Evidence of elevation effect on stable isotopes of water along highlands of a humid tropical mountain belt (Western Ghats, India) experiencing monsoonal climate

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M. Tripti[1, 2], L. Lambs[1, *], I. Moussa[1], D. Corenblit[1, 3]

[1]Ecolab, Université de Toulouse III, Paul Sabatier University, CNRS, INPT, 118 route de Narbonne, F-31062 Toulouse, France.

[2]National Centre for Earth Science Studies, Ministry of Earth Sciences, Akkulam, 695011 Thiruvananthapuram, India.

[3]Université Clermont Auvergne, CNRS, GEOLAB, F-63000 Clermont-Ferrand, France.

*Corresponding author: luc.lambs@univ-tlse3.fr

Abstract

Forest ecosystem plays a major role in controlling moisture dynamics over the continents, particularly in the humid tropics. The montane forest ecosystem in South India supports a characteristic warm tropical climate which affects the weather pattern and the monsoon system. This study focuses on better understanding of the influence of dual monsoonal rainfall on the surface water and groundwater in south-west India, and the role of the Western Ghats mountain belt in governing the water isotope characteristics (i.e., *isotopic elevation, rainfall amount and continental effects*) in the humid tropics of South India. This is achieved through a spatial study of stable isotope ratios of surface and subsurface water (oxygen, $\delta^{18}O$ and hydrogen, $\delta^{2}H$), collected from different tropical river basins located between Kozhikode (Kerala, 10° 30’ N) and Udupi (Karnataka, 13° 30’ N), in the wettest places and highest peaks of the Western Ghats between 2011 and 2014. The results on stable isotope ratios of ground water and springs show that the water from the tropical mountain belt of the Western Ghats exhibit a low elevation effect with an isotopic lapse rate of 0.09 ‰/100 m for $\delta^{18}O$ up to 2050 m asl. Beyond 2050 m asl, a considerable effect of elevation with an isotopic lapse rate of 2.5 ‰/100 m for $\delta^{18}O$ is observed. The water samples from the Nilgiri ranges (1950-2300 m asl) exhibited higher isotopic lapse rate of 1.5 ‰/100 m for $\delta^{18}O$ unlike that of the mountains (Ezhimala, Agumbe and Chembra) close to the eastern Arabian Sea. The difference in isotopic lapse rate is mainly dependent on (i) the dominating seasonality of oceanic source moisture over the subcontinent leading to higher depletion of heavy isotopes for more inland groundwater during the winter monsoon on the eastern slopes of the Western Ghats (ii) the degree of terrestrial moisture feedback mechanisms along the windward slopes of the Ghats belt (i.e., Arabian Sea coast of India) leading to relative enrichment of heavy isotopes in groundwater fed by the highly recycled vapour sources rather than depletion due to amount, elevation or continental effect, and iii) deep cooling of orographically uplifted air moisture at high elevations of inland tropical mountains. The observed isotopic elevation effect on the groundwater and surface water is unique and constrained by specific time scale and mountain ranges within the Western Ghats belt. This study provides new understanding on factors controlling hydrological budget along higher parts of the Western Ghats mountain belt in South India experiencing humid tropical climate.

Keywords

Water cycle; stable isotope; isotopic elevation (altitude) effect; tropical mountainous river, spring, groundwater, Indian monsoon; Western Ghats

1. Introduction

The rich terrestrial biodiversity in the world is harboured by the humid tropical forests, which cover about 19.6 million km^2 of Earth's surface (Pimm and Sugden, 1994). Asia has the second largest humid tropical forest area, after South America with its huge Amazon basin. The humid tropical forests are localized over the hills and mountains in Asia, particularly in the Indian subcontinent, and play a crucial role in controlling the regional moisture dynamics. About half the world population lives in this part of Asia where agriculture (mainly rice and wheat) depends on the monsoon rainfall. The disequilibrium in heating system of water and land over the Earth's surface leads to change in moisture laden wind direction which in turn supports seasonality of monsoon rainfall. During the summer monsoon season (June - September), there is a large flow of air moisture from the ocean towards land and this flow is reversed during the winter monsoon season (October – December) leading to dual monsoon system in the subcontinent. The availability of continuous flow of moisture over the humid tropical regions makes it a prominent zone of anthropogenic activities. Although anthropogenic influence has been active in tropical regions for thousands of years, the encroachment over the humid forest ecosystem has been intense in recent decades. This rapid pace of change in the humid tropical forest directly impacted the global climate (Vitousek et al., 1997). However, the seasonal climatic variability over the tropics is caused by the monsoonal precipitation which is largely influenced by the Inter-Tropical Convergence Zone (ITCZ). As the ITCZs do not remain the same throughout the year, the tropical zones experience a wet summer monsoon and a dry winter monsoon as a part of the Hadley cycle. Consequently, the tropical regions exhibit less seasonal variability in stable isotope ratios (oxygen isotope ratio, $\delta^{18}O$ and hydrogen isotope ratio, $\delta^{2}H$) of precipitation with temperature compared to other climatic regions, as the precipitation is predominantly convective in nature (Sturm et al., 2007). In addition, the small seasonal temperature variability in the tropical region results in lesser seasonal variability of $\delta^{18}O$ and $\delta^{2}H$ in precipitation (Clark and Fritz, 1997). Thus, it is necessary to determine whether the variability in precipitation over the tropics is limited to the strong seasonality of monsoon moisture source, or strongly influenced by topography and the moisture feedback mechanisms over the continent.

1.1. Motivation

The impact of land-sea thermal contrast between Indian Ocean and Tibetan Plateau has been critical for the onset and variability of Asian Summer Monsoon (Li and Yanai, 1996). The major source of Indian Summer Monsoon (ISM) is the moisture brought by south-westerly winds from northern Indian Ocean and Arabian Sea leading to rain along the west coast of India and in the central and eastern parts of the Peninsula. The winter monsoon rain derives moisture carried by the north-easterly winds moving from the Bay of Bengal, South China Sea and continental vapour sources to provide precipitation to the eastern and south-eastern parts of the Peninsular India (Mooley and Shukla, 1987). These two sources of moisture in the two monsoon seasons are known to have distinct stable isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) whose imprints are identifiable in the geographic distribution of isotopes in groundwater and surface water (Deshpande et al., 2003; Tripti et al. 2016) and rain water (Lekshmy et al 2014; Warrier et al., 2010).

A swift transition in monsoonal moisture distribution across short distances due to orography is also well documented in the south Asian region (Biasutti et al., 2012; Xie et al., 2006). In India, the two mountain ranges, i.e. the Himalayas (5000 - 8000 m asl) in the north and the Western Ghats (700 - 2500 m asl) in the south, act as critical barriers for the moisture laden winds leading to non-uniform monsoon rains over the subcontinent. In general, the orographically induced monsoon regions experience heavy rainfall on the windward side whereas a higher aridity is observed on the leeward side of the mountain ranges (Day et al., 2015). This non-uniform distribution of moisture over the continent is evident from the distinct signatures of stable isotope ratios of rain water monitored for a particular location, plateau and individual river basin in South India (Rahul et al., 2016; Resmi et al., 2016; Yadava et al 2007). The δ^2H data compiled for the precipitation and surface water over the Indian subcontinent shows homogenous signature in southern part with relatively higher isotope ratio (δ^2H > -20 ‰) than the north and northeast India due to larger influence of southwest monsoon (Hobson et al., 2012). The initial analysis on impact of climatic conditions on water budgeting and local moisture recycling in the central part of the Western Ghats through stable isotopes of rainwater, river water and groundwater have been reported in our earlier study (Tripti et al., 2016). This study is carried out to provide a spatial monitoring of water isotopes on a synoptic scale of the Western Ghats to account for the hydrological budgeting and monsoonal climate along the humid tropical high mountains.

1.2. Historical background and current status of knowledge

To understand the hydrological cycle and its controlling secondary processes in large ecologically sensitive and critical geomorphic area, there is a need to apply adapted tools and models (McDonnell and Beven, 2014). Stable isotope hydrology is based on interpretation of isotope ratio (δ^2H, δ^{18}O) and its secondary parameter (deuterium-excess, $d = \delta^2H - 8 \times \delta^{18}O$; Dansgaard, 1964) variability in precipitation which are governed by the origin of moisture and cloud processes (Kaseke et al., 2018; Stumpp et al., 2014). Following the pioneering stable isotope works in 1960s (Craig, 1961; Dansgaard, 1964; Epstein and Mayeda, 1953), there has been a significant improvement in our understanding of hydrological cycle on a global scale. Several studies have reported the main factors controlling composition of natural isotopes in precipitation, and established their huge potential for the identification of water origin and characterization of hydrological systems (Froehlich et al., 1998; Vitvar et al., 2004). Stable isotopes were used to address watershed scale analysis only later in 1970s. Stable isotope tracers have proven to be useful in addressing basic water-focused questions such as origin, flow path, mixing and residence time in the watershed (Dincer et al., 1970; Kendall and McDonnell, 1998; Sklash, 1990). These questions form the basis for understanding water availability, biogeochemical cycling, microbial production and other ecological processes (McGuire and McDonnell, 2007).

It has been well documented that the distribution of precipitation isotopes depends on the local temperature, latitude and elevation (Dansgaard, 1964; Friedman et al., 1964). For instance, in the temperate regions, isotopic variations in precipitation have been correlated with mean surface air temperatures (Aggarwal et al., 2012; Araguas-Araguas et al., 2000; Bowen, 2008; Dansgaard, 1964; Rozanski et al., 1993; Sanchez-Murillo et al., 2013) whereas in the tropics, several studies have reported the *rainfall amount effect* as the main controlling factor (Bowen and Revenaugh, 2003; Rozanski et al., 1993). These controlling parameters create an observable spatial and temporal variability in isotopic composition of water over a geographic region which is large enough to trace regional and global patterns (Bowen et al., 2009).

Further, few studies on the mountainous tropical regions (Lachniet and Patterson, 2002, 2009; Vuille et al., 2003) highlight the need for long-term monitoring networks to trace the impact of orographic effect, moisture recycling and canopy interception, intense evapotranspiration, and microclimate on the variability of isotopic composition of water. This study on the Western Ghats, India aims to bring a better understanding on this tropical mountain belt influencing the monsoonal rainfall characteristics through stable isotope investigation of surface and sub-surface water over a period of four years observation (2011-2014). In particular, this work deals with three major factors: (i) the *elevation effect*, (ii) the *rainfall amount effect* and (iii) the *continental effect*. This is discussed in detail below.

(i) The *elevation effect*: Stable isotopes of water have been a useful proxy for understanding the paleo-elevation changes of the mountains from different geographical regions (Chamberlain and Poage, 2000). Moreover, the stable isotopes of water are conservative in their mixing relationship and for explaining flow paths (McGuire and McDonnell, 2007). It is well documented that water at higher elevation is highly depleted in heavy isotopes (^{18}O and ^{2}H) because of Rayleigh distillation and orography (Poage and Chamberlain, 2001) although there are several secondary processes such as evaporation and isotope exchange with ambient vapour which can modify these isotopic signatures (Dansgaard, 1964; Siegenthaler and Oeschger, 1980). In general, the orographically uplifted cooler air mass condenses to form vapour and precipitation which are lighter (^{16}O and ^{1}H) in their isotopic composition relative to the original oceanic moisture brought by advection. Consequently, there is a relatively higher input of lighter isotopes (resulting in low $\delta^{18}O$) to groundwater and surface water at high elevations and/or on the leeward side of mountain ranges than on the lower elevations of the windward side (Gonfiantini et al., 2001).

(ii) The *rainfall amount effect*: In addition to the *elevation effect*, there is a substantial temporal and spatial variability in the stable isotope ratios of precipitation in different ecosystems due to the rainfall amount effect (Dansgaard, 1964; Garcia et al., 1998; Gat, 1996; Gonfiantini et al., 2001; Rozanski et al., 1992; Siegenthaler and Oeschger, 1980; Windhorst et al., 2013). These studies have reported that the precipitation of higher amount exhibits lower stable isotope ratio due to enrichment of lighter isotopes whereas the lower precipitation amount exhibits higher stable isotope ratio due to enrichment of heavy isotopes. However, this difference in the stable isotope ratios with precipitation amount tends to be smaller in the tropical ecosystems (Scholl et al., 2009; Tripti et al., 2016) although there is a large variability in precipitation amount. There are also studies reporting the reversed *rainfall amount effect* on the stable isotope ratios (i.e., a positive correlation of $\delta^{18}O$ and $\delta^{2}H$ with precipitation amount) of precipitation in the tropical region (Yadava et al., 2007).

(iii) The *continental effect*: This effect explains how the rainout system affects the isotopic composition of the rainfall and groundwater. The mean $\delta^{18}O$ of groundwater in both across and along the region between eastern Arabian Sea coast and the western slopes of the Western Ghats is around -3 ± 0.5 ‰, and depicts the signature of homogeneous summer monsoon moisture input rather than that from the rainout history (Deshpande et al., 2003; Tripti et al., 2016). Recently the rain out effect has been reported for the west draining river basins of the Western Ghats where it is observed that the effect is limited only to the onset of summer monsoon and before the availability of excess moisture for undergoing recycling process (Tripti et al., 2018). Several studies (Deshpande et al., 2003, Kumar et al., 1982; Negrel et al. 2011) have reported that more inland in the Deccan plateau, the contribution of the north-east monsoon is significant and the mean groundwater exhibits higher depletion of heavy isotopes with $\delta^{18}O$ varying from -4 to -6 ‰. However, in the tropical semi-arid climatic region, evaporation and post-evaporation processes have a greater impact on water isotopes. Most of the streams are ephemeral and evapotranspiration exceeds rainfall. Farmers rely on groundwater for agriculture which leads to over-pumping problems and water table decline in this region of South India.

The identification of potential influence of these three effects on stable isotope ratio of water is crucial for a better understanding of hydrological budgeting, microclimate conditions and the past climatic changes as observed from paleo-records preserved in natural archives like paleowater, tree ring, speleothem, paleosol, etc.

1.3. Objectives of this study

The present study focuses on determining the *elevation effect* on the isotopic composition of surface and sub-surface water along the Western Ghats and its adjacent plateau in South India. The aim is to account for the major factors controlling the surface and sub-surface hydrology along the higher parts of mountain belt experiencing tropical monsoonal climate using stable water isotopes as a tracer. The study involves investigation of stable isotopic composition of groundwater from the Arabian Sea coast and contrasting hydrologic and climatic regions towards inland, between latitude 10° 30’ N and 13° 30’ N, i.e. from Thrissur (Kerala) to Agumbe (Karnataka). Whenever there was no well to access groundwater, water samples were taken from spring/rivulet and pond/lake.

The three objectives of this study were to evaluate the following effects:

(i) The *elevation effect* on the stable isotope ratio of surface and sub-surface water in the humid tropical mountain belt. Water samples were collected from higher peaks of the Western Ghats in Kudremukh (1100 m asl), Charmadi Ghats (1800 m asl), Mullayanagiri peak (1930 m asl) and the Doddabetta peak in the Nilgiri range (2600 m asl), and compared with samples from lower elevations.

(ii) The *rainfall amount effect* along the tropical monsoon forest belt where there are discernible differences in the rainfall amount. The surface and sub-surface water from wetter inland places of the Western Ghats, such as Agumbe (Karnataka) and the Wayanad plateau around Sultan Bathery (Kerala) were sampled, and compared with those of coastal stations, such as Bakrabail and Kozhikode (Kerala).

