Spatial Variations in the Stable Isotopic Compositions of Surface and Groundwaters across Central Sri Lanka

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Abstract

We present the spatial variations and isotopic fractionations of the stable isotopic compositions of waters across central Sri Lanka and discuss their applicability as tracers in hydrological studies of the island. The stable isotopic compositions of lake waters in the dry zone of the island were affected by evaporative isotopic enrichment and therefore can be used to estimate the evaporative loss from these lakes. The stable isotopic compositions of stream waters in the wet zone indicate a clear equilibrium isotopic fractionation with altitude (the altitude effect), which is useful in tracing water sources. The isotopic compositions of stream waters in the dry and intermediate zones are higher than expected from their altitude, likely stemming from the outflow of water from upstream tanks or reservoirs that are affected by evaporative isotopic enrichment and are unsuitable for estimating the altitude effect in those areas. The stable isotopic compositions of groundwater and tap and bottled waters plot along the local meteoric water line, suggesting that these waters preserve information on the isotopic compositions of rainwater in their recharge areas. Results indicate that the stable isotopic compositions of surface waters can be an effective tool in the hydrological and hydrogeological studies of the island.

Introduction

The wise use of limited water resources requires an understanding of hydrological cycles on a regional or basin-wide scale. Future changes in precipitation and rainfall patterns caused by climate changes are likely to affect the water supply and quality. Thus, in order to meet the increasing water demands, water resources must be managed and developed on the basis of a sound understanding of hydrological cycles. The ratio of stable isotopes $^{18}O/^{16}O$ and $D/^{1}H$ (defined as the conventional delta notation, $\delta^{18}O$ and δD) of water is widely used as an environmental tracer in hydrological and hydrogeological studies and has been applied for investigating the interactions between surface water and groundwater (Blumstock et al. 2015, Dogramaci et al. 2015), separating the baseflow from a streamflow hydrograph (Jones et al. 2006, Tweed et al. 2016), estimating the influx of groundwater into lakes (Sacks et al. 2014, Ala-aho et al. 2015), and identifying the origin of groundwater and flow processes (Kamtchueng et al. 2015).

Rainfall in Sri Lanka is controlled by the tropical monsoon system. Monsoon rains are closely related to the regional livelihood and social water use, making stable water supply and flood/drought management a necessity. Accordingly, various studies have used stable isotopes to investigate the meteorological and hydrological settings in Sri Lanka. Dharmasiri & Athuluwage (1991) reported the monthly stable isotopic variations in rainwater at seven sites to constrain the isotopic input into groundwater. Jayasena et al. (2008) characterized the isotopic compositions of rainwater in the dry and intermediate

climatic zones of the Deduru Oya river basin. Edirisinghe et al. (2017a) revealed seasonal and spatial δ¹⁸O and δD variations in rainwater due to monsoon and convectional rainfall and identified an isotopic fractionation on the basis of their long-term observations across central and northern Sri Lanka. Basin-scale stable isotopic analyses have also been used to understand the evolution of groundwater quality (Song et al. 1999), assess groundwater recharge mechanisms (Edirisinghe et al. 2014), and demonstrate the relationship between groundwater and chronic kidney disease of unknown etiology (CKDu) (Edirisinghe et al. 2017b).

Although the isotopic composition of rainwater is effectively used as an index of regional hydrological cycles, continuous long-term observations are necessary to obtain average stable isotopic compositions of local rainwater because of the large temporal variations during rainfall events and seasonal cycles. Kendall & Coplen (2001) demonstrated that the isotopic composition of surface water matches that of local rainwater, and they concluded that sampling surface water as representative of local precipitation is advantageous because stream waters spatially and temporally integrate the isotopic compositions within catchments. van Geldern et al. (2014) indicated that isotopic fractionations in rainwater (e.g., the altitude effect) can be traced in samples from streams and springs. However, these studies were limited to midlatitude regions, and their applicability in near-equatorial regions has not been shown. Stream water isotopic compositions in Sri Lanka have been insufficiently studied at the regional and national scales. Additionally, evaporation is expected to influence the isotopic composition of stream waters in Sri Lanka owing to the high air temperature. Therefore, the applicability of stream water isotopic compositions to hydrological and hydrogeological research in Sri Lanka remains to be demonstrated.

The objective of this study is to investigate the spatial variations and isotopic fractionations of the stable isotopic compositions of various surface (i.e., streams, lakes, and tap and bottled waters) and groundwater samples in three climatic zones across central Sri Lanka. We used our results to assess the applicability of stable isotopes as a tracer to evaluate the evaporative loss from surface water and the origins of waters.

