To link to this article : DOI : 10.1002/rcm.5104
URL : http://dx.doi.org/10.1002/rcm.5104

To cite this version : Lambs, Luc and Gurumurthy, G. P. and Balakrishna, K. *Tracing the sources of water using stable isotopes: first results along the Mangalore-Udupi region, south-west coast of India.* (2011) Rapid Communications in Mass Spectrometry, vol. 25 (n° 19). pp. 2769-2776. ISSN 0951-4198

DOI: 10.1002/rcm.5104

Tracing the sources of water using stable isotopes: first results along the Mangalore–Udupi region, south-west coast of India†

L. Lambs[1,2]*, G. P. Gurumurthy[3] and K. Balakrishna[3]**

[1]Université de Toulouse, UPS, INPT, Laboratoire d'Ecologie Fonctionnelle (EcoLab), 118 route de Narbonne, F-31062 Toulouse, France
[2]CNRS, Laboratoire d'Ecologie Fonctionnelle (EcoLab), 118 route de Narbonne, F-31062 Toulouse, France
[3]Department of Civil Engineering, Manipal Institute of Technology, Manipal University, Manipal 576104, India

The Mangalore and Udupi region on the south-west coast of India is characterized by small west-flowing rivers (150–250 km in length) originating in the Western Ghats (up to 1940 meters above sea level (m asl)) and joining the Arabian Sea. The area experiences a humid tropical climate with frequent, high-intensity rainfall (4000 mm annual average). Nevertheless, there is a shortage of water during the peak dry season immediately before the onset of monsoon because of a rapid fall in the groundwater level. From the humid high-altitude forests to the intense agriculture in the coastal area, there is an urgent need to understand the movement of water between evapotranspiration, rainfall, river systems and the groundwater compartments in order to achieve better water resource management. Demographic pressure on the area with over half a million inhabitants and industrial activity strongly influence this fragile ecosystem. The coastal area is characterized by shallow open wells, which are particularly sensitive to pollution and eutrophication. Stable water isotopes (^{18}O and deuterium) were used for the first time in this region to determine the isotopic characteristics of the different waters. There is a clear seasonal difference in the isotopic ratios and d-excess values between the summer and winter monsoon periods, with a predominance of lighter isotopes in the latter period. No significant variations in isotopic ratios were observed in relation to altitude because of the possible role of mist formation at high altitude. Greater d-excess values were observed in the west-flowing streams than in rivers flowing east on account of the moist westerly oceanic winds and water vapour recycling.

Hydrological studies have focused on large river catchments in order to understand and calculate the global water budget, carbon fluxes or sediment loads.[1–4] In India, most of the geochemical studies are restricted to the large North Indian rivers, such as the Ganga–Brahmaputra system, the Yamuna River and the rivers draining the Deccan Traps, because of their geochemical influence on the sea and their hydrological characteristics.[4–10] Stable isotopes have been efficiently used to help in the understanding of isotope systematics or weathering and surface processes, among various other effects. Carbon cycle and major ion studies on these river catchments have been carried out by several authors.[8,11–14] In the Deccan Traps area,[8,15] there have been studies aimed at understanding the sources of carbon, the nature of weathering, CO_2 consumption during weathering and long-term climate change. Few isotopic studies have been made on other large east-flowing rivers such as the Mahanadi, Godavari and Krishna.[16,17] Lambs *et al.*[10] were the first to report on the water isotope ratios of all the major Indian rivers. All these rivers are characterized by long drainage basins (up to many thousands of kilometres), high discharge values and huge delta systems. The altitude at the source and the influence of the monsoon climate are both factors that help to contribute to strong seasonal variations in water discharge and quality, and the length of the drainage basin favours the evaporation process.

Studies on small coastal rivers are now considered important because it has been realized that their contribution to the sediment discharge into the ocean is underestimated. This is because of their proximity to the sea and their steep flow gradient.[1,4,18] In south-west India, most of the rivers originate in the Western Ghats and flow westwards for about 150 km before discharging into the Arabian Sea. The west coast stretches from Mumbai in the north to Kanyakumari in the south – a distance of 1600 km – and, within the narrow stretch of coastal land, a number of small west-flowing streams discharge about 200 km^3 of water annually to the sea. The Western Ghats form a barrier from 1200 to 1900 m

* *Correspondence to:* L. Lambs, Université de Toulouse, UPS, INPT, Laboratoire d'Ecologie Fonctionnelle (EcoLab), 118 route de Narbonne, F-31062 Toulouse, France.
E-mail: lambs@cict.fr
** *Correspondence to:* K. Balakrishna, Department of Civil Engineering, Manipal Institute of Technology, Manipal University, Manipal 576104, India.
E-mail: k.balakrishna@manipal.edu

† Presented at the 6th Congress of the French Society of Stable Isotopes (Société Française des Isotopes Stables, SFIS) held 26–29 October 2010 in Toulouse, France.

high against the humid monsoon winds and, therefore, this coastal area is the second wettest place in India (with an average annual rainfall in the studied region of 4000 mm) after Mawsynram, Meghalaya, which is located in the Himalayan foothills.

The westward-flowing coastal rivers do not form deltas, but tend to enter the sea as long estuaries, often diverted into an 'L' shape, flowing along the coast, dammed behind a narrow, semi-continuous sand bar. The most famous example is the backwater system in Kerala. Saline water intrudes through the bar at high tide and mangroves develop along the brackish backwaters.

