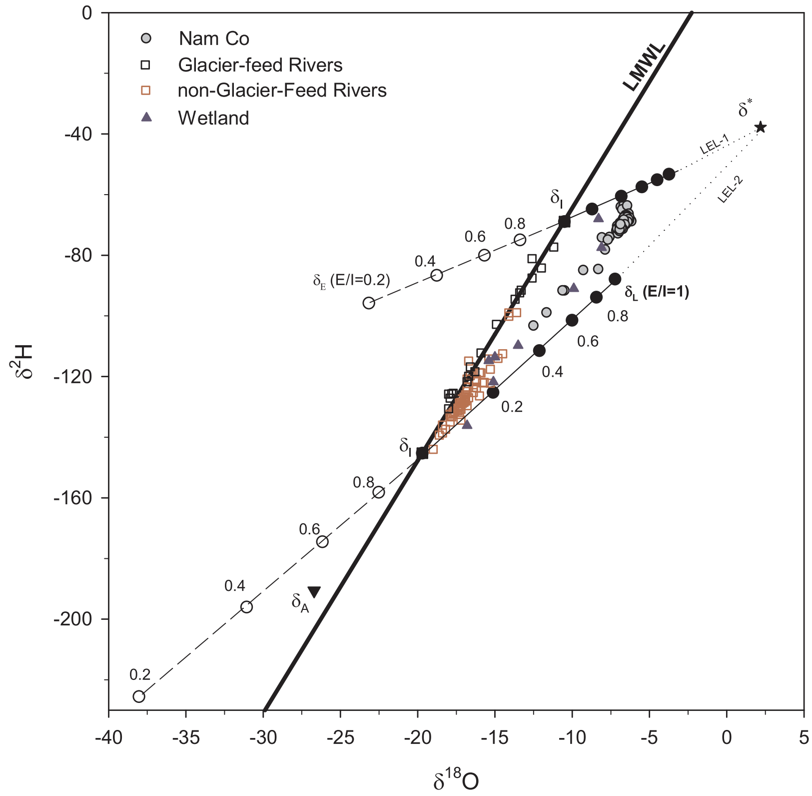

Fig. 5. The isotopic framework for the Nam Co Basin. LMWL are based upon multiple-year observations of precipitation (including rainfall and snow). Isotopic compositions of atmospheric moisture (δ_A)are based upon equilibrium with precipitation-flux-weighted isotopic composition ($\delta_P{}^{fw}$), and limiting isotopic compositions (δ^*) are estimated by Craig-Gordon Model. Two evaporative trajectories are modelled with the mean values of rainfall (δ_R) and snow (δ_S) as inputs (δ_I). Along each individual trajectory, the E/I (Evaporation over Input ratio) status of (0.2, 0.4, 0.6, 0.8, 1) are denoted. Isotopic signatures of surface water samples including Nam Co (δ_L), wetland (δ_{WL}) and streams ($\delta_{str}{}^{glacier}$ and $\delta_{str}{}^{non-glacier}$) are also plotted with the context of the framework.

1981). This value is usually referred as the δ^*, which is the limiting evaporative enrichment in a particular system. Providing the 30 years climate normal during open water season (T = 8 °C; RH = 58%), and ambient atmosphere moisture condition (which is assumed to be equilibrium with $\delta_P{}^{fw}$), we estimate δ^* for the Nam Co Basin to be 2.2‰ and −37.8‰ for δ^{18}O and δ^2H respectively (Table 2). In the δ^{18}O-δ^2H plot (Fig. 5), δ^* is plotted far away from LMWL and significantly enriched than all surface water samples in our field campaign, indicating possibly the most enriched isotopic values in the watershed. Also shown in Fig. 5, the LMWL is presented as the linear expression of $\delta^2H = 8.34 \times \delta^{18}O + 18.63$, which provides a good constraint on the variability of meteoric inputs.