Study site

1. Climate and physical setting

Sri Lanka is a tropical island in the Indian Ocean, situated between 5°55′ and 9°50′N latitude and 79°41′ and 81°53′E longitude. It can be divided into three main geomorphological regions: coastal lowlands, uplands, and highlands [Fig. 1(a)] (Dissanayake & Weerasooriya 1985). The central highlands, reaching 2,524 m above sea level at Pidurutalagala's peak, consist of a number of ridges, peaks, plateaus, basins, valleys, and escarpments (Edirisinghe et al. 2017a).

Sri Lanka's climate is controlled by the tropical monsoon system and is classified into two monsoon periods and two intermonsoon periods: the Southwest Monsoon (SWM, from May to September), Northeast Monsoon (NEM, from December to February), First Intermonsoon (FIM, from March to April), and Second Intermonsoon (SIM, from October to November). During the SWM, moist southwesterly winds orographically lift as they cross the central highlands, resulting in a considerable rainfall on the windward side of the highlands, whereas little rain falls on the lee side (Edirisinghe et al. 2017a). The NEM is dry and stable compared to the SWM, and windward rainfall during January and February is relatively small (Song et al. 1999). During the intermonsoon periods, convectional-type rainfall and tropical depressions (mainly during the SIM) originating in the Bay of Bengal are predominant, and short spells of heavy rainfall are frequent (Malmgren et al. 2003). Based on these large regional differences in annual rainfall, Sri Lanka is classified into wet, dry, and intermediate climatic zones [Fig. 1(b)]. The southwestern part of the island, including most of the central highlands, is classified as the wet zone, the north and southeastern parts are classified as the dry zone, and the belt-like intermediate zone lies between the wet and the dry zones. Both monsoons (NEM and SWM) bring rains to the wet zone, which receives a mean annual rainfall of 2,500 mm, whereas the dry zone receives a mean of 1,000 mm of monsoon rains, which come entirely from the NEM (Jayasena et al. 2008). The intermediate climatic zone receives a mean annual rainfall of 1,700 mm (Jayasena et al. 2008). The annual average evaporation in Sri Lanka is 1,279 mm (Bastiaanssena & Chandrapala 2003). However, evaporation in the dry zone ranges between 1,700 and 1,900 mm, which results in a soil moisture deficit during the dry periods (Panabokke et al. 2002).

The topography in both mountainous and flood plain zones reflects the underlying Precambrian complex geology. More than 90% of the Precambrian high-grade metamorphic rocks in Sri Lanka belong to three major lithotectonic units known as the Highland, Wanni, and Vijayan Complexes [Fig. 1(c)] (Jayawardana et al. 2012). The rest of the island (i.e., the northern and northwest coastal areas) consists of Miocene to Quaternary limestone. Six main types of aquifers have been identified in Sri Lanka: shallow karstic aquifers, coastal sand

aquifers, deep confined aquifers, lateritic aquifers, alluvial aquifers, and shallow regolith aquifers in the hard rock region (Panabokke 2001). These aquifers are governed by the overall geology and represent diverse hydrological conditions. Additionally, the rainfall regime and topography strongly influence the hydrological setting, land use, and the options available for groundwater use (Villholth & Rajasooriyar 2010).

2. Water use

Sri Lanka has 103 distinct river basins covering 90% of the island's surface area (Manchanayake & Madduma Bandara 1999). Most of the main rivers originate in the central highlands and eventually flow into the sea, passing through the lowlands [Fig. 1(a)]. Agriculture in the wet zone is supported mainly by rain-fed cultivation and stream water, without irrigation reservoirs. In the dry zone, in order to overcome unstable and insufficient rainfalls, water collected in surface water reservoirs ("tanks") filled by rainfall and run-off from streams is generally used for agricultural and domestic purposes. Particularly in the dry zone, literally thousands of ancient tanks of varying sizes and shapes are distributed (Manchanayake & Madduma Bandara 1999). The networks of small tanks to large reservoirs "tank cascade systems" were constructed and still act as essential elements of water management for

agriculture in the dry zone (Geekiyanage & Pushpakumara 2013).