(iii) The effect of terrestrial factors (*continental effect*) on the stable isotope ratios of water in the humid tropical mountain ecosystem. Water samples were collected from different hills of the Western Ghats that are very close to the Arabian Sea (within 5 km) at Ezhimala (200 m asl) up to the peaks inland within a distance of about 110 km from the sea at Doddabetta (2600 m asl).

These objectives primarily provide the structural sub-headings used in the following sections of Materials and Methods, Results and Discussion.

2. Study area and sampling sites

2.1. Study area

The Western Ghats (or the Sahyadri range) are often referred as the water tower of South Indian rivers as they form the headwaters of several major and small (in terms of length) rivers in South India (Ramachandra et al., 2016). The Western Ghats mountain belt stretches in parallel to the eastern Arabian Sea coast for about 1600 km covering an area of around 140,000 km^2 which is interrupted only by the 30 km Palghat Gap at around 11 °N latitude in Kerala, South India. This mountain belt hosts a globally significant geomorphic feature with its unique influence on the wide-scale biophysical and ecological processes over the Indian Peninsula (UNESCO, 2012). The Western Ghats provide orography required for the summer monsoon winds in its western part and acts as a climate barrier (Gunnell, 1998; Tawde and Singh., 2015) which makes the plateau arid in the eastern part due to rain shadow effect. The monsoon current strikes the west coast of Peninsula from west and south-west, meets the Western Ghats which presents an almost uninterrupted barrier ranging from 610 to 2134 m asl. The air mass moving across the Western Ghats deposits most of its moisture on the windward side of the mountain ranges, and then sweeps across the leeward side and interior of the Peninsula in the east. The orographic rainfall system leads to variability in the amount of precipitation along the mountain ranges of the Western Ghats. The higher monsoon moisture deposited over the Ghats crest results in the origin of several rivers at higher elevations and the formation of different upper watersheds on either side of the Ghats slopes (Jain et al., 2007). On the western part of the Western Ghats scarp, several indentations have been created by a large number of short, perennial, torrential west flowing rivers (e.g., Nethravati, Gurupur, Swarna, Chaliyar, Periyar, Sharavati, Kali, etc) which traverse the narrow coastal plains before discharging into the Arabian Sea through narrow outlets, creeks and estuaries (see Figure 1.a.).

Most of the larger South Indian Rivers (e.g., Godavari, Krishna and Kaveri) which flow in the east towards the Bay of Bengal have their origin in the Western Ghats. The Krishna River which is the fourth largest river in terms of basin area in India originates in the middle of the Western Ghats, near Mahabaleshwar at an elevation of about 1300 m asl. The southern basins are formed by its major tributaries, Tunga and Bhadra Rivers which originate at elevations ~1100 m asl on the leeward side of Kudremukh peak in Karnataka (see Figure 1.a.). Further south, the Kaveri (Cauvery) River originates at Talakaveri on the Brahmagiri Hills of the Kodagu district at an elevation of 1341 m asl. The river flows in a south-eastern direction for about 800 km through states like Karnataka, Kerala and Tamil Nadu, and descending the Eastern Ghats in a series of great falls (Achyuthan et al., 2010). It also hosts tributaries from the Nilgiris (Bhavani) and Annamalai (Amaravati), the two highest peaks (~ 2600 m asl) in South India. These river basins host larger tropical forest ecosystems.

The river basins of South India receive their maximum rainfall during the south-west monsoon. However, the depressions in the Bay of Bengal causing widespread heavy rains and cyclones contribute moisture to the river basins in the eastern part of the Western Ghats during the winter monsoon period. The rainfall map of South India is given in Figure 1.b., where the asymmetry induced by the Western Ghats is well represented. On the windward side, the narrow Arabian Sea coast of India exhibit annual monsoon rainfall from 2500 to 4000 mm with mostly a unimodal type (dominant summer monsoon). On the leeward side, the monsoon is of bimodal type (dual monsoon system representing summer and winter monsoons) with annual rainfall dropping rapidly from 2500 to 500 mm. The regional monthly rainfall (India Meteorological Department, Government of India) of the sampling locations during 2013 - 2014 is given in Figure 1.c. and the sampling month is marked by blue rectangle, between October and December representing the period after the summer monsoon. The annual rainfall amount and oxygen isotope ratio for selected locations is given in Figure 1.d.

2.2. Sampling sites

Earlier works (Gurumurthy et al., 2015; Lambs et al., 2011; Tripti et al., 2013, 2016, 2018) involved groundwater and river water sampling from southern Karnataka on the Arabian Sea coast within the river basins of Swarna and Nethravati and the nearby Ghats (Kudremukh and Charmadi Ghats). For the purpose of this study, we sampled mainly groundwater, springs and pond water at higher elevations on the Arabian Sea coastal side of the Western Ghats, and also groundwater and lake water at the sources of east flowing rivers with their watersheds draining the eastern part of the Western Ghats.

<Please insert here Figure 1.a.>

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<Please insert here Figure 1.c.>

<Please insert here Figure 1.d.>

< Please insert here Table 1>

Field sites have been selected for collecting representative samples to address the three major factors like elevation, rainfall amount and continental effects as described in the following sections.

2.2.1. Elevation effect

To test the elevation effect, we have sampled water from isolated peaks exhibiting elevation greater than 2000 m asl from the Nilgiri ranges (covers 2500 km^2 area and hosts 24 peaks) which include Doddabetta peak (2640 m asl) and Mukurthi peak (2550 m asl). The elevations of these isolated peaks are higher than the average typical mountain hills (600 to 1300 m asl) of the Western Ghats. Before stating of minimal isotopic *elevation effect* in the Western Ghats, there was a need for spatial sampling at the level of the highest mountain belt of the Nilgiris.

2.2.2. Rainfall amount effect

Outside the rain shadow effects of eastern side of the Western Ghats, there is strong rainfall amount variability along the west coast and at higher peaks in South India (Figures 1b and 1c). The mean annual rainfall increases from South to North, i.e., Thrissur (latitude 10° 30’ N; annual rainfall = 3000 mm) to Udupi (latitude 13° 30’ N; annual rainfall = 4500 mm) which is nearly the maximum for a coastal station (Gunnel, 1998).

To test the rainfall effect, we sampled two wettest places of the Western Ghats, in Karnataka at Agumbe with rainfall traversing through Udupi with a mean value of 5500 mm, and in Kerala, i.e., the Wayanad plateau at Vythiri with rainfall traversing through Kozhikode with a mean value of 3800 mm. These stations display similar geographic features: relatively lower elevation (600 - 800 m asl), close to the Arabian Sea (40-45 km) and surrounded by higher peaks to intercept the monsoon rainfall with an increase of 500-1000 mm/year relative to the corresponding coastal station.

2.2.3. Continental effect

To test the distance from the sea/coastline and possible *continental effect*, sampling was performed in a midland station of north Kerala at Bakrabail and in the inland mountains like Agumbe and Nilgiris during November 2013 which are located at different distances from the Arabian Sea (refer Table 1). Additional sampling was undertaken during October 2014 from locations adjacent to coast at Ezhimala hill (12°01’N, 75°12’E) and Thottada (11° 50’ N, 75° 24’E) to obtain the signatures of the direct sea moisture. This area of North Kerala is unique as it is the single place of abrupt rocky spur (286 m asl), facing directly the Arabian Sea, along the long sandy coast in southwest India which was sampled for this study.

3. Materials and Methods

The methodology followed to investigate the three research questions, i.e. isotopic *elevation effect*, *rainfall amount effect* and *continental effect,* in view to understand the hydrological cycle in the study area (geographic stretch from Agumbe to Ooty) include sampling of the available groundwater, spring and lake on a wider scale of elevation, dry and wet areas, and their distance from the Arabian Sea (here after referred as ‘distance to coastline/sea’). In this study, water sampling has been performed with the same hydrological condition under average water level condition during the end of the monsoon, from October to December depending on the location (Figure 1.c.). The main criteria of the sampled water were its isotopic composition ($\delta^{18}O$ and $\delta^{2}H$ values), and water conductivity and temperature, whenever available.

3.1. Sampling and analysis of water for Stable isotopes

About 50 water samples were collected during the winter monsoon season, soon after the withdrawal of summer monsoon, in November 2013 and October 2014 (Figure 1.c.). For the study of the *elevation effect*, thirteen water samples (groundwater, rivulet, spring and lake) were collected during November 2013 in the area of Mukurthi peak (Pykara lake) and Doddabetta peak between 1990 m to 2630 m asl. For the study of the *rainfall amount effect*, six water samples (groundwater, rivulet and pond) were collected in the area of Agumbe during November 2013 and seven (groundwater, rivulet and spring) in the area of the Wayanad plateau during October 2014. In addition, water samples (rivulet, ponds and pipe flow water from soil sub-surface layer) were collected during November 2013 in the area of Bakrabail (n = 5) and during October 2014 in the area of Ezhimala (n = 16) for the study of the *continental effect*.

The groundwater samples were collected from dug wells (or open well: OW) and hand pumps (or bore well: BW). Dug wells and hand pumps that are regularly used were chosen for sampling. In case of dug well sampling, the samples were collected by lifting the water using a polythene bucket. When dug well or hand pump were not available, water samples were taken from spring or rivulet and pond or lake, at a depth of 50 cm to avoid any surface evaporation effect. For each location, water samples in 10 ml glass vials with tight capswere collected for isotopic measurements. Water temperature (°C, only in 2013) and electrical conductivity ($\mu S\ cm^{-1}$) were determined on-site using HACH multi-parameter probes. The exact positions of the sample sites were located with a GPS. All the sampling sites are shown in Figure 1.a. and details are given in Table 1.

The samples were kept under room temperature until analysis of their stable isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) on an Isoprime 100 continuous flow isotope ratio mass spectrometer (Isoprime, Cheadle Hulme, UK) coupled with a Geo-Multiflow for water–gas equilibration

(Elementar, Hanau, Germany). The stable isotope ratios of oxygen and hydrogen are defined with δ notation and ‰ unit as suggested by Craig (1961) and redefined by Coplen (2011).

The $\delta^{18}O$ value of oxygen isotope is defined as:

$\delta^{18}O_{\text{VSMOW-SLAP}} = (((^{18}O/^{16}O)_{\text{sample}} / (^{18}O/^{16}O)_{\text{standard}}) - 1)$ ‰

For hydrogen isotope, the $\delta^{2}H$ value is defined as:

$\delta^{2}H_{\text{VSMOW-SLAP}} = (((^{2}H/^{1}H)_{\text{sample}} / (^{2}H/^{1}H)_{\text{standard}}) - 1)$ ‰

In the laboratory, 0.3 mL aliquot of water was transferred into capped 3.7 mL vial for analysis. The sample vials used for $\delta^{18}O$ measurements were flushed offline with a gas mixture of 5% CO_2 in helium. The operating vials were then left to equilibrate at 40°C for about 8 hr. The analytical precision of the measurements was ~ 0.2 ‰. In order to measure the $\delta^{2}H$ signatures of the samples, Hokko beads were added to the 3.7 mL vials containing water samples and internal standards, before the vials were flushed offline with a gas mixture of 5% H_2 in helium. The operating vials were then left to equilibrate at 40°C for about 8 hr. The measurements were made in duplicate, and the typical reproducibility was ~2.0 ‰. Four internal standards were used, namely:

W1 ($\delta^{18}O$ = –1.5 ± 0.21 ‰, $\delta^{2}H$ = -5.0 ± 2.1 ‰),

W2 ($\delta^{18}O$ = –6.2 ± 0.23 ‰, $\delta^{2}H$ = -38.0 ± 2.4 ‰),

W3 ($\delta^{18}O$ = –10.5 ± 0.25 ‰, $\delta^{2}H$ = -68.0 ± 1.7 ‰),

W4 ($\delta^{18}O$ = –15.5 ± 0.24 ‰, $\delta^{2}H$ = -110.0 ± 2.7 ‰),

They were regularly checked against international reference standards, V-SMOW and V-SLAP provided by the International Atomic Energy Agency (IAEA, Vienna).

The deuterium excess (d-excess) was calculated according to Craig's formula (Craig, 1961) as explained by Dansgaard (1964), i.e., d-excess (‰) = $\delta^{2}H$ - 8 x $\delta^{18}O$.

3.2. Air masses trajectory analysis

In order to better understand the hydrological conditions during sampling and origin of the previous rainfall, an air mass back trajectory model was used. The program for '*Hybrid Single Particle Lagrangian Integrated Trajectory Mode*l' (HYSPLIT**)** developed by National Oceanic and Atmospheric Administration (NOAA) has been run for the sampling dates of main stations. This model is run for the air masses back trajectories upto five days to check if any short term severe cyclonic event (generally the case during the winter monsoon over Indian subcontinent) has impacted the hydrological systems in the Western Ghats prior to sampling.

3.3. Statistical analysis

The simple mean, standard deviation and regression were calculated using Microsoft Excel 2016, whereas the multiple linear regression analysis was performed using Past v. 3.15. The dependent variable was the $\delta^{18}O$ values, and the independent variables were the elevation (elevation effect), the distance to coastline (*continental effect*) and the annual rainfall amount (*rainfall amount effect*).

4. Results

The physico-chemical parameters (temperature and electrical conductivity) and stable isotopic composition of water samples collected in hills and plateaus along the Western Ghats stretch are given in Table 2. The temperature of water measured onsite is reported here to understand its influence on the stable isotope ratios. It is observed that the water samples display lower oxygen isotope ratios, i.e., more negative $\delta^{18}O$ values at low temperature regions (Figure

2.a.). The relationship of measured $\delta^{18}O$ with water temperature for the study period exhibits a similar trend as observed for the global water ($d\delta^{18}O/dT = 0.66$ ‰/˚C; Dansgaard, 1964) but with a lower slope ($d\delta^{18}O/dT = 0.36$ ‰/˚C) as the monitored water samples correspond to higher temperature range (10-30 ˚C). The electrical conductivity is also provided as it forms a proxy to predict the geologic bedrock composition and the water residence time. Most of the sampled groundwater and spring water (except in the bore well, BW and lake) display low ionic content, with a mean conductivity of 39 ± 20 µS/cm (n = 33) and close to that of rainwater (~20 µS/cm). This is due to the presence of the dominant silicate rock in the basin and the abundant tropical monsoon rainfall which further leads to dilution. The highest conductivity values are measured in lakes where the water is stored for a longer time, and in bore well compared to open well with a mean value of 229 ± 126 µS/cm (n = 11). Human activity also leads to an increased conductivity as observed for the open well in the middle of the town of Sultan Bathery (231 µS/cm) and for the Ooty Lake (450 µS/cm). The high values for the coastal sampling of the river and rivulet at Thottada (up to 387 µS/cm) arise certainly from moderate saline intrusion. Thus, the conductivity of sampled water in these tropical mountainous regions varies between 20 µS/cm and 500 µS/cm depicting higher rainwater input to more water-rock interaction and anthropogenic interventions respectively. The relationship between conductivity and $\delta^{18}O$ values is shown in Figure 2.b.

<please insert here Fig 2.a.>

<please insert here Fig 2.b.>

The overall relationship of $\delta^{18}O$ versus $\delta^{2}H$ is shown in Figure 3. Most of the samples fall on the Global Meteoric Water Line (GMWL) as defined by Craig (1961). Few samples of pond and lake are located below the GMWL with deuterium excess (d-excess) values ranging from -2.1 to 5.3 ‰, showing evaporation effect on the isotope ratios of larger surface water bodies.

On the contrary, mainly at low elevation of the forested area, high d-excess suggests that the source vapour of the available water was formed from recycled moisture, with d-excess values ranging from 13.25 to 18.68 ‰. It is for the first time that such depletion in heavy isotopes of oxygen ($\delta^{18}O < -8$ ‰) in water has been observed in South India. Few rainfall samples obtained at Ooty during the nighttime in November 2013 display $\delta^{18}O$ values between -16 ‰ and -17.9 ‰ (not plotted in Figure 3).