Only limited isotopic data on the west coast rivers and their catchments have been published. Deshpande *et al.*[19] obtained isotopic data for peninsular India and observed progressive depletion of δ^{18}O by ~3 ‰ from the west to the east coast in the south-west monsoon. This depletion is attributed to different moisture sources of the west and east coasts, i.e., moisture derived from the Arabian Sea and the Bay of Bengal, respectively.

The two principal sources of oceanic vapour for the monsoon rainfall on the Indian subcontinent are the Arabian Sea and the Bay of Bengal. During the south-west monsoon (June–September), the west coast of India receives moisture in the wind from the Arabian Sea and the incoming air current is uplifted by the Western Ghats. This section of the Indian south-west monsoon is called the Arabian Sea branch.[20] In addition, the western disturbances that originate in the Mediterranean Sea are responsible for rainfall in many parts of the country during the winter season (October–January). These different sources of precipitation have different isotopic compositions, such that the surface waters of Arabian Sea and Bay of Bengal are reported to have mean δ^{18}O values of +0.6 ‰ and −0.5 ‰, respectively.[21]

This paper focuses on the water cycle in small west-directed river catchments originating in the Karnataka area of the Western Ghats of peninsular India, and flowing towards the Arabian Sea for about 150 km. These rivers are the main sources of water for domestic, drinking and industrial usage in the Mangalore and Udupi districts. The catchment bedrock is composed of rock types of the Tertiary and Quaternary eras in the lower reaches and an Archaean gneissic complex in the headwaters. The bedrock of the headwaters is mainly granitic gneiss, schist and charnockite, structurally characterized by folds and faults. The thickness of the soil and the weathered zone together is in the range 20–40 m,[22] and the basement rocks below this zone host groundwater in fractures and joints. The study area is characterized by high humidity (>70%), and heavy rainfall (3600–4200 mm/year). The basin has a wet equatorial–tropical rain forest and a monsoonal type climate, characterized by a moist tropical maritime and equatorial air mass, yielding heavy rainfall and a monthly average temperature of around 30 °C, with extremely small variation throughout the year.[23] The aim of this study is to identify the different water pools between the Nethravati River (Mangalore area) and the Swarna River (Udupi area), and the influence of the summer and winter monsoon on the hydrology. The δ^{18}O and δ^{2}H measurements give an insight into the water cycle and vapour circulation in this coastal region. This will help in improving the water quality and the water management practices.

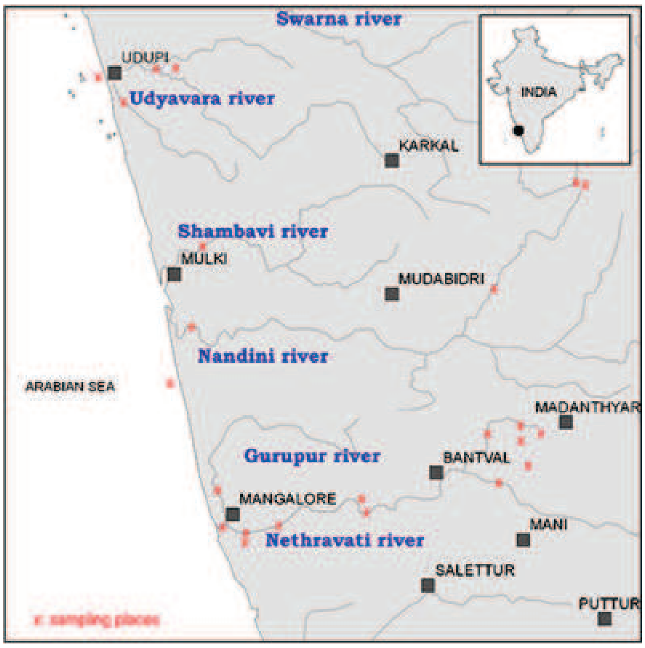

Figure 1. Location of the water samples taken in July 2008, January 2009 and December 2010.

EXPERIMENTAL

Field sites

The locations of the rivers and groundwater sources are shown in Fig. 1. The 2008 sample data were gathered along the coast, from Udupi (north) to Mangalore (south), to gain an overall view of the isotopic variations of the rivers close to their mouths. Two samples of seawater (Arabian Sea) were also taken. In February 2009, the sampling focus was more along the Nethravati river catchment and its tributaries, from the city of Mangalore to a few kilometres east of Bantval. Some groundwater samples were also taken near Mangalore (2008) and Udupi (2009). Most of the groundwaters were sampled from open wells, which are circular stone-wall reservoirs (about 5 m in diameter and 10–20 m deep) fed by shallow groundwater, and rainfall. In December 2010, samples were collected for a second time from most of the 2009 sampling stations, along with ten groundwater samples taken in the same area. A third group of high-altitude waters was collected on the way to Mullayanagiri, the highest peak (1930 meters above sea level (m asl)) in Karnataka.

The area received 3440 mm of rainfall in 2008, 4080 mm in 2009 and 4428 mm in 2010 (see Fig. 2). About 80% of the annual amount arrived during the summer monsoon (June–September), 12% during the winter monsoon (October–January), and 8% during the pre-monsoon period (February–May).

Sample collection

The samples of groundwater and surface runoff water were collected in 10 mL glass bottles from different locations along the Nethravati River catchment and at high altitudes in the Western Ghats for oxygen and hydrogen isotope measurements. The pH, temperature and conductivity were measured with an electrochemical multimeter

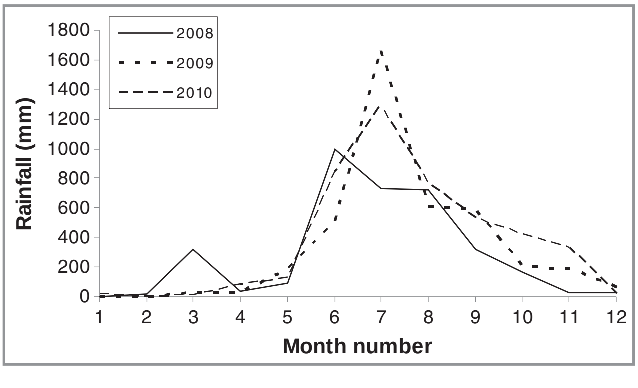

Figure 2. Monthly variation in rainfall at the Dakshin Kannada station near Mangalore, over the years 2008–2010.