Since ancient times, residents have used shallow wells dug through the weathered overburden to access water for drinking and other domestic uses, particularly in the wet zone (Manchanayake & Madduma Bandara 1999). Traditionally, groundwater has been extracted from shallow open wells dug to depths of up to about 5 m; these wells still persist and are used today in rural and semiurban areas. They are suitable for use with shallow and unconfined karst, coastal, and regolith aquifers (Villholth & Rajasooriyar 2010) and have been introduced more recently in the dry zone, where groundwater use (mainly for agriculture) has rapidly increased during the past few decades (IWMI 2005). The two major cities of Sri Lanka, Colombo (the capital) and Kandy, mostly rely on surface water for public water supply, but some relatively large urban centers also base their water supply on groundwaters (Villholth & Rajasooriyar 2010, Herath & Ratnayake 2007). However, water quality problems such as CKDu (Edirisinghe et al. 2017b) and dental fluorosis (Jayawardana et al. 2012), caused by drinking groundwater, are on the rise, and access to safe water supplies is becoming an important issue. Thus, a thorough understanding of the hydrological cycles in Sri Lanka is necessary to manage water resources at the regional scale.
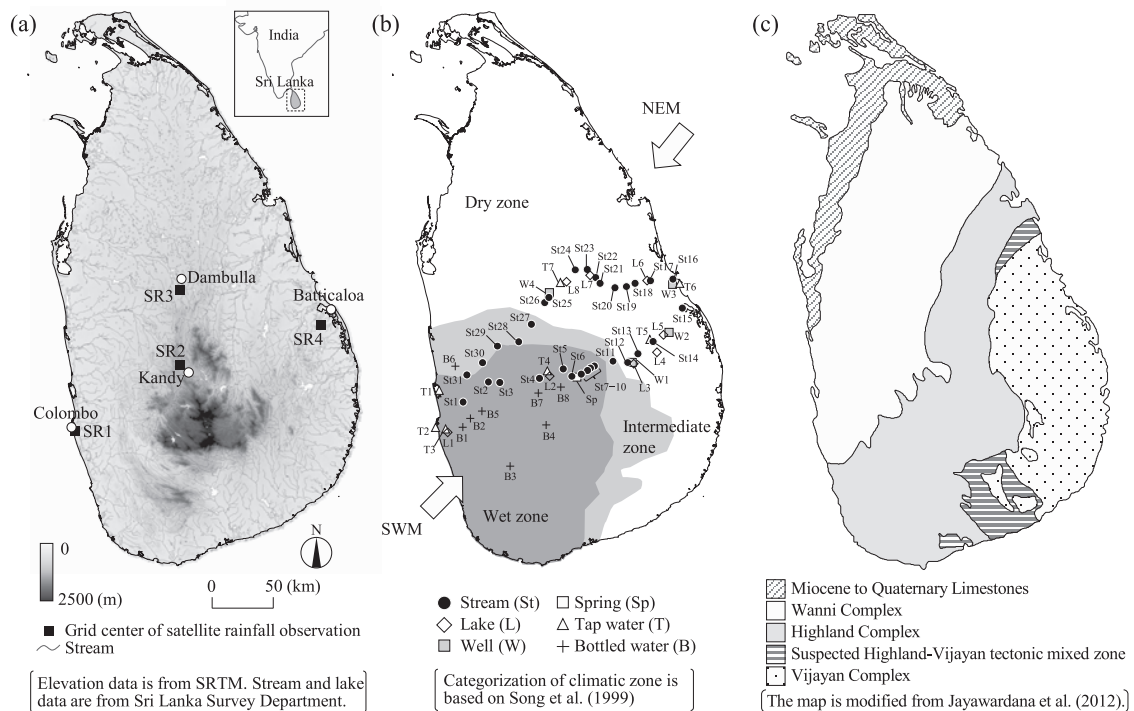

Fig. 1. Study area

(a) Topography of Sri Lanka and satellite observation points for rainfall data, (b) Climatic zones and water sampling points, and (c) Geology. NEM: Northeast Monsoon; SWM: Southwest Monsoon

Methods

1. Sample acquisition

In order to analyze the stable isotopic compositions of meteoric water across central Sri Lanka, we collected water from streams (St1-St31), lakes (L1-L8), wells (W1-W4), springs (SP), taps (T1-T7), and bottled waters (B1-B8) [Fig. 1(b)]. The sampling locations were selected to represent a transverse profile from the wet zone to the dry zone. Relatively large reservoirs and micro- to mesoscale reservoirs (village tanks) were also sampled and are hereafter classified as "lake" samples. The accurate sites/addresses of bottled water sources are not recorded on labels, so the sampling sites shown in Fig. 1(b) are approximate. Water samples were collected from 28 November to 2 December 2016, corresponding to the end of the SIM and the beginning of the NEM.

Figure 2 shows satellite-observed PERSIANN rainfall data (Sorooshian et al. 2000) at four locations (SR1-SR4) during about one month, including our sampling period. SR1-SR4 represent locations at the center of 0.25° grids from the satellite observational area and are nearest to the cities of Colombo, Kandy, Dambulla, and Batticaloa, respectively. In late November, a relatively low rainfall was observed at each location, and the maximum daily rainfall during our investigation period was 21 mm (30 November) at locations near Dambulla and Batticaloa. Therefore, the collected stream waters are considered to be close to baseflow conditions.

Stream and lake water samples were collected from a bank or bridge using a sampling bucket. W1-W3 are shallow domestic wells, and the depth of the water table from the ground surface ranged from 0.2 to 1.1 m. Groundwater samples from W1-W3 were collected using a sampling bucket. W4 is a hand-pump well, and its water depth is unknown. Bottled water samples were purchased from shops. Tap water was collected after running taps for 1 min. All samples were stored in clean polyethylene vials

and brought to our laboratory in Japan for stable isotope analysis.