<please insert here Fig 3.>

4.1. Elevation effect

In general, under the influence of warm tropical climate, the surface and sub-surface water temperature is close to air temperature, 26 ± 2 °C, for the low to middle elevation (<1500 m asl). But, in the Nilgiri mountains, as the elevation reaches 2000 m asl, the temperature decreases rapidly (Table 2). On the summit of the Nilgiris in the Doddabetta peak, spring water temperature of about 12 °C has been measured during November 2013, and the case of frost was reported earlier at the meteorological station on the hilltop (Negi, 1996).

The $\delta^{18}O$ values of water samples from mountainous regions between Arabian Sea coast and Western Ghats are plotted against the elevation of sampling location to identify the presence of *elevation effect* on the stable isotope ratios of water (Figure 4). Clearly, two groups of samples are observed: the first set of samples for elevation below 2050 m asl, with a low slope (-0.09 ‰/100m, $R^2 = 0.4$) and a second set beyond 2050 m asl with a higher slope (-2.5 ‰/100 m, $R^2 = 0.7$). Table 3 summarizes the reported studies on isotopic elevation effect from the pioneer works to more focus on tropical areas and Indian terrain.

<please insert here Fig 4.>

<please insert Table3>

The multiple linear regression shows that for the 51 data points reported in Table 1, the *elevation effect* is very significant ($R^2 = 0.7$, $p < 0.0001$; Table 4) to explain the $\delta^{18}O$ values.

<please insert Table 4>

4.2. Rainfall amount effect

The mean stable isotope ratios of rain water, groundwater and river water in the wettest river basins (annual rainfall amount of 5500 ± 1500 mm in Swarna and Nethravati basins) of the Western Ghats in Karnataka was reported to be around -3.05 ± 0.2 ‰ for $\delta^{18}O$ with d-excess of about 17.7 ± 3.1 ‰ (Tripti et al., 2016). Water samples of Agumbe, the wettest place in South India as well as along the spatial stretch of the Western Ghats display an average isotope ratio of about -3.14 ± 0.6 ‰ for $\delta^{18}O$ with d-excess of about 10.16 ± 4.7 ‰ (excluding pond and waterfall; Table 2). The observed stable isotope ratios of groundwater in the wet locations of the Western Ghats stretch in Karnataka show less depletion of heavy isotopes in water compared to its coastal track at Udupi and Bakrabail (rain water $\delta^{18}O$ = -2.84 ± 0.28 ‰ and d-excess = 16.5 ± 2.1 ‰; Tripti et al., 2016) which receives relatively lower annual rainfall amount of about 4000 ± 500 mm.

The isotope ratios of water samples from the Wayanad plateau, around Sultan Battery, the wettest place (annual rainfall up to 4000 mm) in Kerala, display mean values of about -3.36 ± 0.57 ‰ for $\delta^{18}O$ and 12.95 ± 5.06 ‰ for d-excess (Table 2). This isotopic ratio of groundwater is relatively lower than that of the long-term mean rainfall ($\delta^{18}O$ = -2.97 ± 0.73 ‰ and d-excess = 10.66 ± 0.72 ‰; Warrier et al., 2010) in the corresponding coastal station of Kozhikode receiving annual rainfall amount of 3000 mm. It can be observed from Figure 5 that except the near shore areas like Ezhimala and Thottada, and the inland region close to the Nilgiri range (Pykara and Doddabetta), all other water sample locations independent of their annual rainfall, present a mean $\delta^{18}O$ value similar to that of the west coast groundwater ($\delta^{18}O = -3.1 \pm 0.3$‰; Tripti et al., 2016).

The multiple linear regression shows that for the 51 points reported in Table 1, the annual rainfall parameter or *rainfall amount effect* is not significant ($R^2 = 0.4$, $p = 0.39$; Table 4) to explain the $\delta^{18}O$ values.

4.3. Continental effect

When the air masses move away from the Arabian Sea towards the inland, until the Western Ghats mountain belt, there is a significant *continental effect* on stable isotope ratios of water. The variability in mean $\delta^{18}O$ values as a function of distance to the Arabian Sea for nine sampling regions is plotted in Figure 5. Water samples located close to the sea (distance < 5 km) show $\delta^{18}O$ values of about -2 ‰ which then decreases to -3 ‰ towards the inland (i.e., 5 km < distance < 40 km) along the western part of the Western Ghats, including the sample location on the moderate elevation mountains like Agumbe and Wayanad. Only the water samples from stations located far away from the sea (distance > 100 km), like the Nilgiris, display more depleted oxygen isotopes of about -8 ‰.

<please insert here Fig 5.>

The multiple linear regression shows that for the 51 data points reported in Table 1, the distance to the sea or *continental effect* is not significant ($R^2 = 0.56$, $p = 0.18$; Table 4) to explain the $\delta^{18}O$ values.

4.4. Air masses trajectories

The results of the HYSPLIT simulations are given in Figure 6. For the stations along the Arabian Sea coast (Agumbe and Bakrabail) of mid November 2013, there is an influence of north-east monsoon with *continental effect* at low elevation, and an influence of the Arabian Sea side is observed at higher elevation. For the lower elevation stations on the Nilgiris (Ooty and Pykara) of November 19, 2013, the air masses come from the north-east monsoon, with coastal and maritime effect. For the sampling stations in Doddabetta, Madikeri, Thrissur (respectively on November 18, December 02 and December 05 during 2013) and Ezhimala (October 14, 2014), mainly it is the influence of Bay of Bengal with maritime trajectories as observed in Figure 6. Overall, the sampling was performed under north-east winter monsoon conditions, with more *continental effects* for mid-November sampling to more maritime effects for the early December sampling.

<please insert here Fig 6.>

5. Discussion

In this section, we review the main factors (*elevation*, *amount* and *continental effects*) controlling the water isotope ratios in perspective with the new results obtained for the Western Ghats mountain belt covering a latitudinal stretch of about 500 km between 10° 30' N and 14° N in South India.

5.1. Elevation effect

Most of the climatological, ecological, and geophysical studies reported the effect of elevation on stable isotope ratio of water as *altitude effect* which has been now rephrased as '*elevation effect*' (McVicar and Körner, 2013). The compilation of 68 studies by Poage and Chamberlain

(2001) reports an isotopic lapse rate ranging from -0.10 to -0.51 ‰/100 m asl on $\delta^{18}O$ values (except extreme latitudes, -0.62 to -1.83 ‰/100 m asl), with a mean value of -0.28 ± 0.03 ‰/100 m asl. In the Himalayas, the isotopic lapse rate ranges between -0.14 ‰/100 m asl on the Indian slope and up to -0.25 ‰/100 m asl on the Tibetan plateau (Poage and Chamberlain 2001). Limited studies focused on the *elevation effect* in South India. The study on groundwater isotopes by Deshpande et al. (2003) detected a possible *elevation effect* of -0.4 ‰/100 m asl for $\delta^{18}O$ in well water located at an elevation between 400 and 1000 m asl in Southwest India. But, from the recalculation of slope for the whole set of points located between Arabian Sea coast and 914 m asl, as displayed in Figure 8a of Deshpande et al. (2003), the isotopic lapse rate is only -0.11 ‰/100 m asl. Similar values (-0.12 ‰/100 m asl; Scholl et al., 2009) of isotopic depletion with elevation has been reported for the tropical coastal forest in Puerto Rico. Recent study on the precipitation across the Pamba River, Kerala suggest an isotopic lapse rate of about -0.10 ‰/100 m asl (Resmi et al., 2016). Table 3 summarizes the reported studies on isotopic elevation effect from the pioneer works to more focus on tropical areas and Indian terrain. In Sri Lanka, Edirisinghe et al. (2017) have reported the isotopic lapse rate of -0.6 ‰/100 m asl for the north-east monsoon, but no value for the south-west monsoon has been reported as there was no enough rain water collectors on the south-west of Sri Lanka.

In our previous studies (Lambs et al., 2011; Tripti et al., 2016), the sampling along the hill slopes of Kudremukh, Charmadi Ghats (1300 to 1800 m asl) and Mullayanigiri (1900 m asl; highest peak of Karnataka) did not show any isotopic *elevation effect*. The data on stable isotope ratio of water samples from this work show an isotopic lapse rate of -0.09 ‰/100 m for stations below 2050 m asl which is similar to that reported in other tropical areas (Table 3). But for the region at elevation greater than 2050 m asl in the Western Ghats belt of South India, a stronger isotopic lapse rate of about -2.5 ‰/100 m asl is found with water highly depleted in heavy isotopes of oxygen ($\delta^{18}O$ = -9.5 ‰) as recorded in high mountains of the Nilgiri ranges at Doddabetta peak. The water samples from the Nilgiri ranges (1950-2300 m asl) exhibit higher isotopic lapse rate of 1.5 ‰/100 m asl for $\delta^{18}O$ whereas the mountains close to the eastern Arabian Sea like Ezhimala, Agumbe and Chembra exhibit no such depletion in heavy isotopes of oxygen with elevation (Figure 4). This indicates that there exists a unique relationship between elevation and stable isotope ratios of surface and sub-surface water in different mountain ranges of the Western Ghats. When we recalculate the overall isotopic *elevation effect* from 0 to 2300 m asl, the overall slope value is -0.31 ‰/100 m. The overall isotopic effect observed for the water of the Western Ghats is slightly higher than the global mean isotopic lapse rate. In the humid tropical areas, the isotopic *elevation effect* on the stable isotope ratios of water is lower (around -0.10 ‰/100 m asl) due to the moisture contribution from higher air vapour recycling. But when reaching higher elevation of relatively less humid region, our study reveals that the stable isotope ratios of water are largely controlled by elevation effect in the Western Ghats mountain belt.

Until now, such depletion in heavy isotope (^{18}O) of oxygen (-9.5‰ < $\delta^{18}O$ < -7.3 ‰, present study) has not been reported for river and groundwater in the literature for South India, although the closer values are reported in few studies (Achyuthan et al., 2010; Hameed et al., 2015). Firstly, for the west flowing Chaliyar River, the lowest $\delta^{18}O$ reported is -5.30 ‰ (Hameed et al., 2015) for the water originating at the foothills of the Chembra and Mukurthi range. Secondly, lower oxygen isotope ratios ($\delta^{18}O$ = -7.7 ‰; Achyuthan et al., 2010) have been reported for the east flowing Kaveri river near Mettur Dam due to significant contribution of the tributary flowing from the Nilgiri range. Similar depleted water isotopes were observed during our sampling in November 2013, where a river in Mule hole basin display $\delta^{18}O$ = -6.7 ‰ (Lambs et al., under preparation). All these studies, with oxygen isotope ratios much lower than -4.5 ‰, indicate a possible depletion of heavy isotopes in water at higher peaks of the Western Ghats with elevation greater than 2000 m asl. For other east flowing rivers of South India originating in the Western Ghats, higher variability of stable isotope ratios has been reported, i.e., for the Maheshwaram watershed ($\delta^{18}O$ = -4.7 ‰; Negrel et al., 2011) and for the Mahanadi and Godavari rivers (respectively-6.1 ‰ and -5.5 ‰; Lambs et al., 2005) as they are largely influenced by north-east monsoon.

It can be noted that the small isotopic *elevation effect* (less than 1 ‰ on the $\delta^{18}O$ scale) observed here for the Western Ghats below 2000 m asl is similar to that reported for the cloud forest where there is a secondary control from strong water vapour recycling process (Scholl et al., 2009) with a slope of -0.12 ‰/100m as given in Table 3. On the contrary, in the same Arabian Sea coast, further North as well as in the South, higher isotopic *elevation effect* is found even below 2000 m asl in the drier regions. For instance, the stable isotope measurements carried out on groundwater in Sri Lanka (north-west and south-west slopes on the central mountains) and Rajasthan (on the south-west slope of the Aravalli mountain range) represent an isotopic lapse rate of -0.18 ‰/100 m asl (Figure 7; data from Lambs, under preparation) for the $\delta^{18}O$ values. It is also observed that these water samples display lower oxygen isotope ratios, -8 ‰ < $\delta^{18}O$ < -6 ‰ at 1400 m asl.

<please insert here Fig 7.>

It is also important to consider the possible contribution by isotopic spike effect (Lambs et al., 2018) of storm during the north-east monsoon which leads to higher depletion of heavy isotopes in precipitation water. Compared with normal tropical rainfall, the tropical storms display distinct depletion of heavy isotopes of oxygen in water. During large tropical storms, the strong convective effect generates ^{18}O - depleted rainfall with much lower oxygen isotope ratios between -12 and -8 ‰, as reported by Lawrence (1998) and more recently by Lambs et al. (2018). The water samples obtained from inland regions in the Nilgiri ranges during

November 17-19, 2013 show an impact from the isotopic spike effect of storms. There was effectively an extremely severe cyclonic storm named "Phailin" over the Bay of Bengal during October 04 - 14, 2013, but entered the Indian coast further north-east (in Orissa) of the sampling sites. At a later stage during November 13 - 17, the storm originating from a strong depression in the Bay of Bengal entered the Tamil Nadu coast, and during November 18 - 21, severe cyclone "Helen" made its entry through Andhra Pradesh in South India. The HYSPLIT simulation (Figure 6) shows effectively that the air mass over the Doddabetta peak had its original path from the Bay of Bengal more close to the Andaman Island, from where the cyclone Helen originated. However, the sampled water will not have much influence of storm from cyclone Helen as samples were collected prior to its first landfall rain over the Indian coast. The water isotope ratios for the rainfall obtained during this period in the Nilgiri range were effectively depleted in heavy isotopes with $\delta^{18}O$ of about -17 ± 0.9 ‰ (rain water in equilibrium with cooler water vapour), but the results are from only few samples (n = 2). Nevertheless, the huge water reservoir in Ooty (the Ooty lake) which covers an area of 3.9 km^2 displays depletion in heavy oxygen isotope with $\delta^{18}O$ value of about -5.3 ‰. It is noted that the water from this lake has a d-excess value of -2.1 ‰ which shows a strong evaporation of the lake water. This suggests that the original lake water exhibited more depletion of ^{18}O in water before undergoing evaporation, certainly similar to the groundwater isotope ratios ($\delta^{18}O$ = -7.3 ‰) as observed for the Ooty village. This also indicates that the storm effect was uniform over the Nilgiris and the immediate water sampling displayed a strong elevation effect in this region of the Western Ghats. Thus, it is important to note that along with the northeast monsoon influence, the earlier storms from cyclone Phailin and Bay of Bengal depression had an effective contribution towards the surface water and sub-surface water in the Nilgiris. This has led to lower water isotope ratios at higher elevations inland compared to the coastal groundwater along the eastern Arabian Sea side. The study determines that the water from the higher mountains of the Western Ghats depicts the global elevation effect soon after the strong influence of the monsoon and much before the dominance of secondary processes like evaporation and contribution of recycled vapours from evapo-transpiration. This reveals that the time scale of observation plays a major factor (Poage and Chamberlain, 2001) in monitoring the relationship between elevation and stable isotope ratios of surface and sub-surface water in the Western Ghats mountain belt.