Taking the mean δ_R and δ_S as hypothetical inputs, Fig. 5 also presents two scenarios with contrast input compositions. LEL-1 models the evaporative evolution trajectory starting from an isotopically enriched source (δ_S: −11.6‰ and −71.0‰ in δ^{18}O and δ^2H respectively); whereas LEL-2 modelled the trajectory with an isotopically depleted source (δ_R: −19.7‰ and −145.3‰ in δ^{18}O and δ^2H respectively). Along each LELs, compositions with a series of hypothetical E/I (Evaporation over Input ratios) status (i.e., E/I = 0.2, 0.4, 0.6, 0.8 and 1) are projected; corresponding δ_E estimations are also noted with a different symbol. As isotopic compositions of a water body move along linear LELs toward δ^*, the proportion of evaporation losses in lake water budget becomes greater. The point of E/I = 1 implies the evaporation losses completely balance the input. Further beyond the E/I = 1 point indicates that inputs can not sustain evaporation anymore and the water body shall become desiccated over time. Although the evaporation trajectory for a specific water body may vary from year to year due to changes in the overall isotopic compositions of input water, the two scenarios appear to embrace our observations of various types of surface water (δ_L, δ_{WL}, $\delta_{str}{}^{non-glacier}$ and $\delta_{str}{}^{glacier}$), suggesting the framework reconstitute the reality well. As the first step toward isotopic modelling, the framework can be used to provide a qualitative water budget evaluation without detailed hydroclimatic information, which takes time and efforts to compile. According to the relative positions to the predicted E/I = 1 point (Fig. 5), we are confidence that all lakes and wetlands sampled in this study have a status of E/I < 1, which indicating the evaporation loss usually less than the total of inputs from various sources.

The establishment of an isotope framework for the Nam Co Basin provides a context to understand isotopic signatures in the watershed. Any observation of significant deviation from the framework trajectories should draw serious attention to the possibility of significant change in hydrosphere in the Nam Co Basin. As discussed in the following section, further assessments of the isotopic composition of input water (δ_I), water balance status (E/I) and basin scale water yields (Wy) for a specific year are also performed based on the framework.

Table 3
annual evaluation of input water and water balance conditions for the Nam Co.

	2006	2007	2008
T (°C)	7.4	7.2	6.3
h (%)	59.8	59.1	64
$\delta_P{}^{fw}$(‰)	(−16.05; −114.3)	(−17.60; −130.8)	(−15.1; −106)
$_{7A}$ (‰)	(−26.70; − 191.8)	(−27.09; −194.1)	(−25.87; −185.3)
δ_L (‰)	(−6.5; −67.3)	(−6.7; −68.7)	(−6.7; −70.2)
δ_I (‰)	(−12.2; −83)	(−12.3; −84)	(−13.6; −94)
E/I (%)	53.1	52.0	68.3

5. Discussions

5.1. Estimation of input water compositions

Throughout the field campaign, we observed that Nam Co is sustained by multiple sources of inputs. The water resources include direct precipitations, wetland buffeted catchment runoffs especially during the snowmelt period, numerous streams (which are also the main conduits for glaciermelts from mountain ranges) as well as invisible groundwater exchanges and possible permafrost thaw. Providing that different sources bear different isotopic signals, as demonstrated in Fig. 3, an evaluation of overall input water compositions (δ_I) to the Nam Co would bring some insights into the relative roles of various water resources to the lake.

As reported in Section 4.1.4, the intersection of the linear regression of lake water composition ($\delta^2H = 5.93 \times \delta^{18}O - 29.47$) and LMWL provide a first order approximation of overall input water compositions to the Nam Co. The δ_I, in this way, are estimated to be −19.7‰ and −145.8‰ for $\delta^{18}O$ and δ^2H respectively. Comparing to the isotopic range and mean values representing various water resources (Table 1, Fig. 5), this δ_I is similar to mean δ_R (−19.7‰ and −145.3‰ for $\delta^{18}O$ and δ^2H). Because other water resources (including snow, groundwater and glaciermelts) all appear to have more enriched mean isotopic values than estimated δ_I (Table 1), it suggests that rainfalls are an essential component in the mixture of multiple water inputs. However, cautions on the estimation of δ_I in this way should be applied. As presented in Fig. 4a, the regression of Nam Co water compositions is heavily influenced by the isotopic excursion in the March/April 2008, which are more likely episodic (Fig. 4a). In addition, this approach broadly indicates the δ_I without specific meaning to a specific year.