2. Stable isotope analysis

The altitude effect, one of the isotopic fractionation effects, is the observation that the stable isotopic compositions of meteoric water are more depleted at higher altitudes. Although the altitude effect is easily observed in precipitation, it is often different from that observed in recharged water because evaporation occurring before or during infiltration alters the water's stable isotopic composition (Allison et al. 1983). O'Driscoll et al. (2005) measured seasonal $\delta^{18}O$ variations in precipitation, soil water, snowmelt, spring water, and stream baseflow to investigate the seasonal dynamics of groundwater recharge in three catchments of central Pennsylvania. They found that the baseflow data showed the most consistent pattern of altitude effects over the investigation period, although the soil water and precipitation data showed a much higher variability with respect to seasonal altitude effects (O'Driscoll et al. 2005). Stream water samples integrate the spatial variability in the meteorological cycle and provide useful data on the spatial distributions of $\delta^{18}O$ and δD in meteoric waters (Kendall & Coplen 2001).

In this study, stream water samples were used to determine the altitude effect. We established the regression equations between stable isotopic compositions and surface altitudes using the mean altitude of the catchment area upstream of any specific sampling point instead of the altitude of the sampling points (e.g., Tsuchihara et al. 2006, Yamanaka et al. 2007, van Geldern et al. 2014). Terrain data were available from 90 m resolution digital elevation model (DEM) data from the Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007). The mean altitudes of stream catchment areas were calculated after the automatic generation of catchment areas from the SRTM-DEM data by Quantum GIS ver. 2.18.4 (http://www.qgis.org/). The stable isotopic compositions of tap
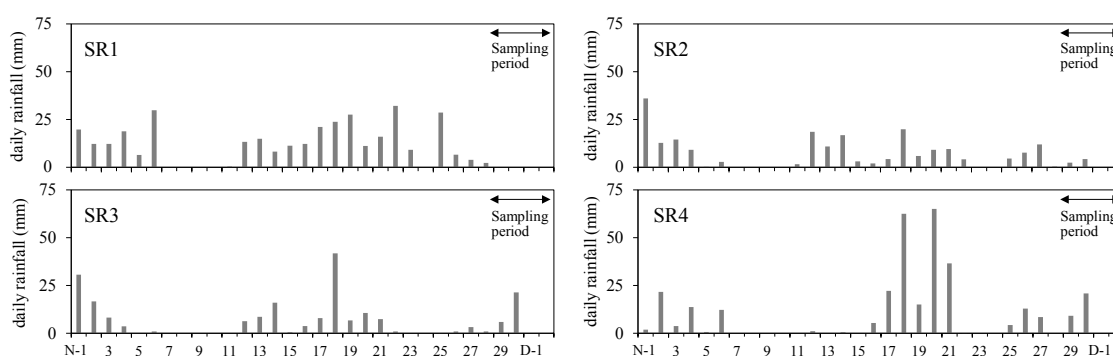

Fig. 2. Satellite-observed rainfall data from 1 November to 2 December 2016

waters, lake waters, groundwaters from wells, and spring waters were compared with the altitudes of the sampling points, because these catchment areas cannot be identified from the topography on the ground surface. The altitudes of bottled waters refer to the water sources labeled on the bottles.

The stable isotopic composition of water was measured with respect to the Vienna Standard Mean Ocean Water standard and described here in ''delta'' notation (parts per thousand, ‰) as follows:

$$\delta \ (‰) = (R_{sample}/R_{std} - 1) \times 1{,}000, \tag{1}$$

where R_{sample} and R_{std} are the ratios of heavy to light isotopes (i.e., $^{18}O/^{16}O$, $D/^{1}H$) in a sample and the standard, respectively. $\delta^{18}O$ and δD of the sampled waters were measured at a laboratory at the National Agriculture and Food Research Organization in Japan using the cavity ringdown spectrometer-based water isotope analyzer (Picarro L2140-i). The precision in this study was within ±0.05‰ and ±0.50‰ for $\delta^{18}O$ and δD, respectively. The deuterium excess (d-excess, used to indicate the kinetic fractionation effect of evaporation; Gat 1996) of each

water sample was calculated as d-excess = $\delta D - 8\delta^{18}O$.

Results and Discussion

1. Spatial variations of stable isotopic compositions

Table 1 shows the average, maximum, and minimum of $\delta^{18}O$, δD, and d-excess values of the collected waters. The δ-values of groundwaters from wells and spring waters are lower than those of lake waters. The $\delta^{18}O$ and δD values of stream waters are higher than those of groundwaters, and they vary over a relatively wide range from −6.2 to −0.7‰ and from −35.1 to −4.8‰, respectively. The groundwater samples have relatively high d-excess values on average, whereas lake samples show the lowest values. The average d-excess of stream waters lies within the average d-excess of groundwaters and lake waters.