(model C531; Consort, Turnhout, Belgium) during different field campaigns. The collected samples were sealed with Parafilm™ (Pechney, Chicago, IL, USA) immediately to prevent loss of water by evaporation. In order to avoid any surface evaporation effect on the sample water, the samples were collected at a depth of 30 cm below the water level and, in the case of a bore well, an initial volume of water was pumped out for about 10 min and the sample was then collected.

The samples were collected at different time periods (summer monsoon for July 2008, pre-monsoon for February 2009, winter monsoon for December 2010) in order to discern the isotopic fractionation due to evaporation moisture cycling during the different time periods. The high-altitude spring water samples were collected from the peak of Mullayanagiri, Chickamagalur, Karnataka (an elevation of about 1930 m asl) in December 2010. In the July 2008 field campaign, during the high-flow season when most of the stream water was fed by incoming precipitation and surface runoff, the water samples were collected from the lower catchments of the Nethravati and Udupi regions. The samples for oxygen and hydrogen measurements were sent immediately for isotopic measurements.

Isotopic analysis

The stable isotope composition of water is reported with reference to the Standard Mean Ocean Water and the Standard Light Arctic Precipitation (V-SMOW/SLAP), in parts per thousand. The definition for δ^{18}O is:

$$\delta^{18}\mathrm{O}\ _{\text{V-SMOW}}(‰) = \left[\frac{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\text{sample}}}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\text{standard}}} - 1\right] \times 1000‰,$$

and for deuterium:

$$\delta^{2}\mathrm{H}\ \text{V-}_{\text{SMOW}}(‰) = \left[\frac{(^{2}\mathrm{H}/^{1}\mathrm{H})_{\text{sample}}}{(^{2}\mathrm{H}/^{1}\mathrm{H})_{\text{standard}}} - 1\right] \times 1000‰.$$

The samples collected in the July 2008 and January 2009 field campaigns were measured by continuous flow isotope ratio mass spectrometry (CF-IRMS) at the Iso-Analytical Laboratory (Crewe, UK). The water samples were headspace equilibrated on an ANCA-GSL preparation module and the obtained gas was measured on a GEO 20–20 isotope ratio mass spectrometer (both instruments from PDZ Europa, Crewe, UK). The mass spectrometer was fitted with a long spur flight tube to allow separation of hydrogen from helium. Three working standards were used during the analysis, *viz.*, IA-R052, IA-R053 and IA-R054, all traceable to V-SMOW2/V-SLAP2. Each water sample was measured in triplicate, and the value given in Tables 1(a) and 1(b) is the mean value. The overall δ^{18}O mean standard deviation (sd) was around ±0.05, and the δ^{2}H mean sd was ±0.67 in 2008 and ±1.71 in 2009.

The samples from the December 2010 field campaign were analyzed by CF-IRMS at Shiva Isotopic Platform, Laboratory Ecolab in Toulouse, France. The water vials were headspace equilibrated on a MultiFlow-Geo and the obtained gas was measured in an IsoPrime100 mass spectrometer (both instruments from Elementar, Hanau, Germany). Four working laboratory standards were used, i.e., BRE, MSE, GAR and SVS, all traceable to V-SMOW2/V-SLAP2. Each water sample was measured in duplicate, and the given value in Table 1(c) is the mean value. The overall δ^{18}O mean standard deviation (sd) was around ±0.29, and the δ^{2}H overall mean sd was ±2.62.

Because of rapid evaporation in the precipitation source areas, the fractionation of oxygen and hydrogen does not normally occur under equilibrium conditions so there is a difference between δ^{18}O and δ^{2}H. Dansgaard[24] defined a parameter called the d-excess, which is both an indicator of non-equilibrium conditions and an index of the evaporation rate. This index is calculated from the obtained δ^{18}O and δ^{2}H values by the equation:

$$\text{d-excess} = \delta^{2}\mathrm{H} - 8 \times \delta^{18}\mathrm{O}$$

RESULTS

General physicochemical data

The river water and groundwater samples collected in years 2009 and 2010 show a homogeneous temperature of around 27 °C (Table 1). Samples collected in 2010 were relatively colder than those in previous years by 1.2 °C for the rivers and 0.3 °C for the groundwater. The conductivity of the river water ranged between 40 and 50 μS/cm^{-1}. These low values can be explained by the presence of granite gneiss basement rocks and dilution by the intense tropical rainfall. The groundwater conductivity was also low, with a mean value between 110 and 120 μS/cm^{-1}. However, the Sanghabettu bore well (sample #23) and the Uppinangadi open well (sample #27) registered higher values. Higher conductivity at the Sanghabettu bore well could have been because of a higher groundwater interaction with the surrounding rocks for a long period of time as the sample was extracted from a depth of 46 m. The Uppinangadi bore well water could have been contaminated because of its urban location. The entire river remained mildly alkaline during the sampling period (pH 7.4–7.6), but some groundwaters were acidic with a pH <5.2), which could have been because of leaching of ions such as fluoride and sulphate from the acidic igneous rocks.