Alternatively, within the isotope framework, it is possible to apply the coupled isotope approach to estimate input water compositions on annual basis (Yi et al., 2008). Based upon hydroclimatic and precipitation observations during open water seasons for three consecutive years, we estimate year-specific Nam Co δ_I values for 2006, 2007 and 2008 (see Table 3). Much more enriched δ_I values are estimated. For example, the δ_I for 2007 are estimated to be −12.3‰ and −84‰ for $\delta^{18}O$ and δ^2H respectively. From 2006 to 2008, the year-specific δ_I values all appears to be higher than the −15‰–−16‰ range in the $\delta^{18}O$, (the general isotopic range overlapped by many water resources). This strongly suggests that the contribution of isotopically enriched water resources, such as the snowmelts, may play very important role in the annual water budget for Nam Co. Among the three years (2006–2008), δ_I evaluations are the most isotopically depleted in 2008 (−13.6‰ and −94‰ for $\delta^{18}O$ and δ^2H respectively), which is consistent with the observation of highest precipitation in 2008 since 2007 (Zhou et al., 2013). The isotopic excursion in the March/April 2008 (Fig. 4a) may also reflect the input of isotopically depleted water resources in 2008.

Two means of evaluating overall isotopic compositions of input water (δ_I) are presented here. While both approaches reflect the mixing nature of multiple inputs to the Nam Co, the year-specific δ_I values (coupled isotope method) are more enriched than the first order approximation of overall δ_I (LEL and LMWL interception). The apparent differences between the two approaches alert possible high uncertainties in δ_I estimations based upon either method, which is expected for a lake with multiple sources. Moreover, all δ_I estimations are bracketed by observed ranges and the isotope framework (Table 2, Fig. 5). The discrepancies in δ_I from different approaches also highlight the dynamics of isotopically depleted water resources (such as $\delta_{R,}$ and δ_{GW}) and isotopically enriched water resources (such as δ_S) from year to year in the basin. Snowmelt and rainfall are usually lumped together as precipitation in hydrological model development for the basin (Wu et al., 2014). Providing the contrasting isotopic signatures between δ_R and δ_S, isotopic monitoring and modelling shall be incorporated with hydrological modelling to better tracking, quantifying and understanding hydrological roles of individual water resources in the Nam Co basin.

5.2. E/I status of Nam Co (2006–2008)

Accompanying the estimation of δ_I by the coupled isotope approach, the exercise also reports E/I quantifications, which reconcile the common discrepancies between $\delta^{18}O$ and δ^2H alone (Yi et al., 2008; Turner et al., 2010; Biggs et al., 2015). As presented in the isotope framework (Fig. 5), the annual E/I ratios are reported between 52.0% and 68.3% during the period of 2006–2008 (Table 3). From an isotopic perspective, it is very clearly that the Nam Co lake maintains a positive water budget.

The below-unity E/I status provides a quantitative argument that catchment inputs are more than direct water loss via evaporation. Keep in mind that Nam Co is an endorheic lake system without any surface outlet. The positive water budget would be transferred into increasing water level, which has been reported by numerous investigations (Wang et al., 2009; Wu et al., 2014), although the annual water level increase (estimated to be around 0.180 m per year, Wu et al., 2014) is considerably small comparing

Table 4
Sensitivity of Isotope Mass Balance Model to changes of input parameters (± 5%). Take the 2008 scenario as an example.

Parameter Change by ± 5%	T	RH	δ_A
δ_I ^{18}O (‰) variations	−13·6 / −13·5	−13.4/ −13.7	−12.3/ −14.7
δ_I ^{2}H (‰) variations	−94/ −95	−93/ −95	−84/ −104
E/I (%) variations	68.1 / 68.5	58.4/ 85.7	64.8/ 72.2

to the water depth (> 90 m) of the lake. The salinity of Nam Co were commonly reported less than 3 g/L (Williams, 1991; Matthews et al., 2004; Keil et al., 2010), which is significantly less than salinity (ranging from 16.2 g/l to 24.3 g/l) reported for lakes usually found in adjacent region (Guan et al., 1984) and shown a decreasing pattern for decades long (Keil et al., 2010), which is counter-intuitive to the accumulation of salt if evaporation is the only means of water loss for a water body. To explain these intriguing characteristics, Zhou et al. (2013) proposed significant subsurface water seepage from Lake Nam Co by detailed accounting individual water budget components. This isotopic investigation provides another line of evidence that the subsurface leakage from the Nam Co is likely. Our results imply that more than 30% of catchment inputs would be lost by subsurface leakage, with the consideration of a minor increase in water level.