Figure 3 shows the spatial distributions of $\delta^{18}O$ and d-excess values of streams, lakes, groundwaters from wells, and spring waters. Stream waters in the dry zone show higher $\delta^{18}O$ and lower d-excess values

Table 1. Summary of the stable isotopic compositions of collected waters

	Altitude (m)	δ^{18}O (‰)			δD (‰)			d-excess (‰)		
		AVG.	MAX.	MIN.	AVG.	MAX.	MIN.	AVG.	MAX.	MIN.
Stream (n=31)	15 - 1080*	−3.8	−0.7	−6.2	−21.7	−4.8	−35.1	8.4	15.1	0.8
Lake (n=8)	7 - 520	−2.2	1.8	−4.3	−14.4	1.5	−23.1	3.4	11.4	−12.8
Well (n=4)	15 - 179	−5.4	−5.0	−5.8	−32.7	−30.0	−35.0	10.9	12.0	10.0
Spring (n=1)	830	−6.3			−37.5			13.2		
Tap water (n=7)	7 - 514	−4.9	−3.3	−6.2	−28.4	−20.5	−37.6	11.1	12.7	5.8
Bottled water (n=8)	17 - 1240	−5.0	−3.8	−6.4	−27.8	−19.0	−38.6	12.1	12.9	11.0

* Stream altitudes represent the mean altitude of the catchment area upstream of the sampling point.

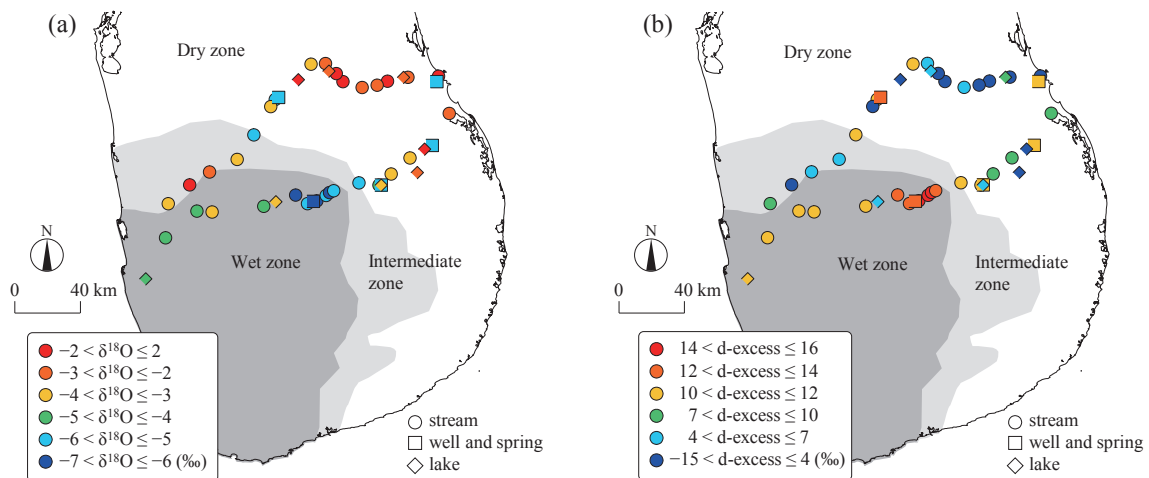**Fig. 3. Spatial distribution of (a) δ^{18}O and (b) d-excess values of stream waters, lake waters, and groundwaters from wells and springs**

similar to lake waters, whereas those in the wet zone are characterized by lower $\delta^{18}O$ and higher d-excess values. At the regional or basin scale, $\delta^{18}O$ and δD values of rainwater decrease inland from the coast (the continental effect) and decrease with increasing altitude as expected from the altitude effect. These effects are controlled by equilibrium isotopic fractionation; thus, d-excess, which is quantified by nonequilibrium (kinetic) fractionation (Dansgaard 1964), does not change under equilibrium conditions. The variation of d-excess values of stream waters in the wet and dry zones indicates that the variation of $\delta^{18}O$ values of stream waters is affected not only by equilibrium fractionation but also by kinetic isotopic fractionation.