5.2. Rainfall amount effect

The highest rainfall (21.32 mm/day; Tawde and Singh, 2015) in South India during summer monsoon season is observed over windward side of the Western Ghats mountain range in Karnataka, centered at 13° 13’ N latitude, close to Udupi. The variability in monsoonal rainfall (Figure 1.d.) with changing longitude (west-east direction) and latitude (south- north direction) i.e., across and along the Western Ghats (Gunnel, 1997) corresponds to the topographic structures of the mountain barriers and the contribution from seasonal monsoon sources. It is reported that the maximum rainfall due to orography of the Western Ghats during summer monsoon season is on an average 50 km before the highest peak and corresponds to an elevation of about 600 m asl, beyond that the rainfall decreases (Tawde and Singh, 2015). It is at this middle elevation that the wettest places are found in Karnataka (Hulikal at 13° 43’ N and Agumbe at 13° 30’ N) and in Kerala (Vythiri on the edge of the Wayanad plateau at 11° 33’ N and Walakkad in the Silent Valley at 11° 03’ N).

Tropical coastal areas are typically characterized by rain water with $\delta^{18}O$ of about -3 ± 1 ‰ (GNIP database) and the groundwater of several tropical coasts and islands reflect similar mean $\delta^{18}O$ values (Lambs et al., 2016, 2018). This is also the case for the west coast of South India, with similar groundwater stable isotope ratios at Udupi ($\delta^{18}O$ = -3.09 ± 0.05 ‰, n=34;

Tripti et al., 2016). This $\delta^{18}O$ value corresponds with the rainfall mean weighted values in the nearest GNIP station, Kozhikode ($\delta^{18}O$ = -2.97 ± 0.73 ‰; Warrier et al., 2010). Only the water from the eastern part of South India which is mainly influenced by the north-east winter monsoon and higher *continental effect* display lower isotope ratios ($\delta^{18}O$ = -6 ‰; Deshpande et al., 2003).

In this study, the mean oxygen isotope ratios of water at sampling stations of Agumbe ($\delta^{18}O$ = -2.95 ± 0.66 ‰; n = 6), Bakrabail ($\delta^{18}O$ = -3.05 ± 0.34 ‰; n = 5) and Thrissur ($\delta^{18}O$ = -3.11‰) are very similar, although these stations received contrasting annual rainfall amount from 6000 mm (Agumbe) to 3000 mm (Thrissur). Similar case is found further south between the Wayanad plateau around Sultan Bathery (mean groundwater $\delta^{18}O$ = -3.1 ± 0.5 ‰) and the relative drier coastal station at Kozhikode ($\delta^{18}O$ = -2.97 ± 0.73 ‰; Warrier et al., 2010). All these sampling stations confirm the low *rainfall amount effect* on the water isotopic ratio along the spatial stretch of the Western Ghats belt.

The study on stable isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) of groundwater, surface water and rainfall from coast to inland in south-west of Karnataka shows weaker *rainfall amount effect* on the water isotope ratios due to the influence of higher continental vapour recycling process (as represented by higher d-excess values of about 15 ‰) in the two humid tropical basins of the Western Ghats (Tripti et al., 2016). On the contrary, a reversed *rainfall amount effect* on the $\delta^{18}O$ variability was observed for the precipitation over Mangalore (Yadava et al., 2007), although they still show a weaker *rainfall amount effect* within the monsoonal months. At Kunnamangalam, 12 km inland of Kozhikode (Kerala), the study by Warrier et al. (2010) shows a poor correlation between rainfall amount and $\delta^{18}O/\delta^{2}H$ values over the three years period from 2005 to 2007. The authors stated that the region receives a continuous supply of moist air masses as the south-west monsoon currents move across extended marine regions before reaching Kozhikode. In addition, the study on the $\delta^{18}O$ variability in precipitation along the Kerala stretch suggests the influence of large-scale convection and cloud spread (Lekshmy et al., 2014) rather than the *rainfall amount effect*. Recent studies (Hameed et al., 2016; Resmi et al., 2016) on the spatial variability of stable isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) of precipitation over the Kerala region also support weaker *rainfall amount effect* and have attributed it to the steady state supply of moisture and also vapour recycling over the continent. Thus, the water in the west coast and along moderate elevations of the Western Ghats stretch in South India does not display a high correlation between the stable isotope ratios of water and precipitation amount.

5.3. Continental and seasonal effects

As stated in the previous section, precipitation (rain water) along the tropical coasts display $\delta^{18}O$ value of about -3 ± 1 ‰ (GNIP database) and represents relative depletion of heavy isotopes than that of the seawater ($\delta^{18}O$ = 0 ‰, by definition). The two GNIP stations in South India, Kozhikode and Tirunelveli (Figure 1.b.) display very similar weighted mean $\delta^{18}O$ values of about -2.97 and -2.79 ‰ respectively. In our earlier studies (Lambs et al., 2011; Tripti et al., 2013, 2016), it was reported that there is a homogeneity in the groundwater isotopic signature from coastal plain up to the moderate elevation (< 1500 m asl) of the Ghats. The mean value of $\delta^{18}O$ in water samples was around -3.15 ± 0.63 ‰, close to the GNIP rainwater $\delta^{18}O$ value (-2.97 ‰) of Kozhikode (Figure 1.b.). Only the coastal stations adjacent to the Arabian Sea, like the groundwater in the estuarine zone of the Swarna River at Hude displayed enrichment of heavy isotopes with $\delta^{18}O$ value of about -2.26 ‰ (Tripti et al., 2016).

In this study, the costal stations of Ezhimala and Thottada which receive directly the sea moisture display respectively, $\delta^{18}O$ = -1.92 ± 0.55 ‰ (n=8) and $\delta^{18}O$ = -2.31 ± 0.74 ‰

(n = 8). Further inland, the groundwater at low elevation stations show a homogenous groundwater with $\delta^{18}O$ around -3 ‰. This is clearly represented in Figure 5, where the water isotope ratios ($\delta^{18}O$) vary between -2.95 ‰ and -3.36 ‰, except for the sample stations of Ezhimala and Thottada. This represents that for the region stretching to about 500 km distance along the Western Ghats i.e., from Udupi (Karnataka) to Thrissur (Kerala), the groundwater and surface water display a similar oxygen isotope ratio ($\delta^{18}O$) of about -3.0 ± 0.5 ‰, before any evaporation. It is interesting that water homogeneity extends till 50 to 70 km inland, including moderately elevated plateaus like Agumbe, Madikeri and Wayanad of the Western Ghats. The higher moisture availability and the thick vegetation cover favour higher continental vapour recycling in this region. The higher continental moisture recycling in the western part of the Western Ghats and the uniform distribution of recycled moisture over the short distance led to homogenous signatures in the stable isotope ratios of groundwater (Tripti et al. 2016). However, there is a shift in this homogeneity further inland, extending beyond 100 km from the Arabian Sea coast, at higher elevations in the Western Ghats with groundwater exhibiting higher depletion of heavy isotopes ($\delta^{18}O$ = -7.0 ± 1.5 ‰) as observed for the Nilgiri ranges. The water in this inland region exhibited colder temperature relative to that of the coastal and moderate elevation stations in the Western Ghats. In addition, these inland stations receive relatively higher north-east monsoon precipitation than the west coast, and thus, the surface water and sub-surface water are recharged with more continental rainfall characterized by water with higher depletion of heavy isotopes.

5.4. Variability of deuterium-excess

There is a higher variability of d-excess in the surface and subsurface water of the Western Ghats with mean values ranging from + 6.5 to + 13.42 ‰. The plot (Figure 8) of d-excess as a function of distance from the coastline and elevation displays a lower increasing trend unlike that of the global water (Bershaw, 2018) associated either with source moisture mixing or sub-cloud evaporation. The calculated d-excess ranges between 3 ‰ and 20 ‰. The observed d-excess variability in this humid tropical region corresponds to that reported in the Jeju Island, Korea and northeast Asia (Lee et al., 2003). However, the d-excess variability observed in this study corresponds less to the seasonal moisture source contribution as the west coast samples which are dominated by precipitation input from hot humid tropical marine air mass from Arabian Sea exhibit higher values and a larger range of d-excess. This is mainly dependent on the degree of regional continental moisture recycling process and distribution of the recycled vapours (Tripti et al., 2016) influencing the incoming marine source moisture along the eastern Arabian Sea coast of India.

<please insert here Fig. 8>

5.5. Statistical analysis

Multiple linear regression analysis was carried out for determining the extent to which the *elevation effect*, *continental effect* and *rainfall amount effect* influence the $\delta^{18}O$ values. When running the statistical test for the whole set of points (n = 51), the *elevation effect* appears to be the most significant explicative parameter, and the influence of two other effects remain insignificant. If we split the dataset into two groups, like in Figure 4, for the first 42 points with elevation lower than 2050 m asl (Table 4), there is neither a strong nor a significant contribution from one specific parameter. It is a global contribution which enables observation of the $\delta^{18}O$ values to decrease from -2 ‰ along the eastern coast of Arabian Sea to -4.0‰ more inland at 1800 m asl in the Western Ghats. For the last 9 points, i.e. above 2050 m asl, the *elevation effect* and the *rainfall amount effect* become significant ($R^2 = 0.77$, p

< 0.1 and $R^2 = 0.81$, $p < 0.05$ respectively) in controlling stable isotope ratios of water at high elevation of the Western Ghats. This suggests that for the tropical mountains of high elevation and with less relative humidity, the lower isotopic ratios of surface water and sub-surface water were characteristics of deep cooling due to high orographic upliftment of seasonal air moisture, severe storm effect and higher annual rainfall input.

5.6. Implications of stable isotopes of water in the Western Ghats mountain belt

This study and the earlier reported work (Lambs et al., 2011; Tripti et al., 2013, 2016) suggest that in the tropical monsoon climate region of the Western Ghats, the high water vapour recycling is due to higher precipitation, warmer temperature, wetlands and large vegetation cover (around 40% of forest). The higher moisture input (~ 2000 mm < annual precipitation < 6000 mm; Figure 1.b.) from the nearby oceanic source coupled with suitable temperature (i.e., ~ 20 < t < 30° C) and land-use/land cover (i.e., vegetation) in the continent supports high relative air humidity (75-100 %) which triggers higher vapour recycling (Breitenbach et al., 2010) in this region. This indicates the dominance of terrestrial moisture recycling process over the Western Ghats rather than the Rayleigh distillation process of moisture from oceanic source. This is reflected by the higher stable isotope ratios of water over the continent leading to less depletion of heavy isotopes (~ $\delta^{18}O$ = -3 ‰) and higher d-excess values (~15 ‰) for the wetter regions of west coast. However, the effect of vapour recycling on the isotopic signature of incoming moisture becomes less dominant in the region where the moisture input is relatively minimal (~ annual precipitation < 2000 mm) from the summer monsoon mainly due to the rain shadow effect. However, these inland regions exhibit relatively cooler temperature (i.e., T < 20 °C) due to high air lifting and contribution from north-east monsoon. There is a higher reflection of original moisture source and the mixing process on the stable isotope ratios of water in such semi-arid tropical regions. Thus, a clear indication of Rayleigh distillation or *elevation effect* is observed on the isotopic signatures of moisture which in turn leads to more depletion of heavy isotopes (~ $\delta^{18}O < -6‰$) in water present in inland regions. This shows that the continental vapour recycling process and their role in controlling moisture flux (Froehlich et al., 2002; Risi et al., 2013; Sturm et al., 2007) are important factors even in the humid coastal regions receiving higher precipitation. Although there could be several factors that control the moisture isotopic signatures and their subsequent reflection in the groundwater and surface water, this study shows that temperature coupled with higher seasonal moisture input (mainly precipitation amount) and vegetation cover play a significant role in governing the stable isotope ratios of water over the regional scale and the subsequent water cycle over the highlands of the Western Ghats mountain belt in India. Also, it is important to note that the stable isotopes of water show homogenous signature up to moderate elevation (i.e., 2000 m asl) for the humid tropical mountains, and the isotopic *elevation effect* is observed only in the mountains of elevation greater than 2000 m asl of the Western Ghats. The findings of this study are significant as it has implications on the studies involving past climate and paleoelevation of the tropical mountain belt using records preserved in paleoarchives. This will help in improving the understanding of isotopic signatures of paleowater, tree ring, speleothem and other geological records found in South India. With less GNIP observations stationed in South India, the present study (though the observation is mainly from surface and subsurface water) adds to the global database, as it provides the new evidence on the isotopic *elevation effect* along the highlands of tropical mountain rainforest ecosystem of India. This also has larger implications on the hydrological and Indian monsoonal climatic systems, and further helps in the sustainable water resource management of South India.

6. Conclusions

Humid tropical mountains display a lower isotopic *elevation effect* due to limited temperature gradient, high relative humidity, evergreen forest evapotranspiration and high water vapour recycling. The Western Ghats mountain belt of South India has similar characteristics, and as such the stable isotope ratios of rainfall and water bodies exhibits lower variability with elevation up to 2000 m asl with a mean oxygen isotope ratio ($\delta^{18}O$) of about -2.5 ± 0.5 ‰ and a limited seasonal effect (maximum difference in mean $\delta^{18}O$ between seasons is ± 0.5 ‰ for larger river basins and ± 0.2 ‰ for smaller basins). The homogeneity in the ground water isotope ratio along the western coastal plain from Udupi to Thrissur in South India is explained by the wide-scale marine moisture distribution from the dominant south-west summer monsoon system. The moisture characteristics on the foothills of the Western Ghats are more affected by the water vapour recycling as observed from the higher d-excess (around 15 ‰), particularly in the vegetation covered and wetland regions.

The present study reveals for the first time that beyond 2000 m asl in the Western Ghats, such as in the Nilgiri ranges, the surface and subsurface water exhibit relatively lower stable isotope ratios with $\delta^{18}O$ values ranging from -5.3 ‰ for the lake to -9.5 ‰ for the springs and open wells of hills at higher elevation. This reflects a very strong isotopic *elevation effect* (1.8 ‰/100 m for $\delta^{18}O$) for the water from the Western Ghats mountain belt between 2000 and 2600 m asl where the cold air temperature (i.e., 10 - 20 ˚C) prevails. The water contribution from the recycled vapours masks the strong effect of elevation, rainfall amount and continental effect on water isotope ratios under the following conditions: i) when there is an increased availability of terrestrial moisture to undergo secondary processes like recycling and evaporation, and ii) after the vapours from short severe storm effect recedes. As the Western Ghats mountain belt forms the source of major South Indian Rivers and provides a platform for the dual monsoon system observation, this study has a global implication with a new understanding on the dynamic role of tropical mountains in monitoring the humid climatic system, the Indian monsoon and regional hydrology of South India. The monsoon arrival and its interannual variability affect numerous people living in these fertile mountain ranges, and in the context of global climate change, emphasize the sensitive response of these tropical mountains to anthropogenic influences. Thus, a minor change in the land use/land cover (such as deforestation, agricultural activities and urbanization) and topography of the Western Ghats can have a significant impact on the degree of atmospheric moisture feedback mechanisms and is directly reflected by the climatic conditions of tropical monsoon forest ecosystem in India.

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In Memoriam

We dedicate this work to our esteemed colleague, Dr. C. Unnikrishnan Warrier, former Head of Isotope Hydrology Divison, Centre for Water Resources Development and Management, Kozhikode, Kerala. He passed away untimely in a tragic road accident during October 2017. He initiated the monitoring of rainfall for isotopic composition in 2004 at Kunnamangalam, Kozhikode the data which was subsequently included in the GNIP-data base.

We also dedicate our work to Dr. R. Ramesh, Professor (rtd.), Geosciences Division, Physical Research Laboratory, Ahmedabad and National Institute of Science Education and Research, Bhubaneswar. He passed away during April 2018. He was one of the meritorious researchers in India in implementing stable isotope techniques to address multidisciplinary questions in the field of Earth Sciences.

Their contributions in the field of stable isotopes provide strong base for future research.