The uncertainty of the E/I and δ_I evaluations are demonstrated through a series of sensitivity tests. As presented in Table 4, the variations of $\delta^{18}O_I$, δ^2H_I and E/I are evaluated for the 2008 scenario by varying the most important input parameters including T, RH and δ_A by ± 5%. The sensitivity tests suggest that temperature (T) has little impacts on either δ_I or E/I. Relative humidity (RH) has significant impact on the E/I calculation. ± 5% variations of RH can lead to changes of E/I between 58.4% and 85.7%. While the range of E/I are still below unity, consistent with the positive water balance for the Nam Co, the strong sensitivity of E/I to RH inputs shall be noted as the representativeness of RH at appropriate scales is critical to quantitatively refine the water balance through the isotopic approach. δ_A appears to affect δ_I outputs more than E/I output (Table 4). ± 5% variations of δA only leads to 7.4% changes in E/I evaluations (between 64.8% and 72.2%), while the variation of δ^2H_I can be up to 20‰ (between −84‰ and −104‰), which is the largest range comparing to the sensitivity test on RH and T. Therefore, to better understanding source contributions to the Nam Co, it is important to have a strong constraint on the δ_A inputs. One essential caveat in this exercise is the assumption of hydrological and isotopic steady-state (Gibson et al., 2016). The subtle, but noticeable, changes of water level from year to year may void the hydrological steady-state assumption. Sophisticate transient isotopic modelling with isotopic and water volume measurements should be the next step to further refine the quantitative evaluation of lake water budgets.

5.3. Water yield estimation

Although there is still room to improve the E/I estimations due to the caveat of the steady-state assumption, we think it could be an informative exercise to further use the isotope-based E/I results constraining ungauged runoff into the Nam Co. The basis of water yield estimation with isotope-based E/I has been reviewed in details by Gibson et al. (2016), and the application have been widely employed in Northern Canada for site-specific evaluation of water yields (i.e., depth equivalent runoff) for ungauged small catchments (Gibson and Edwards, 2002; Gibson and Reid 2010). This is the first time that isotope-based water yield evaluations are performed for TP lakes. Providing that relevant hydroclimatic and geomorphological parameters are only available for the years of 2007 and 2008 (Table 5), we estimate that the annual water yields for the entire Nam Co basin are 183.8 mm and 40.9 mm for 2007 and 2008 respectively.

The estimations are also in a reasonable agreement with the range of water yields reported from regions with a seasonal climate. On a regional scale, Gibson and Edwards (2002) reported water yield estimation ~180 mm for tundra catchments; ~125 mm for catchments located near treeline; and ~40 mm for catchments characterized with boreal forest. It has been argued that the water yields can be affected by the landscape characteristics, effective drainage area and connectivity of multiple sub-catchments within a catchment (Gibson and Reid 2014). In a study of runoff from 80 undisturbed boreal catchments ranging from 0.12 to 67 km^2, Lyon et al. (2012) reported a positive correlation between runoff and percentage of wet area (i.e., wetlands, mires and lakes). It is possible that various geomorphometric units (as suggested by Keil et al., 2010) have different capacities of water yielding and spatial heterogeneity exists within the basin.

Indeed, Zhou et al. (2013) made tremendous efforts to measure and gauge runoff from three catchments within the Nam Co basin

Table 5
Annual water yeild (Wy) estimated for the entire Nam Co Basin.