2. Effects of evaporative enrichment

The relationship between $\delta^{18}O$ and δD values in our samples is shown in Figure 4. The local meteoric water line (LMWL) illustrated in Figure 4 was identified by the long-term observations of rainwater across Sri Lanka (Edirisinghe et al. 2017a). Groundwaters from wells and spring, tap, and bottled waters plot near the LMWL. Stream waters with $\delta^{18}O$ values less than −4‰ plot near the LMWL, but those with $\delta^{18}O$ values greater than −4‰ deviate from the LMWL. Lake waters deviate from the LMWL, similar to the stream waters with higher stable isotopic compositions. Figure 5 compares the $\delta^{18}O$ and δD values of lake, well, and spring waters to the LMWL. The stable isotopic compositions of lake waters define the local evaporation line (LEL) with a slope of 4.25 (Fig. 5). The kinetic fractionation of oxygen and hydrogen isotopes by evaporation enriches waters in the heavier isotopes, producing trends with slopes ranging from 4 to 7, in contrast to isotopic compositional trends associated with equilibrium isotopic fractionation that lie near the meteoric water line and have a slope close to 8 (Gibson et al. 2002). The deviation from the LMWL of lakes in the dry zone (L4-L8) is larger than for those in the wet zone (L1, L2) (Fig. 5). It follows that the lakes in the dry zone are more severely affected by evaporative isotopic enrichment than those in the wet zone. The difference in the influence of evaporation is likely to be related to the surface area, depth, and residence time of lakes, in addition to the climatic conditions.

Stream water samples in the dry and intermediate zones show relatively higher $\delta^{18}O$ and lower d-excess values than those in the wet zone (Fig. 3). Sri Lanka has vast dry low-lying plains irrigated using traditional tanks or reservoirs constructed since ancient times (Manchanayake & Madduma Bandara 1999, Geekiyanage & Pushpakumara 2013). Many of the rivers sampled in this study, especially those in the dry zone, have tanks or reservoirs within their upstream catchment area. We thus consider that the higher $\delta^{18}O$ and lower d-excess values of stream waters in the dry and intermediate zones result from the outflow of water from the tanks or reservoirs, which are affected by evaporative isotopic enrichment.

Particularly in the dry zone, evaporative isotopic enrichments of shallow groundwater have been reported by Song et al. (1999), Edirisinghe et al. (2014), and Edirisinghe et al. (2017b). However, groundwater and spring water samples in this study plot along the LMWL, indicating less evaporative isotopic enrichment (Fig. 5).
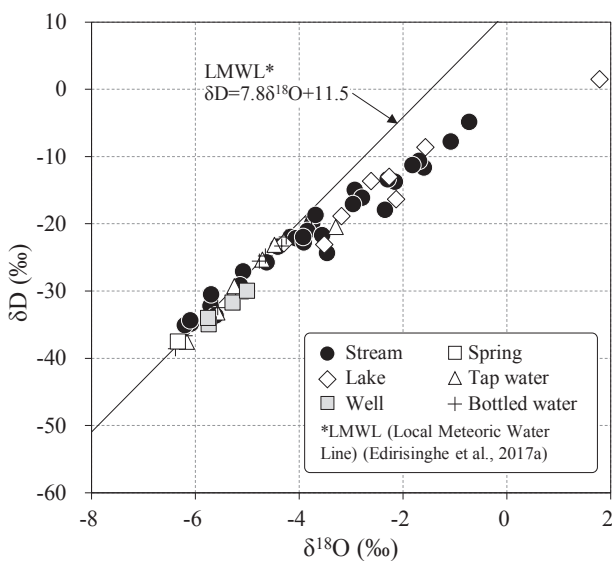

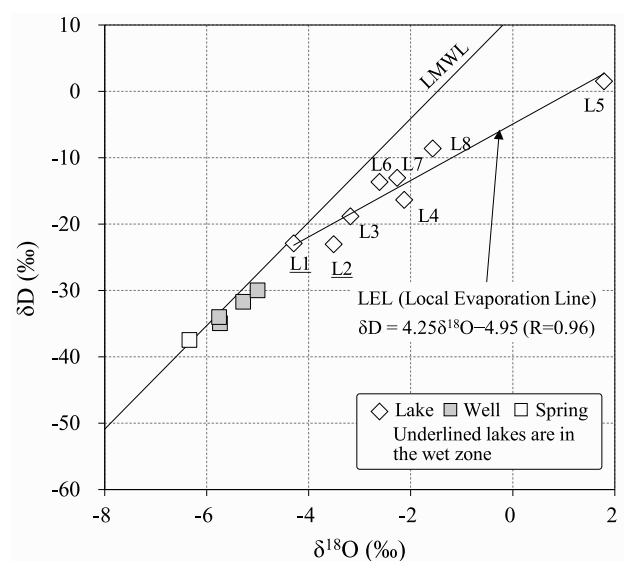**Fig. 4. Relationship between $\delta^{18}O$ and δD values of all collected waters**

Fig. 5. Relationship between $\delta^{18}O$ and δD values of lake waters and groundwaters from wells and springs

Edirisinghe et al. (2014) reported the isotopic enrichments in groundwater during the dry period due to surface water inputs. Although ponds or tanks, which may be affected by evaporation, exist near the groundwater sampling points in this study, our results indicate that the infiltration from these ponds or tanks into the groundwater was small. The tap and bottled waters plot along the LMWL, with d-excess values ranging from approximately 11 to 12, indicating a limited influence of evaporation before or during recharge processes (Table 1 and Fig. 4).