For the samples collected at higher altitudes, the temperatures decreased at a rate of about 0.56 °C for every 100 m elevation. Similarly, the conductivity also decreased to as low as 20 μS cm$^{-1.}$

Table 1. Physicochemical and isotopic characteristics of the water samples, with the calculated mean values and standard deviation (sd). (GW = groundwater, nd = not determined, asl = above sea level)

Number	Location	Temperature (°C)	pH	Conductivity (µs/cm)	Altitude (m asl)	$\delta^{18}O$ (V-SMOW)	δD (V-SMOW)	d-excess
(a) July 2008								
1	Udupi sea	nd	nd	36000	0	0.60	8.53	3.73
2	Suratkal sea	nd	nd	38000	0	0.63	7.41	2.38
	Mean Arabic Sea ± sd					**0.61 ± 0.02**	**7.97 ± 0.79**	**3.06 ± 0.96**
3	Nethravati river near sea	nd	nd	1255	0.5	−2.16	−4.62	12.66
4	Mulki river near sea	nd	nd	3466	0.5	−2.15	−7.04	10.16
5	Nethravati/Gurupur confluence near sea	nd	nd	3806	0	−2.08	−4.57	12.09
	mean Estuaries ± sd					**−2.13 ± 0.04**	**−5.41 ± 1.41**	**11.63 ± 1.31**
6	Mughir GW	nd	nd	234	2	−2.34	−5.57	13.12
7	Mangalore GW	nd	nd	215	3	−2.69	−11.29	10.25
	mean GW ± sd			**225 ± 13**		**−2.51 ± 0.25**	**−8.43 ± 4.04**	**11.69 ± 2.03**
8	Manipur river	nd	nd	59	3	−1.90	−6.46	8.72
9	Udyavara river	nd	nd	325	3	−2.15	−5.93	11.28
10	Nandini river	nd	nd	402	3	−2.27	−8.36	9.76
11	Gurupur river	nd	nd	370	1	−2.17	−5.45	11.91
	mean Rivers ± sd			**289 ± 157**		**−2.12 ± 0.16**	**−6.55 ± 1.45**	**10.42 ± 1.45**
(b) February 2009								
12	Open well, Parkala, Udupi	26.9	6.52	88	46	−2.21	−9.59	8.13
13	Borewell, Parkala, Udupi	27.9	6.67	110	49	−2,06	−8.62	7.88
14	Hand pump, Parkala, Udupi	27.5	6.85	140	52	−2.13	−8.75	8.26
	mean GW ± sd	**27.4 ± 0.5**	**6.68 ± 0.17**	**113 ± 26**		**−2.13 ± 0.08**	**−8.98 ± 0.53**	**8.09 ± 0.19**
15	BC Road, Nethravathi river	27.5	7.86	52	9	−1.25	0.24	10.24
16	Mugera, Nethravathi R	27.4	7.45	50	32	−1.79	0.04	14.34
17	Shanthimugeru,Kumaradhara R	28.4	7.66	51	63	−1.76	−2.34	11.75
18	Gundia Hole, Kumaradhara R	27.0	7.71	54	81	−1.83	−1.09	13.56
19	Shishila Hole, Nethravathi R	28.8	nd	35	102	−2.15	−4.89	12.30
20	Neriya Hole,Nethravathi R	27.3	7.43	44	90	−2.23	−4.39	13.47
21	Dharmasthala, Nethravathi R	28.9	7.48	54	63	−1.88	−3.75	11.27
22	Mundaje Hole/ Mruthyunjaya Hole, Nethravathi R	26.8	7.58	51	110	−2.37	−6.81	12.19
	mean River ± sd	**27.8 ± 0.8**	**7.60 ± 0.16**	**49 ± 7**		**−2.16 ± 0.35**	**−4.98 ± 2.51**	**12.31 ± 1.35**
(c) December 2010								
23	Sanghabettu bore well	27.7	7.23	365	92	−2.65	−9.12	12.06
24	Sanghabettu well	26.5	5.65	40	86	−3.14	−7.94	17.21
25	Bantwal well	27.6	5.97	83	20	−3.76	−12.52	17.58
26	Balthila well	27.1	5.48	44	33	−3.36	−2.33	24.54
27	Uppinangadi well	27.2	6.10	296	43	−2.87	−4.73	18.19

(*Continues*)

28	Kadaba well	28.1	5.60	74	123	−3.67	−9.49	19.89
29	Parpikal well	26.7	5.17	26	112	−2.83	−3.81	18.83
30	Mundaje well	26.6	5.84	104	112	−3.11	−7.13	17.74
	mean GW ± sd	**27.1 ± 0.6**	**5.88 ± 0.62**	**129 ± 128**		**−3.17 ± 0.40**	**−7.13 ± 3.36**	**18.26 ± 3.44**
31	Bantwal river	26.8	7.44	46	10	−3.50	−12.68	15.30
32	Mugeru river	26.8	7.22	44	34	−3.45	−11.77	15.83
33	Shanthi Mogeru river	26.4	7.41	41	69	−3.33	−11.15	15.45
34	Gundhiya hole river	25.9	7.52	44	86	−3.19	−13.24	12.30
35	Shishila hole river	27.1	7.55	39	108	−3.51	−10.06	17.98
36	Neriya hole river	26.3	7.06	38	94	−3.71	−14.97	14.69
37	Dharmasthala river	26.8	7.44	48	101	−3.57	−12.22	16.31
38	Mundaje river	26.8	7.66	46	116	−3.53	−14.99	13.22
39	Gurupura river	26.4	6.87	37	11	−3.73	−14.46	15.35
	mean Rivers ± sd	**26.6 ± 0.4**	**7.35 ± 0.25**	**42 ± 4**		**−3.50 ± 0.17**	**−12.84 ± 1.74**	**15.16 ± 1.66**
40	Charmadi Ghat spring	22.4	7.32	29	743	−4.09	−11.01	21.70
41	Charmadi Ghat spring	21.4	7.52	19	832	−3.91	−9.70	21.58
42	Mullayanagiri spring	19.4	7.52	27	1478	−3.84	−15.96	14.74
43	Mullayanagiri spring bis	19.4	7.52	27	1478	−3.96	−18.09	13.56
44	Mullayanagiri spring 2 high	18.1	7.50	16	1599	−3.91	−16.15	15.10
45	Mullayanagiri cave	19.4	7.11	79	1905	−3.62	−17.52	11.47
46	Mullayanagiri cave bis	19.4	7.11	79	1905	−3.73	−12.84	17.03
	mean Mountains ± sd	**19.9 ± 1.5**	**7.37 ± 0.19**	**39 ± 28**		**−3.87 ± 0.15**	**−14.47 ± 3.29**	**16.45 ± 3.92**