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List of Tables

Table 1: Sampling places during November / December 2013 and October 2014 with location, elevation range, distance to the Arabian Sea coast, number of samples (n) and date.

Table 2: Physicochemical parameters, elevation, stable water isotope ratio ($\delta^{18}O$ and $\delta^{2}H$) and calculated d-excess for the November/December 2013 and October 2014 samples. Note that GW is for groundwater, OW for open well, BW for bore well and sd is for standard deviation.

Table 3: Summary of relevant studies on the isotopic elevation effect.

Table 4: Multiple Linear Regression results as obtained from the Past program version 3.15. The dependent variable was oxygen isotope ratio ($\delta^{18}O$) and the independent variables were the elevation above mean sea level (elevation effect), the distance from the coast (Rayleigh distillation and continental effect) and the annual rainfall amount (amount effect).

List of Figures

Fig. 1.a.: Hydrographic map of Southwest India showing different river basins (written in blue) from North to South, of the Krishna river (Tunga, Badra and Vedavati), of the Cauvery river (Cauvery itself, Kabini, Moyar and Bhavani) and the main coastal rivers (Swarna, Nethravati and Chaliyar). The river basin boundary is represented as black line and the white dashed lines correspond to state borders. The higher peaks of the Western Ghats are localised in white (Mullayanagiri 1930 m, Kudremukh and Charmadi 1800 m, Tadiandamol 1850 m, Chembra 2100 m and Doddabetta 2600 m; above mean sea level). The sampling sites for the present study during November 2013 and October 2014 are underlined in black (details in Table 1), and the sites previously sampled in dashed line. The different type of sampled water is given by the following symbol: rainfall samples as triangle, stream, rivulet and spring as circle, groundwater as square, lake and ponds by plus.

Fig. 1.b.: Rainfall map of South India showing higher amount along the west coast, parallel to the eastern Arabian Sea due to the orographic barrier effect of the Western Ghats for the major southwest monsoonal moisture and the drier leeward eastern slopes (Map adapted from C. Sudhakar Reddy et al. 2015). The study area corresponding with Fig. 1.a. is given by the black frame. The location name in white corresponds to the available GNIP (Global Network of Isotopes in Precipitation) station except for Bakrabail (2013 samples; this study) with values in brackets corresponding to the weighted mean $\delta^{18}O$ values. Note: Belgaum in North Karnataka, elevation 747 m asl, average annual rainfall 1200 mm, temperature 24.4 °C. Bangalore, in East of Karnataka, elevation 897 m asl, annual rainfall 850 mm, temperature 24.1°C. Kozhikode (Kunnamangalam) in North Kerala, elevation 20 m asl, annual rainfall 3050 mm, temperature 27.9°C. Tirunelveli in Tamil Nadu, elevation 4 m asl, annual rainfall 750 mm, temperature 29.1°C.

Fig. 1.c.: Monthly rainfall (India Meteorological Department, Government of India) during 2013 and 2014 in coastal districts (include regions stretching between west coast to highlands in the western slopes of Western Ghats) like Udupi/Dakshin Kannada (for stations Agumbe and Bakrabail), Kasaragod/Kannur (Ezhimala, Thottada), Kozhikode and Thrissur receiving mainly the summer monsoon during June – September, and the inland districts (include regions from the Ghats top to eastern foothills of the Western Ghats) like Shivamogga (eastern part of Agumbe), Kodagu (Madikeri), Wayanad (Gudalur, Sultan Bathery) and Nilgiris (Ooty, Pykara) receiving additional winter monsoon during October-December. The sampling period is given by the navy blue rectangles. The x-axis represents the months from January to December and the y-axis represents the monthly rainfall amount (mm) data. Annual rainfall (mm) of corresponding sampling year is given in legend.

Fig. 1.d.: Rainfall variability (rainfall amount data from www.worldweatheronline.com and corresponding station spring/groundwater isotope ratio from our study) along the west coast and inland regions adjacent to the Western Ghats, South India.

Fig. 2.a.: Relationship between water temperature and oxygen isotope ratio ($\delta^{18}O$) for the November 2013 samples.

Fig. 2.b.: Relationship between conductivity and oxygen isotope ratio ($\delta^{18}O$) for the November/December 2013 water samples (Agumbe, Bakrabail, Pykara, Doddabetta, Sultan Bathery and Thrissur) and the October 2014 water samples (Ezhimala and Thottada).

Fig. 3: Relationship between oxygen isotope ratio ($\delta^{18}O$) and hydrogen isotope ratio ($\delta^{2}H$) for the water samples of November/December 2013 and October 2014. The solid blue line

represents the Global Meteoric Water Line ($\delta^2H = (8 \times \delta^{18}O) + 10$; Craig, 1961). The sampling sites are given from the Northern location i.e. Agumbe (13° 30'N) to the Southern location i.e. Thrissur (10° 30'N). All these locations are marked in Figure 1.a. Pykara and Ooty samples correspond to the sampling in the Nilgiri range with elevation around 2000 m asl.

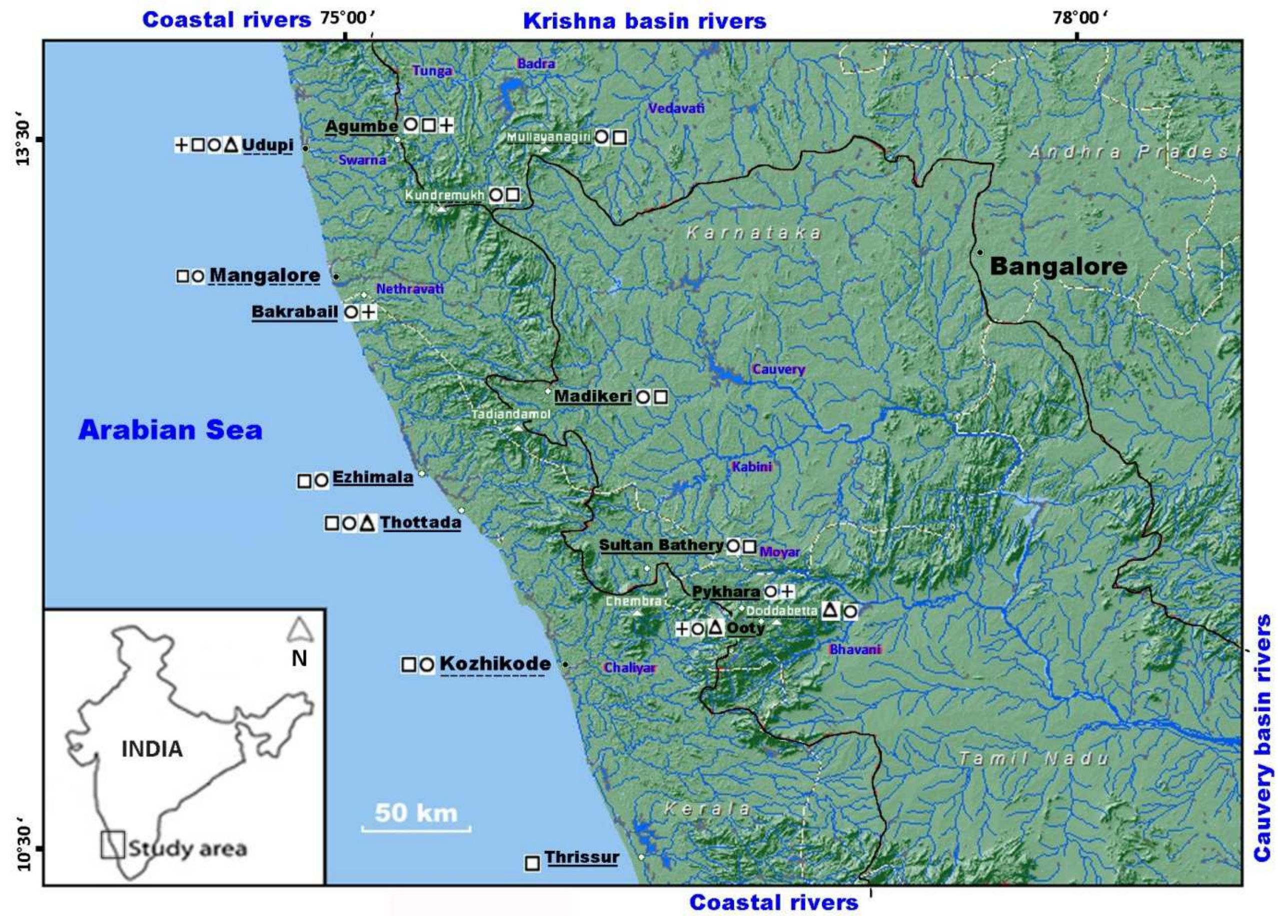
Fig. 4: Relationship between elevation and oxygen isotope ratio ($\delta^{18}O$) along the mountain belt of the Western Ghats. The first regression line in green colour is for the stations below 2050 m asl and the second line in blue is for the stations beyond 2050 m asl in the Nilgiri ranges. The overall slope of 0.31 ‰/100 m for the isotope ratios of water from the west coast to the highest elevation (sampled here at 2300 m asl) of the Western Ghats is given in red to compare with the reported global isotopic lapse rate (0.28 ‰/100 m; Poage and Chamberlain, 2001). Note the data for Mullyanagiri - Charmadi Ghat (Lambs et al. 2011) and Kudremukh (Tripti et al. 2016) are from published work.

Fig. 5: The variability of oxygen isotope ratio ($\delta^{18}O$) for nine major sampling locations as a function of their distance to the Arabian Sea coast. The grey box corresponds to the mean oxygen isotope ratio ($\delta^{18}O = -3.1 \pm 0.3$‰; Tripti et al. 2016) of groundwater in southwest coast of India.

Fig. 6: Results from NOAA Hysplit simulations for the eight main sampling stations with air masses back trajectory up to 5 days.

Fig. 7: Plot showing relationship between elevation and oxygen isotope ratio ($\delta^{18}O$) for groundwater in Sri Lanka (July 2012) and Rajasthan (December 2011 and November 2014), India (data from Lambs, under preparation).

Fig. 8: The variability of deuterium-excess in the sampled water (lake, pond and bore well samples are not included to avoid any effect from evaporation) along the Western Ghats and its adjacent slopes during this study. Note that water from the mountains close to the west coast of India exhibit higher d-excess range between 3 ‰ and 20 ‰ whereas lower variability is observed in inland region corresponding to highest elevations in the Western Ghats monitored during this study.



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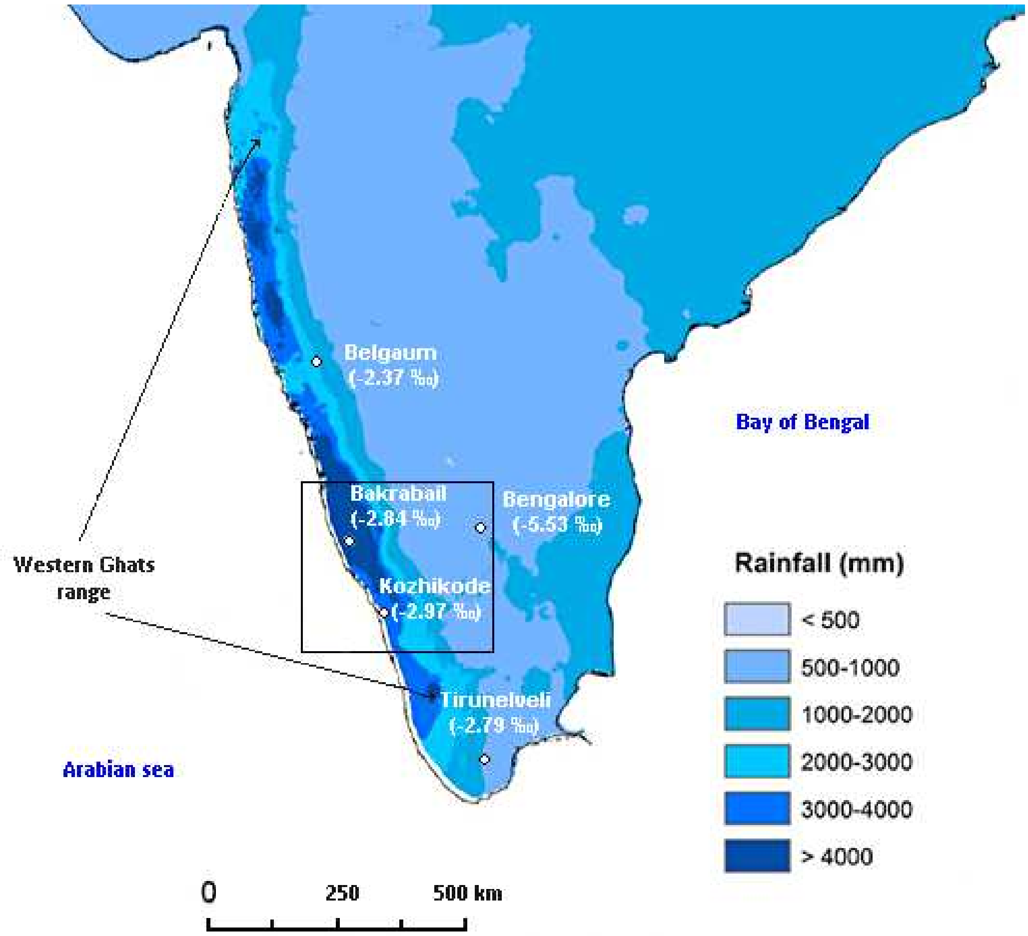

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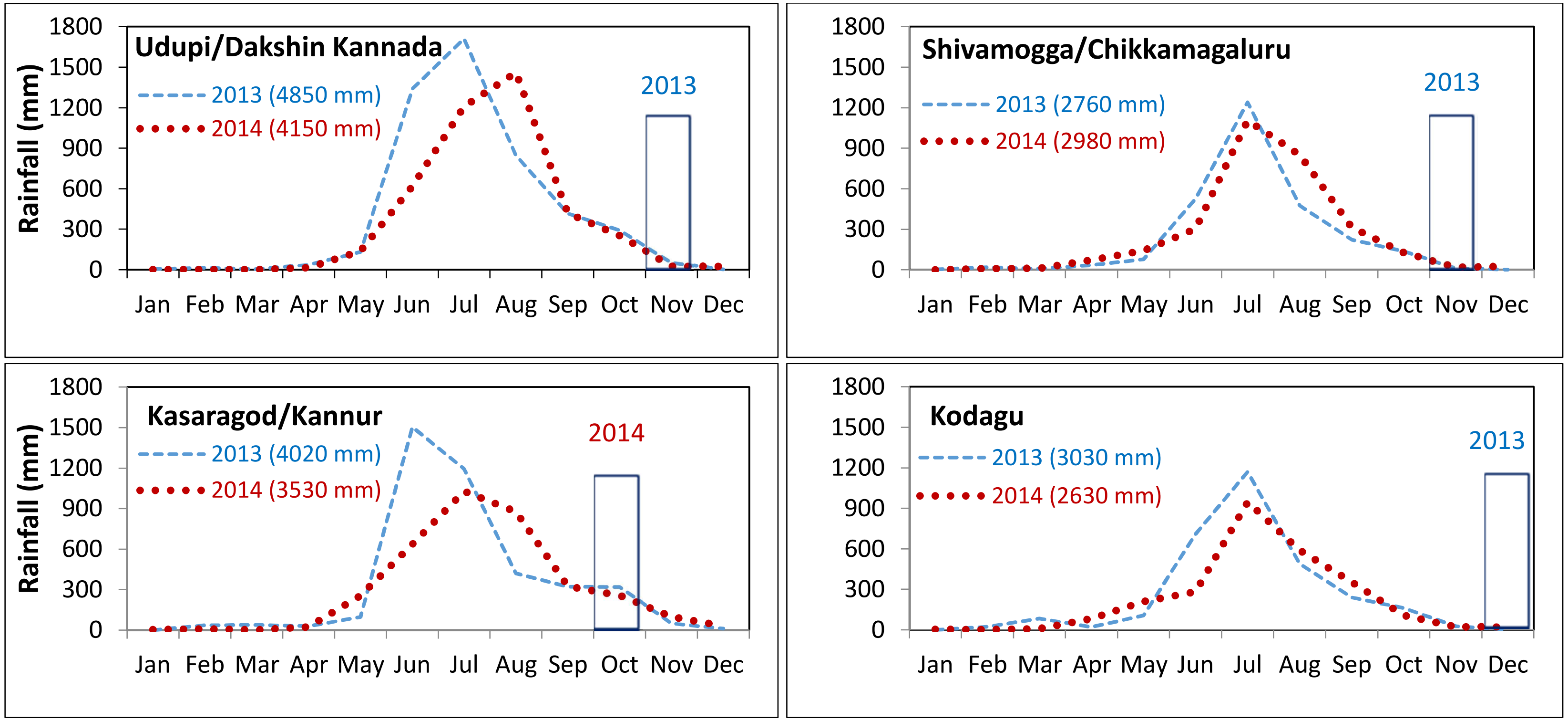