3. The altitude effect

The relationship between the altitude and the stable isotopic compositions of collected waters is shown in Figure 6. The altitudes of stream waters correspond to the mean altitudes of the catchment areas upstream of the sampling points, whereas the altitudes of other waters are the altitudes of the sampling points. The altitude effect, as will be described later, is determined on the basis of the stable isotopic compositions of stream waters. Therefore, other water samples are plotted together with stream water samples in Figure 6 for comparison with the altitude effect, despite the difference in the definition of altitude. The streams in the wet zone originate in the central highlands, and these catchment areas range in altitude from 94 to 1,081 m, whereas the altitudes of catchment areas of the streams in the dry and intermediate zones flowing through the lowlands range from 15 to 319 m. Low-altitude streams show relatively higher isotopic compositions for their altitudes as a result of evaporative enrichment as described above.

In order to determine the local altitude effect, in this study, we focused on stream waters in the wet zone (St1-St10), which show higher d-excess values and thus

are less affected by evaporative isotopic enrichment. The $\delta^{18}O$ and δD values of stream waters in the wet zone are negatively correlated with altitude ($R = 0.89$ and 0.90, respectively), defining altitude effects of $-0.21‰/100\,m$ for $\delta^{18}O$ and $-1.35‰/100\,m$ for δD (Fig. 7). Edirisinghe et al. (2017a) determined the altitude effect of $-0.6‰/100\,m$ for $\delta^{18}O$ in the dry zone on the basis of the long-term observations of stable isotopic compositions of rainwaters. This altitude effect, which has a slightly large isotopic depletion rate, differs from the altitude effect in the wet zone obtained in this study. The magnitude of the altitude effect depends on the local climate and topography; the typical altitude effect for rainwaters lie in the ranges of -0.5 to $-0.15‰/100\,m$ ($\delta^{18}O$) and -4 to $-1.5‰/100\,m$ (δD) (Yurtsever & Gat 1981). Our results are in agreement with these ranges and the global average $\delta^{18}O$ altitude effect for mid- to-low latitude mountains, $-0.28‰/100\,m$ (Poage & Chamberlain 2001).

Groundwaters from wells and spring waters have lower stable isotopic compositions than expected from their altitudes, plotting below the regression line of the altitude effect (Figs. 6 and 7). It is likely that ground and spring waters are recharged at higher altitudes than the sampling points, and these recharged areas can be estimated by the obtained altitude effect. Tap water is relatively easy to collect and can be used as a proxy for understanding the characteristics of stable isotopic compositions of rainwater (Bowen et al. 2007, Li et al. 2015), and easily available bottled water can provide a regional and national-scale dataset of stable isotopic compositions and supply information about the water sources (Bowen et al. 2005, Rangarajan & Ghosh 2011). However, the relationship between the altitude and the stable isotopic compositions of tap and bottled waters in
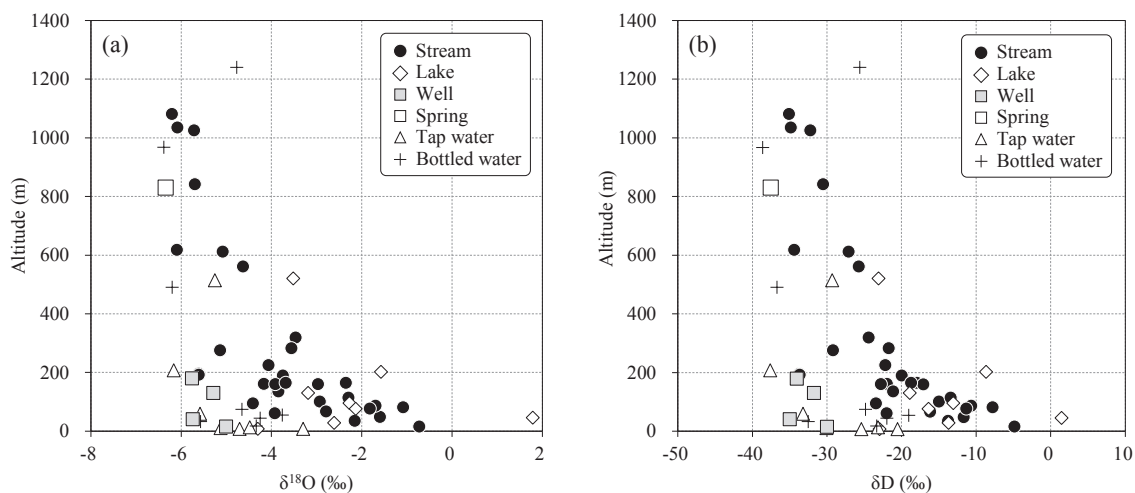

Fig. 6. Relationship between the altitude and (a) $\delta^{18}O$ and (b) δD values of all collected waters

this study is not clear (Fig. 6). It is thus difficult to directly apply tap and bottled waters to estimate the altitude effect. It is probable that the sources of these waters are at higher altitudes than the sampling points and those altitudes can be estimated using the altitude effect of stream waters.