Isotopic data

The 2008–2009 isotopic results (see Tables 1(a) and 1(b)) show homogeneity in the rainfall inputs over Udupi and Mangalore area, with no significant difference between the river water and groundwater (mean $\delta^{18}O = -2.2$). Furthermore, the d-excess (10.4–12.3) for these samples remained close to the Global Meteoric Water Line (GMWL), i.e., 10, except for a few groundwater samples near Udupi. The groundwater samples revealed lower d-excess values (mean 8.1), indicating low evaporation rates from these wide-open wells, a possibility that is supported by the high conductivity values.

In contrast, the 2010 low altitude isotopic values are more negative (Table 1(c)) by around −1.2 ‰ for $\delta^{18}O$, whereas the mean d-excess value range is higher than the 2008–2009 samples, ranging from 15.2 to 19.1. It is interesting to note that only a bore well with water at deeper levels reveals isotopic values close to the earlier ones, with a d-excess at 12.1. For the seven identical sampling sites of river water taken in February 2009 and December 2010, Fig. 3 indicates the shift of the $\delta^{18}O$ values between these two periods. The mean shift is around 1.5 ‰. The more negative values in December 2010 indicate a more pronounced fractionation process, showing the possible entry of different air mass moisture.

On Mullayanagiri Mountain the isotopic ratios of the samples show almost no altitude gradient. Samples collected at mid altitude (743–832 m asl) are from springs that could have water originating at much higher elevations and thus they reflect high-altitude ratios. Samples collected at the highest altitude (1905 m asl) were from caves, and these showed less negative values than other high-elevation samples. This could be because of an evaporation and recondensation process. The overall decrease in $\delta^{18}O$ was only by 0.5 ‰, which gives an isotopic gradient of 0.03 ‰ per 100 m.

Figure 4 summarizes all the isotopic data in the form of plot of $\delta^{2}H$ versus $\delta^{18}O$ values. The three time periods as well as the water type (river or groundwater) are plotted with separate symbols, showing clearly two sets of data. The 2008 samples are close to the local meteorological water line 1 (LMWL1), which is quite similar to the GMWL. The groundwater samples from 2009 are located under the GMWL, showing the same isotopic behaviour, whereas the river water samples are spread between LMWL1 and LMWL2, showing a possible shift in response to different air masses. All the first group of $\delta^{18}O$

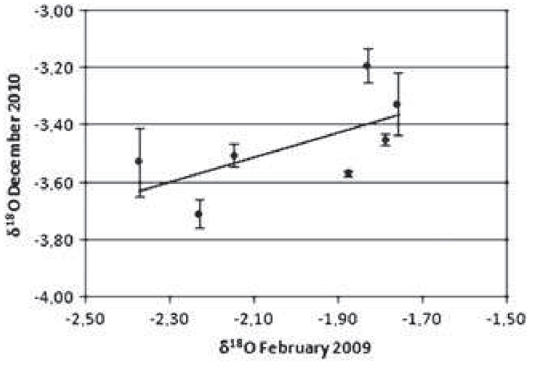

Figure 3. Shift between the February 2009 and December 2010 $\delta^{18}O$ values for the seven river waters, showing the origin change of the air masses.

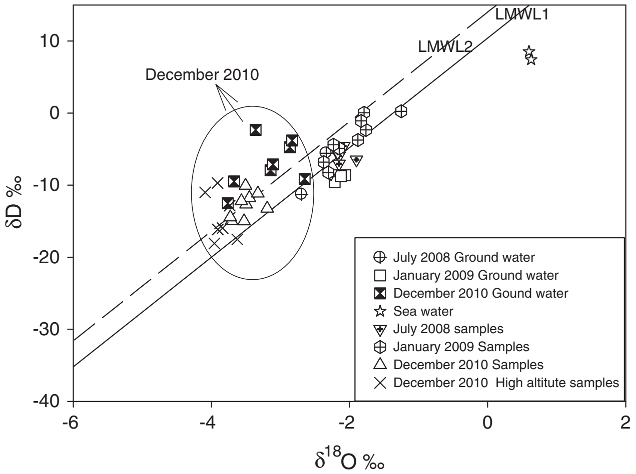

Figure 4. Overall relation between the δ^{18}O and δ^2H values from 2008 to 2010. The first solid line (LMWL1) corresponds to the Local Meteoric Water Line as defined by Warrier *et al.*[28] [$\delta^2H = (7.6 \times \delta^{18}O \pm 0.13) + (10.4 \pm 0.81)$]. The second line, LMWL2, has the same slope but with an intercept of 14 and corresponds to the winter north-east monsoon conditions, see Discussion section for details.

values range from −1.3 to −2.6 ‰. The second group (from 2010) display more depleted values of −2.6 to −5.2 ‰. The more negative values correspond to the higher latitude sampling. Furthermore, all the points of this second isotope group are more centred on the LMWL2 position, revealing a different climatic condition with a higher d-excess.