Udupi/Dakshin Kannada
2013 (4850 mm)
2014 (4150 mm)
2013
Shivamogga/Chikkamagaluru
2013 (2760 mm)
2014 (2980 mm)
2013
Kasaragod/Kannur
2013 (4020 mm)
2014 (3530 mm)
2014
Kodagu
2013 (3030 mm)
2014 (2630 mm)
2013
Rainfall (mm)
1800 1500 1200 900 600 300 0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

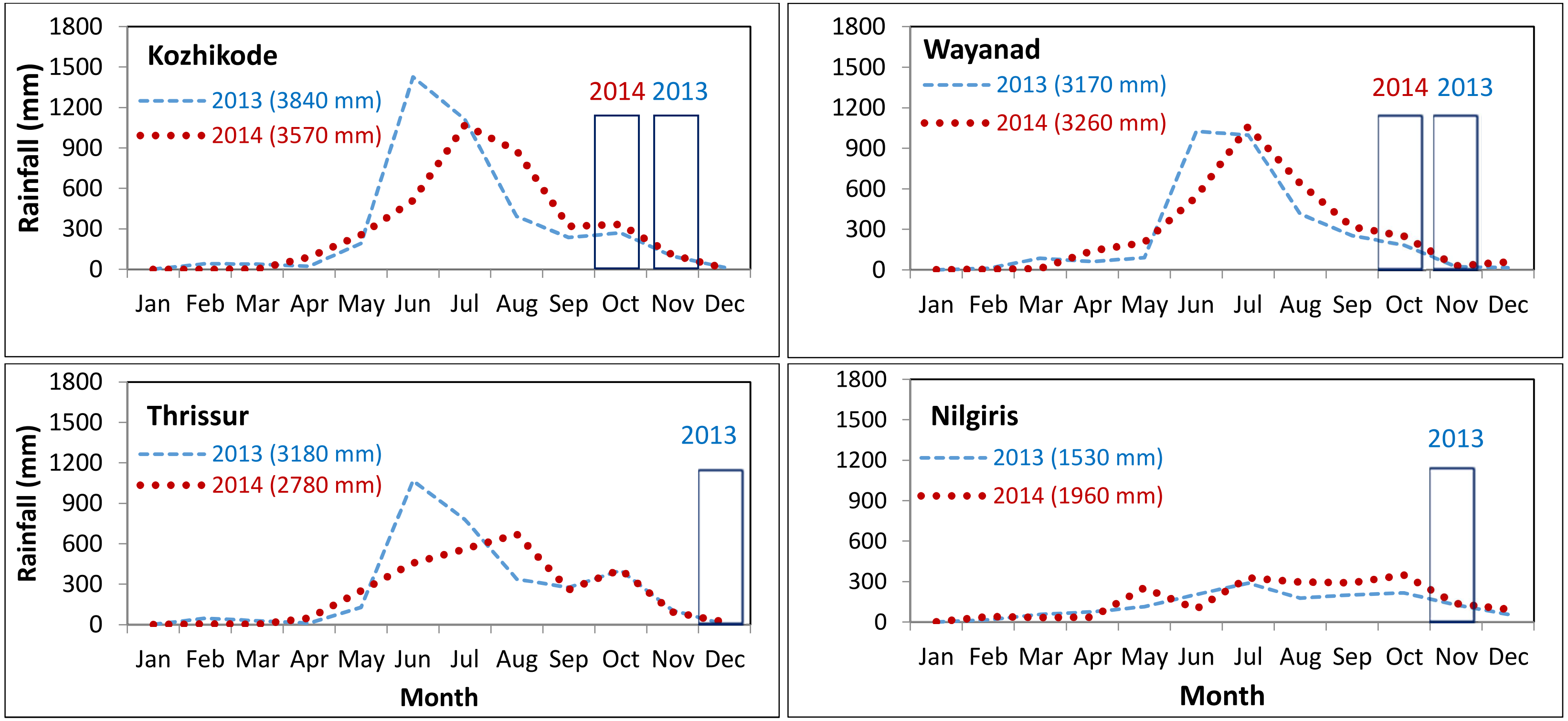


Fig. 1.c.: Monthly rainfall (India Meteorological Department, Government of India) during 2013 and 2014 in coastal districts (include regions stretching between west coast to highlands in the western slopes of Western Ghats) like Udupi/Dakshin Kannada (for stations Agumbe and Bakrabail), Kasaragod/Kannur (Ezhimala, Thottada), Kozhikode and Thrissur receiving mainly the summer monsoon during June – September, and the inland districts (include regions from the Ghats top to eastern foothills of the Western Ghats) like Shivamogga (eastern part of Agumbe), Kodagu (Madikeri), Wayanad (Gudalur, Sultan Bathery) and Nilgiris (Ooty, Pykara) receiving additional winter monsoon during October-December. The sampling period is given by the navy blue rectangles. The x-axis represents the months from January to December and the y-axis represents the monthly rainfall amount (mm) data. Annual rainfall (mm) of corresponding sampling year is given in legend.

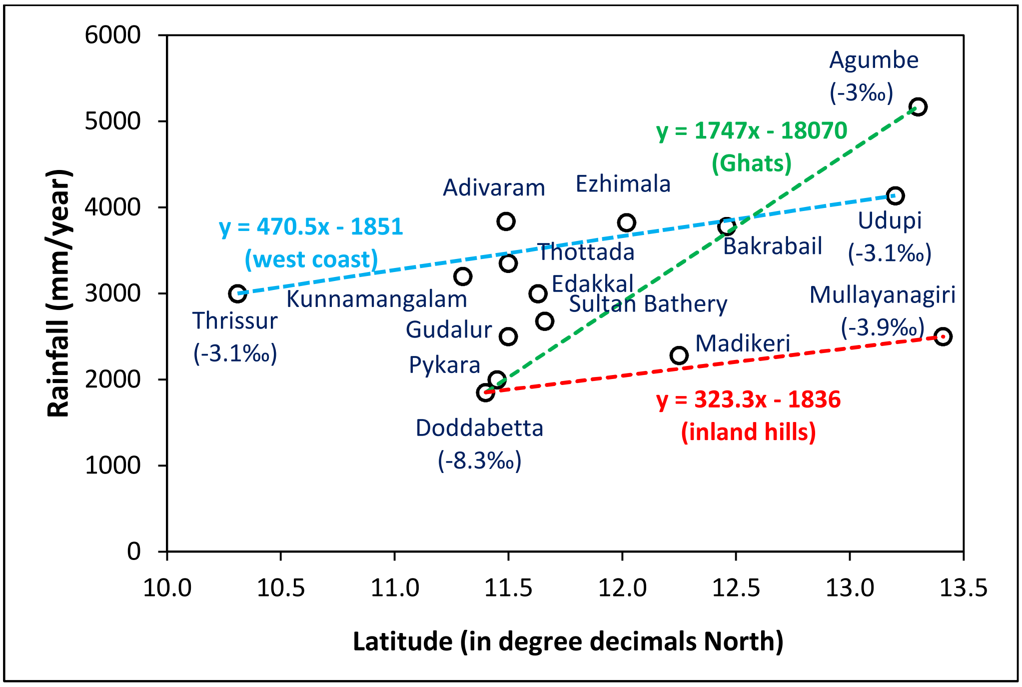


Fig. 1.d.: Rainfall variability (rainfall amount data from www.worldweatheronline.com and corresponding station spring/groundwater isotope ratio from our study) along the west coast and inland regions adjacent to the Western Ghats, South India.

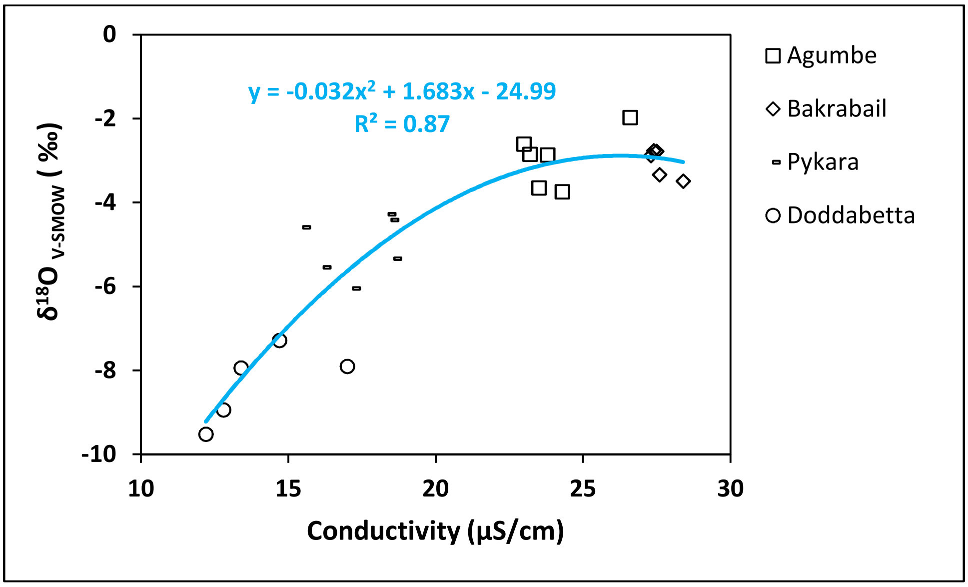


Fig. 2.a.: Relationship between water temperature and oxygen isotope ratio ($\delta^{18}O$) for the November 2013 samples.

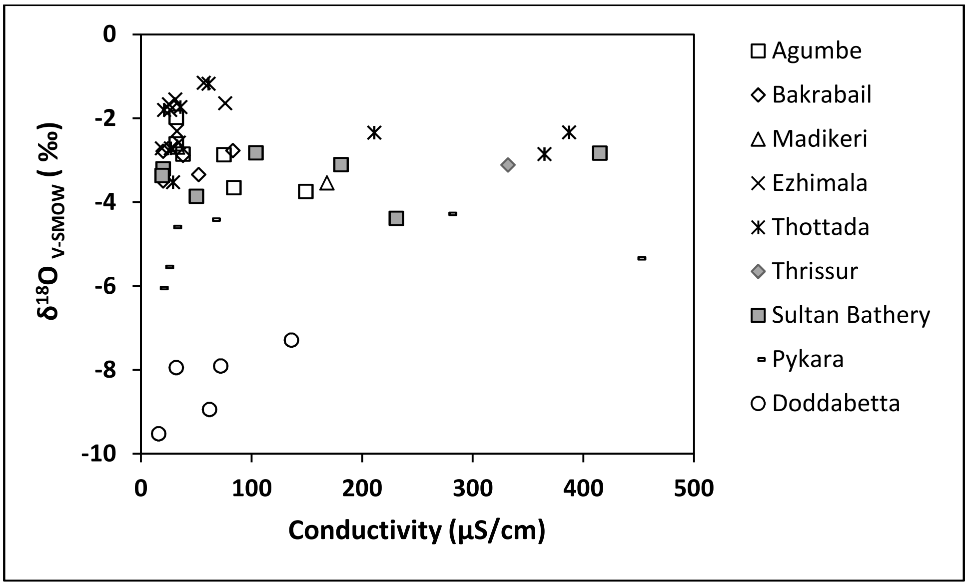


Fig. 2.b.: Relationship between conductivity and oxygen isotope ratio ($\delta^{18}O$) for the November/December 2013 water samples (Agumbe, Bakrabail, Pykara, Doddabetta, Sultan Bathery and Thrissur) and the October 2014 water samples (Ezhimala and Thottada).

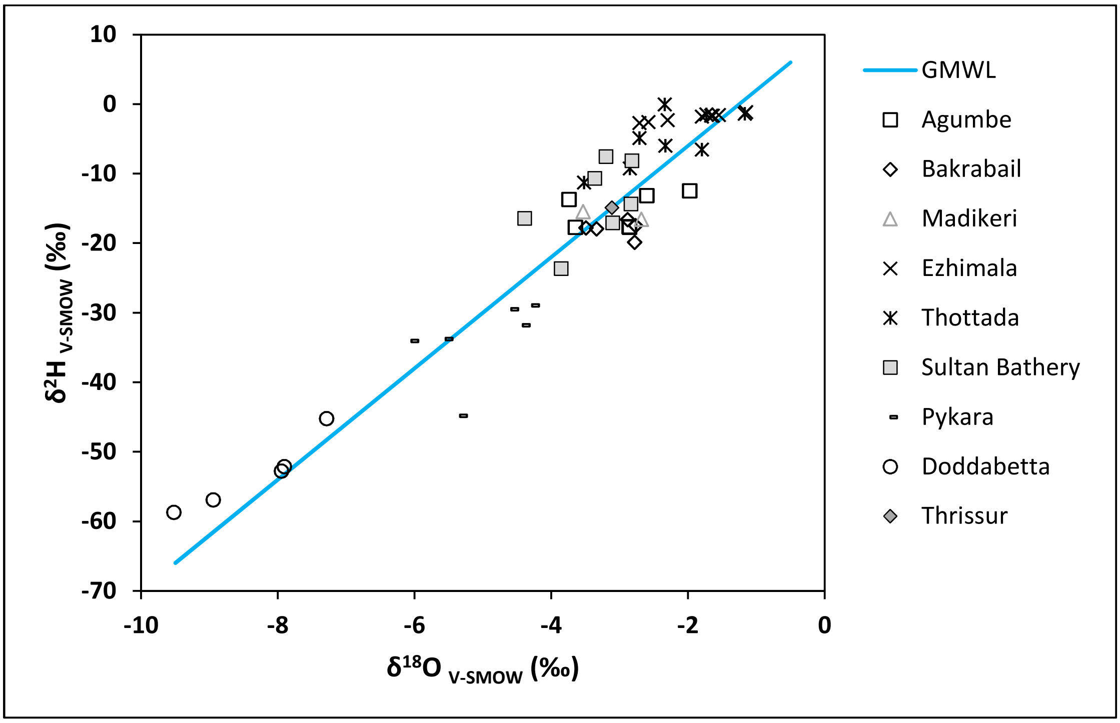


Fig. 3: Relationship between oxygen isotope ratio ($\delta^{18}O$) and hydrogen isotope ratio ($\delta^{2}H$) for the water samples of November/December 2013 and October 2014. The solid blue line represents the Global Meteoric Water Line ($\delta^{2}H = (8 \times \delta^{18}O) + 10$; Craig, 1961). The sampling sites are given from the Northern location i.e. Agumbe (13° 30’N) to the Southern location i.e. Thrissur (10° 30’N). All these locations are marked in Figure 1.a. Pykara and Ooty samples correspond to the sampling in the Nilgiri range with elevation around 2000 m asl.