4. Applicability of stable isotopic compositions

The stable isotopic compositions of lake waters in the dry zone were affected by evaporative isotopic enrichment. Based on a stable isotope mass balance in the lake using the Craig-Gordon model with isotopic and climatic data, the estimation of evaporative loss of a lake, which is the fraction of water lost by evaporation from the water body, has been demonstrated and verified (e.g., Gibson & Reid 2010, Tsuchihara et al. 2011, Skrzypek et al. 2015). Therefore, the stable isotopic compositions of lake waters in Sri Lanka can be used to estimate the evaporative loss from these lakes. Stream waters receiving outflow from upstream tanks or reservoirs in the dry and intermediate zones were also enriched with heavy isotopes. On the other hand, although there are a few samples, the groundwaters collected in this study were less affected by evaporative isotopic enrichment. This difference between the stable isotopic compositions of surface and groundwaters can be used to estimate groundwater discharge into a river or a lake. For instance, Rock & Mayer (2007) revealed the mixing of groundwater with river water in the Oldman River basin in Canada.

We have demonstrated the altitude effect on the basis of the stable isotopic compositions of stream waters in the wet zone. Although the major cities in the wet zone mostly rely on surface water for public water supply, groundwater contributes to river flow as a baseflow (delayed subsurface

discharge). Most of the bottled waters also originate from groundwater sources in the wet zone. The altitude effect can thus be effectively used for tracing water sources by estimating the altitude of these groundwater recharge areas. As groundwater pumping will increase with growing water demands, correct identification of groundwater recharge sources will contribute to the future wise management of groundwater resources.

Stream water in the dry and intermediate zones was affected by evaporative isotopic enrichment and is unsuitable for estimating the altitude effect. In addition, the northern part of the island, representing the majority of the dry and intermediate zones, consists of low-lying flat lands, where estimating the altitude effect may be difficult. Tap and bottled waters were not useful for estimating the altitude effect. However, the small evaporative isotopic enrichment evident in those waters suggests that they preserve information on rainwater in their recharge areas. These isotopic data will be useful in guiding future research on hydrological cycles and as a tool for traceability studies.

Concluding remarks

In this study, we presented spatial variations and isotopic fractionations of stable isotopic compositions of waters across central Sri Lanka. Our results demonstrated that the stable isotopic compositions of surface waters across the island can be an effective tool for use in hydrological and hydrogeological studies, such as tracing water sources and estimating evaporative loss. Further investigations and accumulation of isotopic data, including in areas not covered in this study, will provide
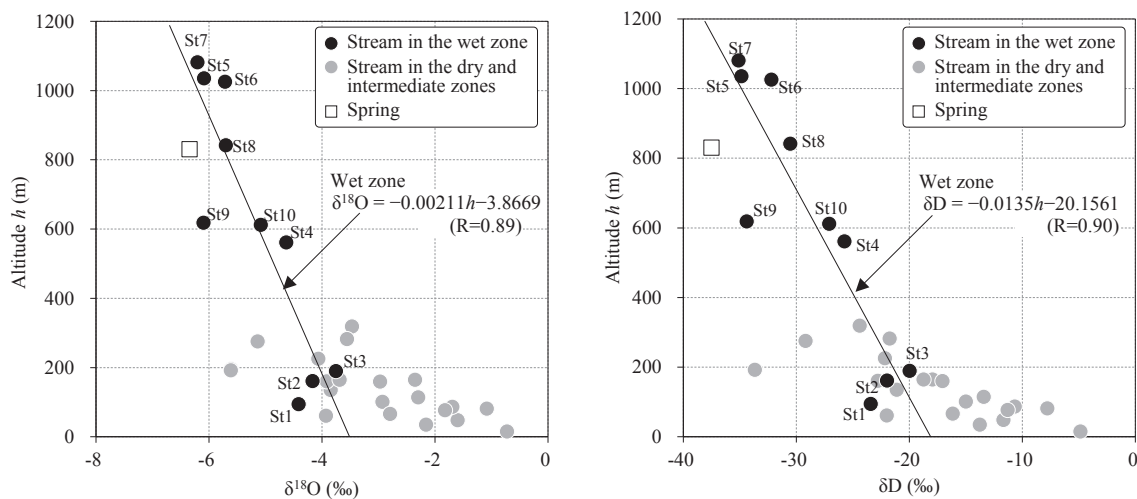

Fig. 7. Relationship between the altitude and (a) δ¹⁸O and (b) δD values of stream and spring waters

deeper insights into the hydrological cycle and contribute to the appropriate development and management of water resources in Sri Lanka.

Acknowledgements

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