DISCUSSION

The 2008 isotopic results reveal a homogeneity in the rainfall patterns over the narrow coastal area from Udupi to Mangalore There is a small fractionation of isotopes during the south-west summer monsoon between the sea-water ($\delta^{18}O = +0.6$ ‰) and the rivers and the nearby groundwater ($\delta^{18}O = -1.6$ to -2.4 ‰), because of a moderate continental effect. The Western Ghats, lying less than 200 km from the shore, cause precipitation of cold, saturated ocean air moisture. These values are consistent with our previous result[10] and the results of Deshpande *et al.*[19] These authors also show that on the east coast the depletion is much more pronounced with δ^{18}O values reaching −4 to −5 ‰ because of drier air masses and a more pronounced continental effect.

The 2008 samples and most of the 2009 samples have d-excess values ranging between 10 and 12, overlapping with the GMWL of 10 (Table 1 and Fig. 4). This indicates no evaporation process, except in the northern part, near Udupi, where three groundwater samples show a d-excess of around 8.1. During the winter monsoon conditions (December 2010), the isotopic values shifted to more negative values by about 1.5 delta units for δ^{18}O values, with the mean temperature values also going down. This indicates cooler conditions, resulting from the fractionation of the rainfall coming from the north-east. Furthermore, the d-excess increased by 14 to 19 units, indicating a water source of continental origin. Some data for February 2009 also display d-excess values close to 14.

Surprisingly, the samples from altitude do not become more negative than $\delta^{18}O = -4.1$ ‰. The isotopic gradient over altitude (0.03 unit/100 m) is very low compared with a classical mountain gradient of 0.2–0.4 units. For the south Indian west coast, Deshpande *et al.*[19] report a general altitudinal decrease in the δ^{18}O by 0.42 ‰ per 100 m increase in altitude, but for the Mangalore area this value is close to zero. Interestingly, they also report high d-excess values in the coastal region of Mangalore but not elsewhere. This low gradient with altitude could be because of the presence of a fog or mist-like atmosphere in the tropical evergreen forests, which could reduce the δ^{18}O values.[25] This mist is produced because of the confrontation of vapour-laden western winds with the dry winds of the east. To understand this concept further, the influence of the two different Indian monsoons on the isotopic systematics and the unique positioning of the Western Ghats should be studied.

Rainfall over south India

Most isotopic studies of the large north Indian rivers[7,10] and rainfall over New Delhi[5] show a similarity with the GMWL as described by Rozanski *et al.*[26] The slopes are between 7.2 and 7.8, and the intercept values range between 5 and 10, showing little or no evaporation. This apparent overlap of the LMWL onto the GMWL, as seen from these mean annual values, hides the fact that there is indeed a pronounced seasonal and regional effect in the isotopic ratios. This is because of the changes in monsoon regimes and a specific uplift of air masses adjoining the mountains.[27] Table 2 helps provide a better understanding of the north–south gradient in the isotopic specificity and the uniqueness of the Western Ghats.

Table 2 shows a gradual decrease in the isotopic $\delta^{18}O/\delta^2H$ slope along the north–south axis. The temperature enhancement affects the evaporation process and, during the dry season, the slope could be even less. In contrast, the d-excess values do not follow this axis, but reveal the influence of the continental winter monsoon on the south Indian coasts. The d-excess also reveals a difference between south-east India and the south-western region because the latter is characterized by wetter conditions and a narrow coastal strip compared with the drier and wider coastline of the Eastern Ghats. To support this observation, Lambs *et al.*[10] reported higher d-excess values in the Nethravati River flowing in the south-western coast than in other southern rivers flowing to the east coast.

The variation in isotopic composition of precipitation in different parts of India can be explained by the fact that the rainwater characteristics in the southern Indian peninsula are controlled by precipitation during the summer south-west and winter north-east monsoons, in contrast to the north, which only receives the summer monsoon. The south-west

Table 2. LMWL values over India and Sri Lanka

Area	Slope	Intercept	Reference
New Delhi	7.8	7.2	Dalai *et al.*[5]
South-east India	7.82	10.2	Kumar *et al.*[20]
South-west Ghats	7.6	10.4	Warrier *et al.*[28]
Sri Lanka	7.3	7.6	Song *et al.*[29]

monsoon operates during the months of June–September, and the north-east monsoon operates during the months of October–January.[20] The causal mechanism for these monsoon systems is the seasonal reversal of temperature and pressure gradients, and the associated wind circulation following the annual northward and southward movement.[30,31] In addition to the south-west and north-east monsoons, the westerly disturbances from the Mediterranean Sea are responsible for the variability in the isotopic characteristics of precipitation. It has been observed that in most cases the $\delta^{18}O$ isotopic composition of the precipitation is more depleted in the month of September than in July and August every year.