	E/I	e	p	LA	DBA	Wy
	%	mm[a]	mm[a]	km^2 [b]	km^2	mm
2007	52	630	420	2012.47	10680	183.8
2008	68.3	530	600	2015.36	10680	40.9

[a] Refer to Zhou S.Q. et al., 2013.
[b] Refer to Zhang G.Q. et al., 2013.

in 2008. They reported a wide range of annual water yields from individual catchment: 280 mm, 930 mm and 400 mm for Angqu (1463 km^2), Qugaqie (59 km^2) and Niyaqu (409 km^2) respectively. Among them, the highest water yield catchment – Qugaqie, 930 mm – is a glaciated-catchment with a strong support of glaciermelts during open water season, while the lowest water yield catchment – Angqu, 280 mm – locates in the Southwestern Mountains characterized by steep slopes and a large catchment area. The isotope-based water yield estimations (40.9-183.8 mm) are significantly lower than the field observations from a glaciated-catchment (930 mm), but much closer to the measurements (280 mm) in the non-glaciated terrain with a steep slope.

It is very interesting to note that lower water yield were estimated for 2008, when precipitation is higher comparing to 2007 (600 mm vs 420 mm). Kang et al. (2009) reported much weaker glacier-melt from Zhadang Glacier (a well documented glacier within the basin) in 2008 when summer temperature was lower and rain season was earlier comparing to 2007. Water yield in our estimations consistently capture the changes in glacier-melt contributions. However, the suppressed glacier melt may not be the only reason for the significant temporal and spatial water yield differences as demonstrated in this study. In addition to the soil moistures, rain seasonality, drainage connectivity and many other factors affecting the conversion from the precipitation to the water yields (i.e., the Wy/P ratio), the mosaic landscape in the watershed may be the most important factor to be considered and understood for the complex and dynamic runoff generation processes within the basin.

Gentle terrains featuring ridge-and-valley landscape in the Western Highlands and Northwestern hogbacks (account for 40% area of the basin) shall contribute to the water yield to some extent. Although much higher local water yields have been measured in the steep mountainous regions (Zhou et al., 2013), the hydrological role of ridge-and-valley landscape with vast areas and low runoff potentials shall not be ignored at a basin scale, as suggested by the significant differences between our isotope estimations and localized runoff measurements. We believe the differences between isotope-based water yield estimations and field runoff observations are mainly due to spatial scales. The applications of results from Zhou et al. (2013) over the entire Nam Co watershed shall be only considered as the upper limits of runoff generation for the basin, and investigations in the Western Highlands and Northwestern hogbacks are yet to be conducted to provide a more holistic pictures on the spatial heterogeneity of the runoff generation in the basin.

6. Conclusions

This study systematically reports water isotopic signatures from multiple source water and various surface water types in the Nam Co basin, provides mean isotopic values and variations ranges for rainfall (δ_R), snow (δ_S), glaciermelts (δ_{GM}), groundwater (δ_{GW}), streams ($\delta_{str}{}^{non-glacier}$ and $\delta_{str}{}^{glacier}$), wetlands (δ_{WL}) and Nam Co lake (δ_L). We highlight the usage of amount-weighted isotopic signatures to representing and tracing water in the Nam Co basin. In the combination of the availability of long-term hydroclimatic mean for the region and the observation of isotopic means from various water resources, we establish the first isotope framework at a basin scale to guide the interpretation and monitoring of isotopic signatures in the Nam Co basin. Two inputs scenarios (one is based upon mean δ_R, and the other is based upon mean δ_S) were modelled to embrace all observations of various water types. Within the framework, we estimate the isotopic composition of input water (δ_I) for the Nam Co, evaluate the E/I status for three consecutive years, and assess the water yields (Wy) at a basin scale. Although these quantitative estimations shall be considered as preliminary with the limitation of steady-state assumptions, the results clearly suggest a positive water budget (i.e., $E/I < 1$) for Nam Co, providing another line of evidence that the subsurface leakage from Nam Co is likely. The basin-wide estimations of water yields (< 200 mm) are significantly different from field observations (> 280 mm) in individual catchments, suggesting that the low water yielding terrain in the basin (for example the vast ridge-and-valley area in the western highlands and northwestern hogbacks) are yet to be investigated. With the establishment of a robust isotope framework for the Nam Co basin, we strongly recommend future isotopic results from the Nam Co basin, as well as adjacent region, to be investigated within the framework, therefore links contemporary observations with historical and long-term averages to detect and understand possible changes in hydrological processes with the context of climatic and environmental changes on the TP.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2017.05.007.

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