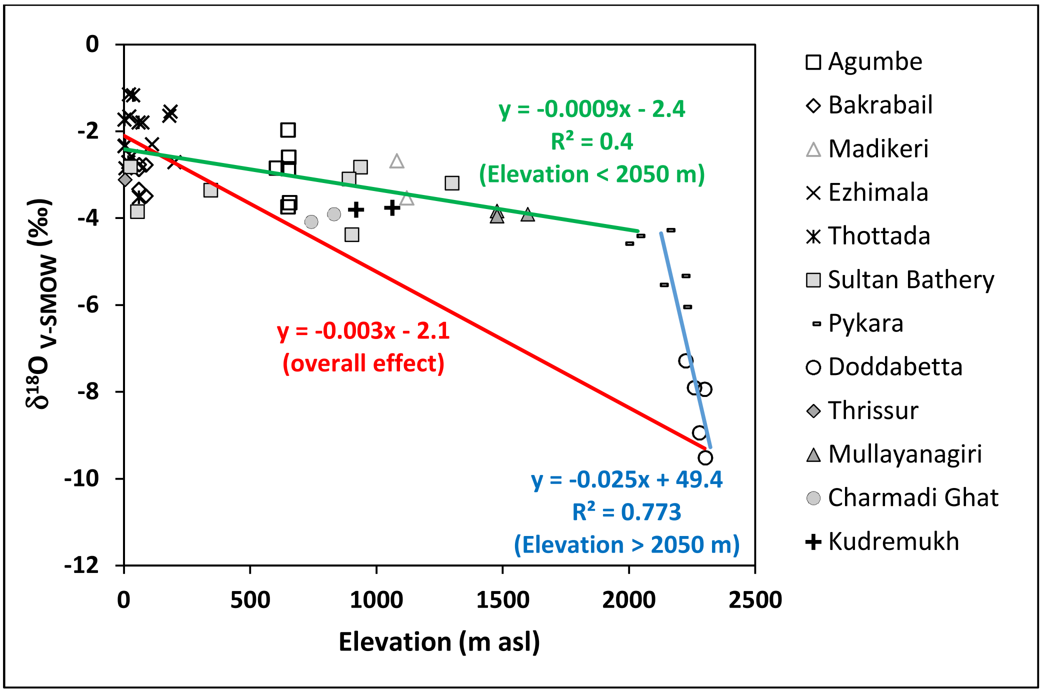


Fig. 4: Relationship between elevation and oxygen isotope ratio ($\delta^{18}O$) along the mountain belt of the Western Ghats. The first regression line in green colour is for the stations below 2050 m asl and the second line in blue is for the stations beyond 2050 m asl in the Nilgiri ranges. The overall slope of 0.31 ‰/100 m for the isotope ratios of water from the west coast to the highest elevation (sampled here at 2300 m asl) of the Western Ghats is given in red to compare with the reported global isotopic lapse rate (0.28 ‰/100 m; Poage and Chamberlain, 2001). Note the data for Mullyanagiri - Charmadi Ghat (Lambs et al. 2011) and Kudremukh (Tripti et al. 2016) are from published work.

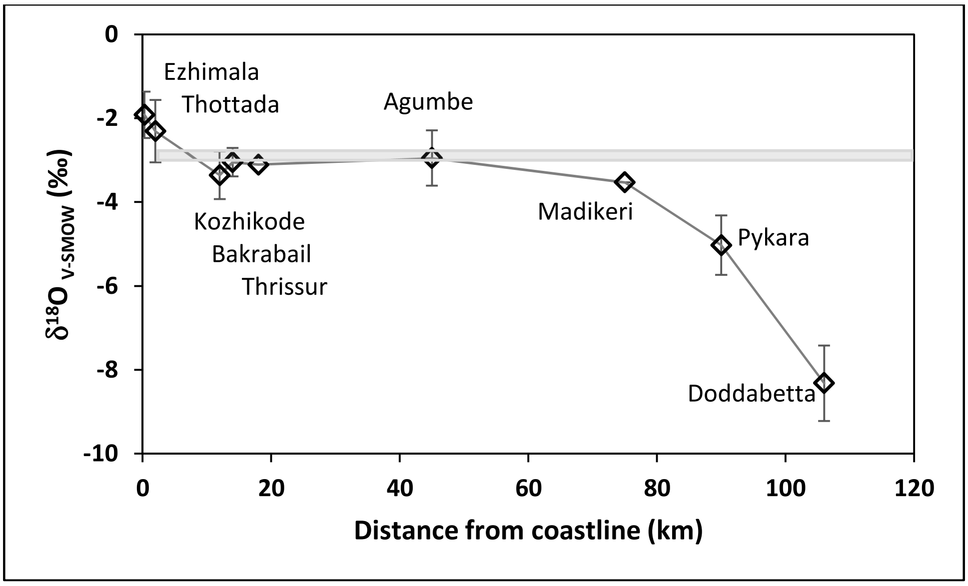
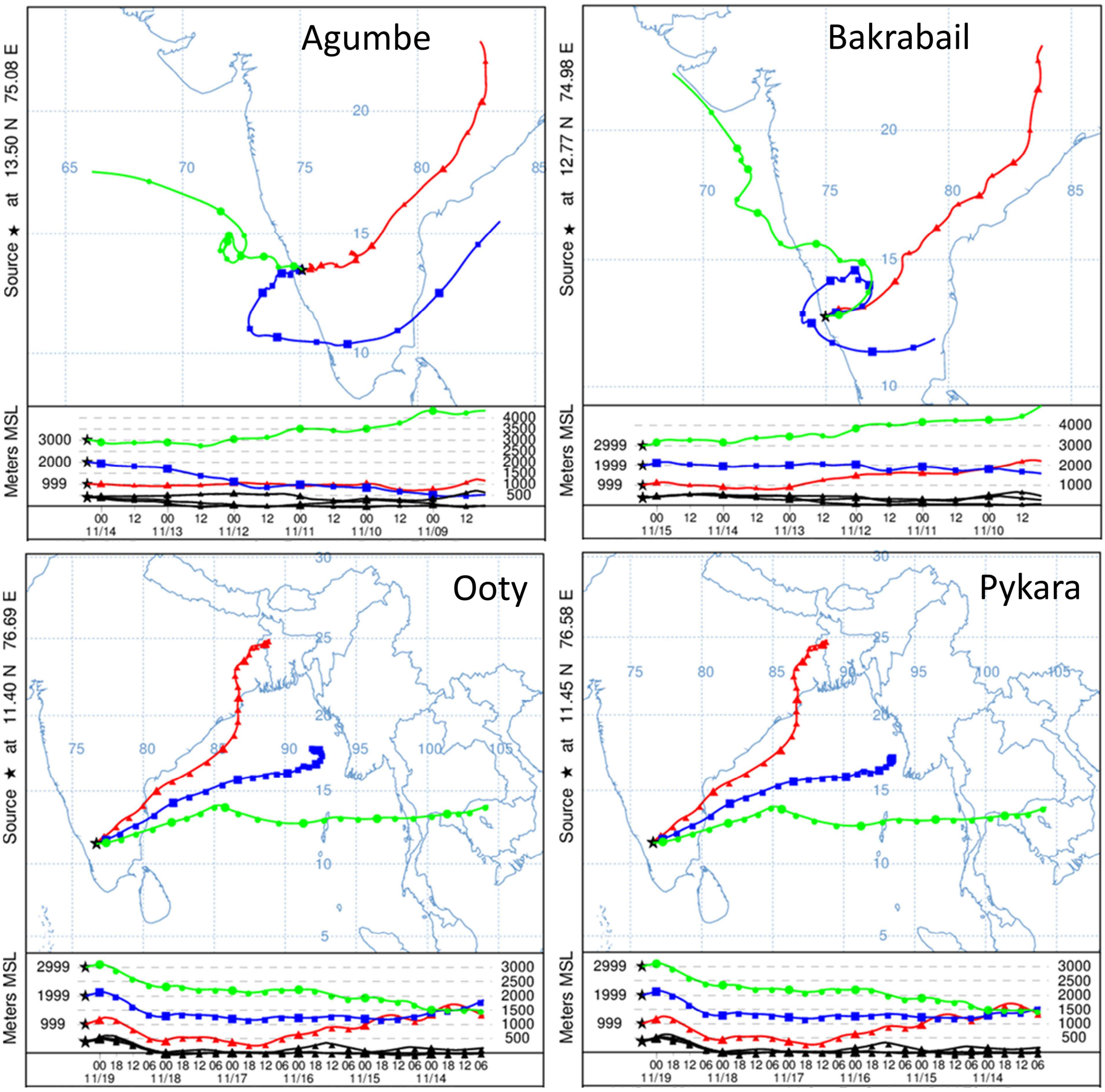


Fig. 5: The variability of oxygen isotope ratio ($\delta^{18}O$) for nine major sampling locations as a function of their distance to the Arabian Sea coast. The grey box corresponds to the mean oxygen isotope ratio ($\delta^{18}O$ = -3.1 ± 0.3‰; Tripti et al. 2016) of groundwater in southwest coast of India.


Agumbe
Source ★ at 13.50 N 75.08 E
Meters MSL
3000
2000
999
Bakrabail
Source ★ at 12.77 N 74.98 E
Meters MSL
2999
1999
999
Ooty
Source ★ at 11.40 N 76.69 E
Meters MSL
2999
1999
999
Pykara
Source ★ at 11.45 N 76.58 E
Meters MSL
2999
1999
999

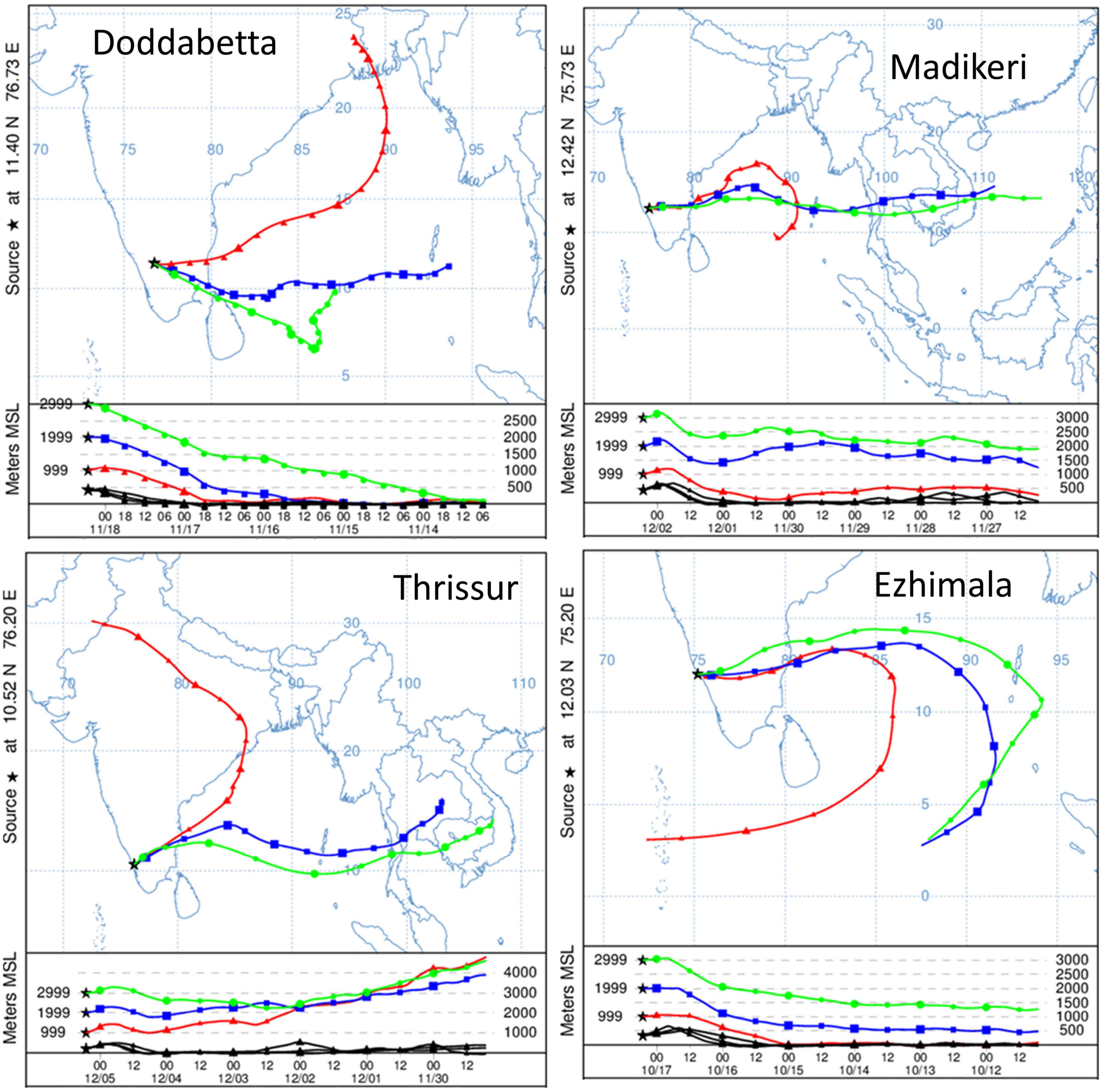


Fig. 6: Results from NOAA Hysplit simulations for the eight main sampling stations with air masses back trajectory up to 5 days.