Particular case of the south-western Ghats

Warrier *et al*.[28] have studied the rainfall patterns at Kozhikode, North Kerala, approximately 200 km south of Mangalore. The rainfall regime in this area is very similar to that in the Mangalore area. The north–south oriented Western Ghats intercept the south-west monsoon winds and the moist air is progressively uplifted on the windward slopes and gives rise to copious rains. The first outburst of the south-west monsoon over the Indian subcontinent takes place at the southern end of Western Ghats in June, and the heaviest rainfall is observed in June and July. The south-west monsoon contributes about 65–80% of the annual rainfall. The north-east winter monsoon is more or less dry, giving rise to only a small amount of precipitation. The north-east monsoon starts by October and extends up to January, giving 10–20% of the annual amount of precipitation. In these conditions, the air masses coming from the Bay of Bengal and central Asia draw moisture from depleted east oceanic and continental sources, giving rise to more negative isotopic values and higher d-excess values.

The d-excess is defined as the excess deuterium that cannot be accounted for by equilibrium fractionation between water and vapour. Since condensation is an equilibrium process, d-excess is an indicator of kinetic fractionation during evaporation, governed by the molecular diffusivity of isotopic molecular species.[24] Kinetic fractionation can also be affected by the wind speed, temperature and relative humidity. The calculated d-excess value confirms that the vapour sources contributing to precipitation in Kozhikode are of different origin. The marine origin of the south-west summer monsoon samples is clear from its d-excess value of around 10.5, named LMWL1 on Fig. 4. The continental contribution to the winter north-east monsoon samples is characterized by its higher d-excess of around 14, named LMWL2 on Fig. 4.

In July 2008, during our first sampling, there was a summer monsoon, and both river and groundwater δ values fitted with the LMWL1 line with less depleted values, showing that the origin of the rainfall was the nearby Arabian Sea. In contrast, during December 2010, the more negative values and the shift to the LMWL2 were in accordance with the characteristic of continental air masses from the north-east winter monsoon. From October to December, there was a total rainfall of 786 mm, representing a strong winter monsoon contribution of around 18% of the total rainfall for the year. The February 2009 sampling was pre-monsoon, and represented an intermediate condition, with river water values between LMWL1 and LMWL2, and groundwater values a little under the LMWL1, showing limited evaporation during this drier period at low altitude (only 50 mm of rainfall from November 2008 to February 2009).

These changes in air masses between the summer and the winter monsoons also have an influence on the air moisture saturation. During the summer monsoon months, the relative humidity can reach 90%,[32] whereas, during December and January, it can drop to 55%, the high d-excess (>10) being favoured by the evaporation/recycling conditions under low humidity.[33]

CONCLUSIONS

On the one hand, this preliminary study reveals the homogeneity of the water characteristics over this narrow, lowland coastal area between Udupi and Mangalore. On the other hand, there is clearly a dual water source separating the summer monsoon with oceanic air moisture conditions from the winter monsoon with continental air masses. Although the annual total rainfall is high, there can be months with drier conditions as occurred in February 2009 when some shallow groundwater could begin to evaporate near the coastline. By contrast, further inland with greater elevation, the absence of a marked isotopic altitude gradient could suggest an important vapour-recycling process in high air moisture over tropical vegetation. This may lead to water cycling similar to the atmospheric functioning in the Amazon basin, but on a more modest scale. More work is needed to understand better the water/vapour circulation in this area, and to obtain more data on the river and groundwater interactions, constituent ions, and nutrient and contaminant transport.

Acknowledgements

We thank M. Tripti for helping in the field trip and on-site analyses of samples in India, and I. Moussa and D. Dalger for the isotopic measurements on the Shiva platform in Toulouse, France. We are grateful to the Ministry of Environment and Forests, India (project No.19/36/2006-RE), Manipal Centre for European Studies/European Commission for funding to one of the authors (KB), to carry out the field work and sample analysis.

REFERENCES

[1] J. D. Milliman, P. M. Syvitski. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.* **1992**, *100*, 524.

[2] M. Meybeck. Riverine transport of atmospheric carbon: source, global typology and budget. *Water Air Soil Pollut.* **1993**, *70*, 443.

[3] W. Ludwig, J. L. Probst. Predicting the oceanic input of organic carbon by continental erosion. *Global Biogeochem. Cycles* **1998**, *10*, 23.

[4] A. Coynal, H. Etcheber, G. Abril, E. Maneux, J. Dumas, J. E. Hurtrez. Contribution of small mountain rivers to particulate organic carbon input in the Bay of Biscay. *Biogeochemistry* **2005**, *74*, 151.

[5] T. K. Dalai, S. Krishnaswami, M. M. Sarin. Major ion chemistry in the headwaters of the Yamuna river system:

chemical weathering, its temperature dependence and CO_2 consumption rates. *Geochim. Cosmochim. Acta* **2002**, *66*, 3397.

[6] K. Pande, J. T. Padia, R. Ramesh, K. K. Sharma. Stable isotope systematics of surface water bodies in the Himalayans and trans-Himalayan (Kashmir) region. *Proc. Ind. Acad. Sci.* **2000**, *109*, 109.

[7] R. Ramesh, M. M. Sarin. Stable isotope study of the Ganga river system. *J. Hydrol.* **1992**, *139*, 49.

[8] A. Das, S. Krishnaswami, M. M. Sarin, K. Pande. Chemical weathering in the Krishna basin and Western Ghats of the Deccan Traps, India: rates of basalt weathering and their control. *Geochim. Cosmochim. Acta* **2005**, *69*, 2067.

[9] L. Lambs. Interactions between groundwater and surface water at river banks and the confluence of rivers. *J. Hydrol.* **2004**, *288*, 312.

[10] L. Lambs, K. Balakrishna, F. Brunet, J. L. Probst. Oxygen and hydrogen isotopic composition of major Indian rivers: a first global assessment. *Hydrological Processes* **2005**, *19*, 3345.