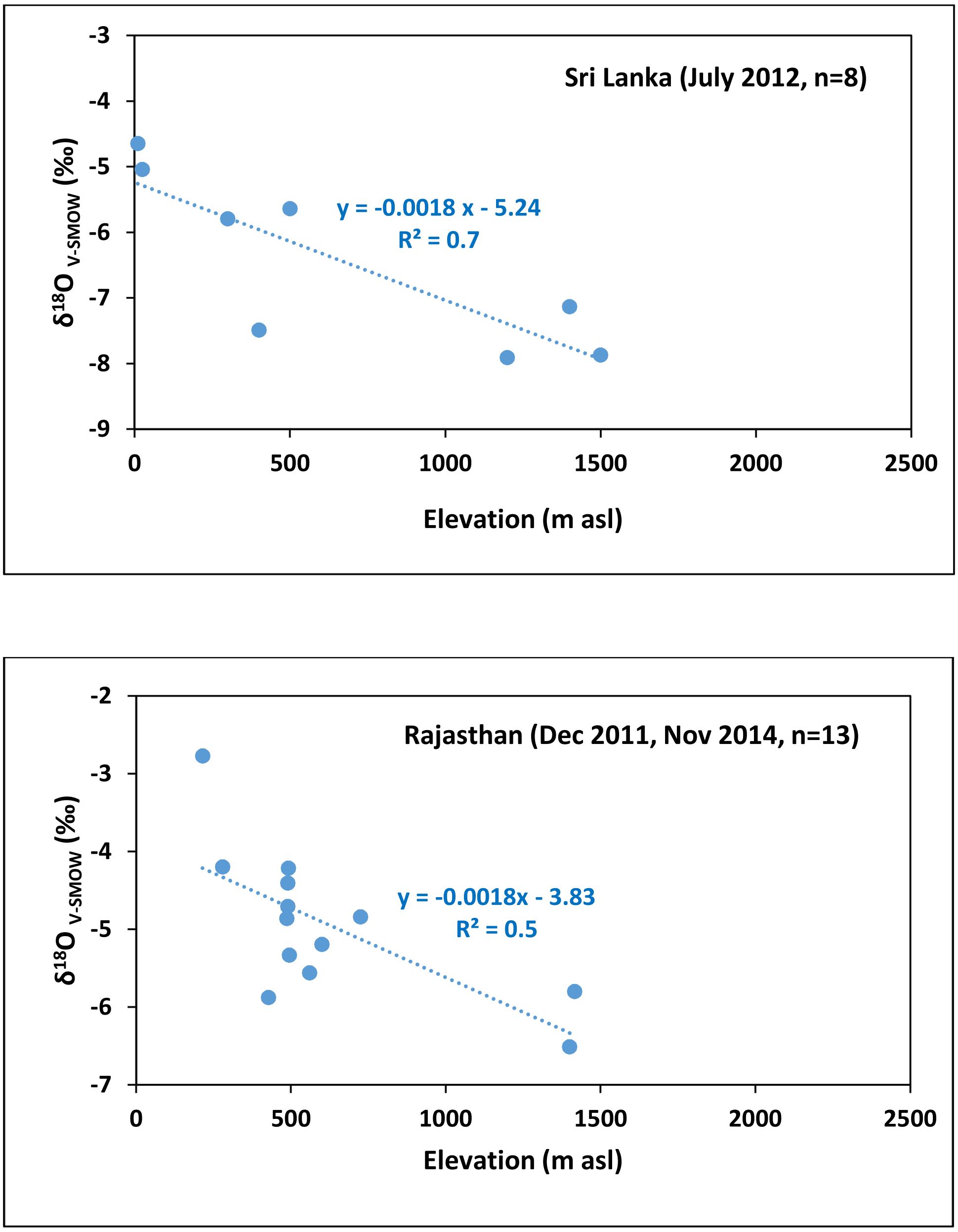


Fig. 7: Plot showing relationship between elevation and oxygen isotope ratio ($\delta^{18}O$) for groundwater in Sri Lanka (July 2012) and Rajasthan (December 2011 and November 2014), India (data from Lambs, under preparation).

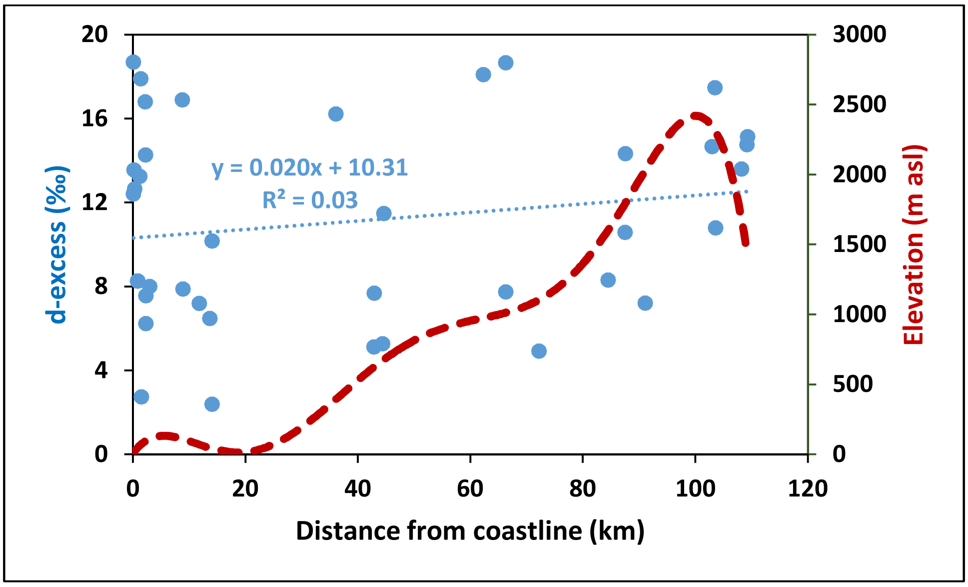


Fig. 8: The variability of deuterium-excess in the sampled water (lake, pond and bore well samples are not included to avoid any effect from evaporation) along the Western Ghats and its adjacent slopes during this study. Note that water from the mountains close to the west coast of India exhibit higher d-excess range between 3 ‰ and 20 ‰ whereas lower variability is observed in inland region corresponding to highest elevations in the Western Ghats monitored during this study.

Table 1: Sampling places during November / December 2013 and October 2014 with location, elevation range, distance to the Arabian Sea coast, number of samples (n) and date.

Place	State	Location	Elevation	Sea distance	n	Date
Agumbe	Karnataka	13°30’N, 75°05’E	605-657 m	45 km	6	Nov 2013
Bakrabail	Kerala	12°46’N, 74°59’E	59-100 m	14 km	5	Nov 2013
Madikeri	Karnataka	12°25’N, 75°44’E	1080-1120 m	75 km	2	Dec 2013
Ezhimala	Kerala	12°02°’N, 75°12’E	20- 200 m	0.3-2.0 km	8	Oct 2014
Tottada	Kerala	11°50’N, 75°24’E	2-60 m	0.2-18 km	8	Oct 2014
Pykara	Tamil Nadu	11°27’N, 76°35’E	1990-2220 m	90 km	6	Nov 2013
Doddabetta	Tamil Nadu	11°24’N, 76°44’E	2225-2600 m	106 km	7	Nov 2013
Sultan Bathery	Kerala	11°42’N, 76°17’E	27-1300 m	12-85 km	7	Nov 2013, Oct 2014
Thrissur	Kerala	10°31’N, 76°12’E	15 m	18 km	1	Dec 2013

Table 2: Physicochemical parameters, elevation, stable water isotope ratio ($\delta^{18}O$ and $\delta^{2}H$) and calculated d-excess for the November/December 2013 and October 2014 samples. Note that GW is for groundwater, OW for open well, BW for bore well and sd is for standard deviation.

Sl. No.	**Location**	**Type**	**Date**	**Conductivity** (μS cm^{-1})	**Temperature** (°C)	**Elevation** (m asl)	$\boldsymbol{\delta^{18}O}$ (‰)	$\boldsymbol{\delta^{2}H}$ (‰)	**d-excess** (‰)
1	Agumbe	Pond	14/Nov/2013	32	26.6	650	-1.97	-12.46	3.34
2	Agumbe	GW	14/Nov/2013	32	23	652	-2.60	-13.15	7.68
3	Agumbe	Waterfall	14/Nov/2013	38	23.2	605	-2.85	-17.72	5.12
4	Agumbe	GW-OW1	14/Nov/2013	75	23.8	651	-2.86	-17.63	5.27
5	Agumbe	GW-BW	14/Nov/2013	149	24.3	650	-3.74	-13.72	16.21
6	Agumbe	GW-OW2	14/Nov/2013	84	23.5	657	-3.65	-17.70	11.48
						mean	**-2.95**	**-15.39**	**8.18**
						sd	***0.66***	***2.54***	***4.84***
7	Bakrabail	Pond 1	15/Nov/2013	83	27.4	61	-2.77	-17.47	4.66
8	Bakrabail	Rivulet	15/Nov/2013	38	27.3	59	-2.88	-16.58	6.48
9	Bakrabail	Pond 2	15/Nov/2013	52	27.6	60	-3.34	-17.94	8.78
10	Bakrabail	Spring 2	15/Nov/2013	20	28.4	87	-3.49	-17.78	10.16
11	Bakrabail	Spring 3	15/Nov/2013	20	27.5	88	-2.78	-19.85	2.39
						mean	**-3.05**	**-17.92**	**6.50**
						sd	***0.34***	***1.20***	***3.12***
12	Madikeri	Rivulet	02/Dec/2013	33		1081	-2.68	-16.55	4.92
13	Madikeri	GW BW	02/Dec/2013	168		1120	-3.53	-15.44	12.84
14	Ezhimala	GW OW1	17/Oct/2014	31		185	-1.55	-4.84	7.56
15	Resorthill	Ezhimala	17/Oct/2014	76		180	-1.64	-6.88	6.24
16	Hanuman temple	GW OW2	17/Oct/2014	19		200	-2.71	-7.42	14.26
17	Chittadi	GW OW3	17/Oct/2014	32		112	-2.30	-10.14	8.26
18	Chittadi	Spring	17/Oct/2014	26		73	-1.80	-6.14	8.26
19	Etikulam 1	GW OW1	17/Oct/2014	25		22	-1.66	-0.03	13.25

20	Etikulam 2	GW OW2	17/Oct/2014	34		31	-2.58	-2.74	17.90
21	Etikulam 3	GW OW3	17/Oct/2014	57		20	-1.15	-6.46	2.74
						mean	**-1.92**	**-5.58**	**9.81**
						sd	***0.55***	***3.08***	***4.93***
22	Venagara temple	GW OW1	17/Oct/2014	27		18	-2.71	-4.88	16.80
23	Venagara road	GW OW2	17/Oct/2014	61		37	-1.17	-1.36	8.00
24	Pariyaram	GW OW	17/Oct/2014	29		60	-3.52	-11.27	16.89
25	Pariyaram	Rivulet	17/Oct/2014	21		58	-1.80	-6.52	7.88
26	Tottada	River	18/Oct/2014	365		6	-2.85	-9.25	13.55
27	Tottada	Rivulet	18/Oct/2014	387		5	-2.33	-5.99	12.65
28	Tottada	Rainfall	18/Oct/2014	36		2	-1.73	-1.44	12.40
29	Tottada	GW OW	18/Oct/2014	211		2	-2.34	-0.04	18.68
						mean	**-2.31**	**-5.09**	**13.36**
						sd	***0.74***	***3.99***	***4.02***
30	Pykara	Lake	19/Nov/2013	65	18.5	2034	-4.42	-31.77	3.55
31	Terrace estate	Rivulet	19/Nov/2013	18	17.2	2219	-6.05	-34.04	14.33
32	Bellevue estate	Rivulet	19/Nov/2013	23	16.2	2127	-5.54	-33.78	10.57
33	TR Bazzar	Rivulet	19/Nov/2013	30	15.5	1990	-4.59	-29.48	7.21
34	Sandynulla	Lake	19/Nov/2013	279	18.4	2153	-4.28	-28.94	5.30
35	Ooty lake	Lake	19/Nov/2013	450	18.6	2213	-5.34	-44.79	-2.10
						mean	**-5.03**	**-33.80**	**6.48**
						sd	***0.71***	***5.78***	***5.70***
36	Ooty	Rainfall 1	17/Nov/2013	30		2225	-17.91	-125.68	17.60
37	Doddabetta	Rainfall 2	17/Nov/2013	13	13.8	2632	-16.03	-107.41	20.82
38	Ooty	GW	18/Nov/2013	136	14.7	2225	-7.29	-45.21	13.09
39	Doddabetta	GW tank	18/Nov/2013	32	13.4	2300	-7.95	-52.77	10.80
40	Doddabetta	Spring	18/Nov/2013	16	12.2	2302	-9.52	-58.69	17.47
41	Doddabetta	Tank-rivulet	18/Nov/2013	62	12.8	2280	-8.94	-56.89	14.66
42	Kodapamund	GW BW	18/Nov/2013	72	17.2	2260	-7.90	-52.14	11.08
						mean	**-8.32**	**-53.14**	**13.42**
						sd	***0.90***	***5.22***	***2.76***
43	Gudalur	GW	20/Nov/2013	415		938	-2.83	-14.34	8.31

44	Sultan Bathery	GW	20/Nov/2013	231	904	-4.39	-16.43	18.66
45	Sultan Bathery	GW OW	23/Oct/2014	181	892	-3.10	-17.06	7.74
46	Edakkal	Spring	23/Oct/2014	20	1300	-3.20	-7.51	18.09
47	Adivaram	Rivulet	23/Oct/2014	19	345	-3.36	-10.65	16.23
48	Kunnamangalam	GW	21/Nov/2013	50	55	-3.85	-23.65	7.19
49	Karanthur	GW BW	23/Oct/2014	104	27	-2.82	-8.13	14.43
					mean	**-3.36**	**-13.97**	**12.95**
					sd	***0.57***	***5.72***	***5.06***
50	Thrissur	GW BW	05/Dec/2013	332	5	-3.11	-14.91	9.99

Table 3: Summary of relevant studies on the isotopic elevation effect.

Sl. No.	Study	Aim of the study	Location	Key findings
1	Dansgaard (1964)	Determining factors influencing fractionation of water isotopes.	Worldwide	The heavy isotope composition in freshwater decreases with latitude and elevation.
2	Ambach et al. (1968)	To measure isotopic elevation, change of rainfall in mountains.	Alps	Isotopic elevation effect of -0.2 ‰/100 m.
3	Siegenthaler and Oeschger (1980)	Variation of $\delta^{18}O$ with temperature and elevation.	Alps	Isotopic elevation effect of -0.45 ± 0.1 ‰/100 m.
4	Yurtsever and Gat (1981)	Elevation effect on water isotope ratios.	GNIP data, worldwide	Isotopic elevation effect of -0.15 to -0.5 ‰/100 m.
5	Gonfiantini et al. (2001)	Elevation effect on the isotopic composition of tropical rains.	Cameroon and Bolivia	Cameroon -0.16 ‰ and Bolivia -0.24 ‰/100 m.
6	Poage and Chamberlain (2001)	Review of 68 studies on isotopic elevation effect.	World wide	Global mean: -0.28 ‰/100 m; Less effect in tropical area: -0.12 to -0.20 ‰/100 m; Higher effect in extreme conditions: -0.62 to -1.83 ‰/100m.
7	Deshpande et al. (2003)	Study of groundwater isotopic composition.	South India	Possible elevation effect of -0.4 ‰/100 m.
8	Scholl et al. (2009)	Orographic rainfall and amount effects.	Puerto Rico	Isotopic elevation effect of -0.12 ‰/100 m.
9	Windhorst et al. (2013)	Effect of elevation and weather condition on event based precipitation.	Ecuador	Isotopic elevation effect of -0.22 ‰/100 m for elevation range of 1800 – 2800 m asl.
10	Resmi et al. (2016)	Precipitation in Pamba river basin.	Kerala, India	Isotopic elevation effect of -0.1 ‰/100 m.
11	Edirisinghe et al. (2017)	Precipitation over northeast and central Sri Lanka.	Sri Lanka	Isotopic elevation effect of -0.6 ‰/100 m.
12	This study	Orographic upliftment effect on isotope ratios of groundwater and spring water.	South India	Isotopic elevation effect of: -0.09 ‰/100m, below 2050 m asl; -1.5 to -2.5 ‰/100m, beyond 2000 m asl; Mean value of -0.30 ‰/100m (0 - 2500 m asl).

Table 4: Multiple Linear Regression results as obtained from the Past program version 3.15. The dependent variable was oxygen isotope ratio ($\delta^{18}O$) and the independent variables were the elevation above mean sea level (elevation effect), the distance from the coast (Rayleigh distillation and continental effect) and the annual rainfall amount (amount effect).

Number of point	**Variable**	**F**	**R^2**	**p**	**Significance**
51 (all)	isotope values	35.91	0.70	<0.0001	yes
	elevation		0.68	0.0002	yes
	continental		0.56	0.18	no
	amount		0.40	0.39	no
42 (below 2050 m)	isotope values	10.61	0.46	<0.0001	yes
	elevation		0.41	0.96	no
	continental		0.45	0.11	no
	amount		0.12	0.62	no
9 (over 2050 m)	isotopes values	17.33	0.96	0.004	yes
	elevation		0.77	0.08	yes
	continental		0.36	0.21	no
	amount		0.81	0.04	yes