[11] M. M. Sarin, S. Krishnaswami, K. Dilli, B. L. K. Somayujulu, W. S. Moore. Major ion chemistry of the Ganga-Brahma putra river system: weathering processes and fluxes to the Bay of Bengal. *Geochim. Cosmochim. Acta* **1989**, *53*, 997.

[12] S. Krishnaswami, S. K. Singh, T. Dalai. Silicate weathering in the Himalaya: role in contributing to major ions and radiogenic Sr to the Bengal Bay, in *Ocean Science: Trends and Future Directions* (Proceedings INSA Seminar), (Ed: B. L. K. Somayujulu), Akademia Books International, New Delhi, **1999**, pp. 23–51.

[13] V. Galy, C. France-Lanord, B. Lartiges. Loading and fate of particulate organic carbon from the Himalaya to the Ganga-Brahmaputra delta. *Geochim. Cosmochim. Acta* **2008**, *72*, 1767.

[14] T. K. Dalai, S. Krishnaswami, A. Kumar. Sr and $^{87/86}$Sr in the Yamuna river system in the Himalaya: sources, fluxes and control on Sr isotope composition. *Geochim. Cosmochim. Acta* **2003**, *67*, 2931.

[15] C. Dessert, B. Dupré, L. M. Francois, J. Schott, J. Gaillardet, G. Chakrapani, S. Bajpai. Erosion of Deccan traps determined by river geochemistry: impact on the global climate and the $^{87/86}$Sr of sea water. *Earth Planet. Sci. Lett.* **2001**, *188*, 459.

[16] K. Balakrishna, J. L. Probst. Organic carbon transport and C/N ratio variations in alarge tropical river: Godavari as a case study, India. *Biogeochemistry* **2005**, *73*, 457.

[17] M. Sharma, K. Balakrishna, A. W. Hoffman, R. Shankar. The transport of osmium and strontium isotopes through a tropical estuary. *Geochim. Cosmochim. Acta* **2007**, *71*, 4856.

[18] E. Maneux, J. Dumas, O. Clement, H. Etchebert, X. Charritton, J. Etchart, E. Veyssy, P. Rimmelin. Assessment of suspended matter input into the oceans by small mountainous coastal rivers: the case of the Bay of Biscay. *CR Acad. Sci.* **1999**, *329*, 413.

[19] R. D. Deshpande, S. K. Bhattacharya, R. A. Jani, S. K. Gupta. Distribution of oxygen and hydrogen isotopes in shallow ground waters from southern India: influence of a dual monsoon system. *J. Hydrol.* **2003**, *271*, pp. 226–239.

[20] B. Kumar, S. P. Rai, U. S. Kumar, S. K. Verma, P. Garg, S. V. Vijaya Kumar, R. Jaiswal, B. K. Purendra, N. G. Pande. Isotopic characteristics of Indian precipitation. *Water Resources Res.* **2010**, *46*, W12548.

[21] G. Delaygue, E. Bard, C. Rollion, J. Jouzel, M. Stievenard, J. C. Duplessy, G. Ganssen. Oxygen isotope/salinity relationship in the northern Indian Ocean. *J. Geophys. Res.* **2001**, *106*, 4565.

[22] R. Rajesh. Hydrogeological studies of Nethravathi River Basin, Karnataka State, India, *PhD. thesis* (unpublished), Mangalore University, **1999**.

[23] T. R. S. Murthy, M. N. Madhyastha, I. J. Rao, K. N. Chandrashekarappa. A study of physical determinants of natural environments and their impacts on land use in Nethravati and Gurpur river basins of Western Ghats region, Karnataka. Project report, Ministry of Environment and Forest, Government of India, New Delhi, **1988**, p. 60.

[24] W. Dansgaard. Stable isotopes in precipitation. *Tellus* **1964**, *16*, 436.

[25] M. A. Scholl, S. B. Gingerich, G. W. Tribble. The influence of microclimates and fog on stable isotope signatures used in interpretation of regional hydrology: East Maui, Hawaii. *J. Hydrol.* **2002**, *264*, 170.

[26] K. Rozanski, L. Araguas-Araguas, R. Gonfiantini. Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records*, Geophys. Monogr. Ser., vol. 78, (Eds: P. K. Swart, *et al.*), AGU, Washington, DC, **1993**, pp. 1–36.

[27] S. K. Gupta, R. D. Despande. Synoptic hydrology of India from the data of isotopes in precipitation. *Curr. Sci.* **2003**, *85*, 1591.

[28] C. U. Warrier, M. P. Babu, P. Manjula, K. T. Velayudhan, A. S. Hameed, K. Vasu. Isotopic characterization of dual monsoon precipitation-evidence from Kerala, India. *Curr. Sci.* **2010**, *98*, 1487.

[29] X. Song, I. Kayane, T. Tanaka, J. Shimada. A study of the ground cycle in Sri Lanka using stable isotopes. *Hydrological Processes* **1999**, *13*, 1479.

[30] C. K. Rajan. Studies on some characteristics of Indian rainfall. *PhD. thesis*, Cochin University of Science and Technology, Cochin, India, **1988**.

[31] Y. P. Rao. Southwest monsoon, Meteorol. Monogr., Synoptic Meteorol. 1/**1976**, 367 pp., Indian Meteorol. Dep. Monogr., New Delhi.

[32] M. K. M. Rao, P. Jagannathan. Hydrometeorology. Geo Karnataka, MGD Centenary volume, Karnataka Assistant Geologists Association, **1994**, pp. 388–395.

[33] J. R. Gat, I. Carmi. Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. *J. Geophys. Res.* **1970**, *75*, 3039.