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Oxygen and hydrogen isotopic composition of major Indian rivers: a first global assessment

L. Lambs,[1]* K. Balakrishna,[2†] F. Brunet[2] and J. L. Probst[2‡]

[1] *Laboratoire Dynamique de la Biodiversité (LADYBIO), UMR 5172 CNRS–Université Paul Sabatier, 29 rue Marvig, 31055 Toulouse Cedex 04, France*
[2] *Laboratoire des Mécanismes de Transfert en Géologie (LMTG), UMR 5563 CNRS–Université Paul Sabatier, 14 avenue Edouard Belin, 31400 Toulouse, France*

Abstract:

Nine major rivers have been sampled around the Indian subcontinent to give an overview of the surface water characteristics. Both ^{18}O and deuterium have been measured to determine the origin of the water and the possible evapotranspiration process. The major ions have also been analysed to obtain complementary information. Although some basins have been studied previously (mainly in the north), this is the first attempt at a wider investigation of major Indian rivers. The results are discussed from the perspective of the hydroclimatological, geographical and geological specificity of the river basins. $\delta^{18}O$ values vary from light-isotope-enriched Himalayan rivers to heavy-isotope-enriched peninsular Indian rivers in a northwest–southeast gradient across the subcontinent. There is more evapotranspiration, leading to heavy isotope enrichment, in the peninsular (southern Deccan) rivers compared with the light-isotope-enriched snow- and glacier-melt-derived waters of the Himalayan rivers. The $\delta^{18}O$ values of Indian rivers correspond roughly to the $\delta^{18}O$ values of the rains falling over the subcontinent. However, the influence of tributaries is dominant over rainfall in rivers like the Narmada and Tapti. The Cauvery and Krishna rivers show maximum evapotranspiration and sodium pollution, as indicated by the $\delta^{18}O$ values, deuterium excess and major ion data. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS Indian rivers; stable isotopes; oxygen-18; deuterium

INTRODUCTION

India is a wide peninsula bordered by the Indian Ocean in the south, the Bay of Bengal in the east and the Arabian Sea in the west (Frederic, 1984). Northwest India is bound by the Thar Desert, and the north and northeast of India by the long Himalayan ranges. Most of the isotopic studies on water are focused on these areas (Ramesh and Sarin, 1992; Yadav, 1997; Pande *et al*., 2000; Dalai *et al*., 2002a).

The Indian rivers can be classified as (i) Himalayan, (ii) peninsular, (iii) coastal and (iv) inland. In the north, the high Himalayan Mountains (peaks from 6000 to 8800 m) represent a big reservoir of water with their snow and glacier systems. The two largest rivers flowing in India originate in the Himalayan ranges. The River Ganga comes from one part of these mountain valleys often ending by a long swamp band called *Terai* or *Dûar*, and the southern tributaries come from the Rajasthan and Madhya Pradesh hills, which are less perennial. The River Brahmaputra originates from the Tibetan side and comes back to India after skirting the mountains in the east. The combined delta of the Ganga and Brahmaputra represents the world's third largest

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*Correspondence to: L. Lambs, Laboratoire Dynamique de la Biodiversité (LADYBIO), UMR 5172 CNRS–Université Paul Sabatier, 29 rue Marvig, 31055 Toulouse Cedex 04, France. E-mail: lambs@cict.fr

† Present address: Department of Chemical Engineering, National Institute of Technology Karnataka, PO Srinivasnagar 575 025, Mangalore, India.

‡ Present address: Institut National Polytechnique, ENSAT/Agronomie Environnement Ecotoxicologie, Avenue de l'Agrobiopole, BP 107, 31326 Castanet Tolosan Cedex, France.

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river water discharge to the oceans, after the Amazon and Congo rivers. The peninsular rivers are located in the south on the old *Deccan* plateau (altitude from 500 to 1000 m) and are delimited by two coastal mountain ranges called *Ghâts* (altitude on the western side up to 2700m and on the eastern side up to 1300m). Owing to the slope of the Western Ghats, most of the rivers (Mahanadi, Godavari, Krishna and Cauvery) flow from west to east, into the Bay of Bengal. These rivers have denuded their beds for long geological ages and have developed flat valleys with low gradients. As they are entirely rain fed, many of them shrink into rivulets during the hot (lean flow) season. The coastal rivers originating from the Western Ghats flow to the Arabian Sea. The River Nethravati (Western Ghats) is one of them. Rivers of the inland system are centred in western Rajasthan State, like the Sambhar, which is lost in the desert sands. Only rivers located more to the south around Mount Vindhya, like the Rivers Narmada and Tapti, discharge into the Arabian Sea in the Gulf of Cambay.

The rainfall is very variable over this subcontinent, ranging from less than 250 mm in the Thar Desert to 5–7 m in Assam. Globally, the foothills (Himalayan slope and coastal part of the Western Ghats) are well watered, whereas it is drier from the Pakistan border to the central lands. But the rainfall is not regular over the year, mainly being supplied by the two monsoons. The violent summer monsoon (May/June–October) comes from the southwest and is responsible for the floods. The more moderate winter monsoon (April–May) comes from the northeast.

MATERIALS AND METHODS

Sampling techniques

Nine Indian rivers have been sampled; from east to west, these are the Brahmaputra, Ganga, Mahanadi, Godavari, Krishna, Cauvery, Nethravati, Narmada and Tapti (see Figure 1 and Table I). The first two are of Himalayan type, the next four are of the peninsular type, the seventh (Nethravati) is of the coastal type, and the last two are of the inland type. At the beginning of the summer monsoon (August 2001) for each river, three samples were collected close to their mouths, one for isotope analyses, one for major anion analyses and one for major cation analyses. Water samples were collected from the centre of the river from a bridge or a boat. The samples for major ions were collected in pre-cleaned ultra-pure water-soaked polypropylene bottles and were filtered by 0·45 μm pore size Millipore filters within a few hours of sample collection. The river waters for isotopic analysis were collected in 10 ml glass vials with secure caps and sent to the isotopic laboratory.

Table I. Indian basin river characteristics (mainly from University of New Hampshire, Global Runoff Data Center: http://www.grdc.sr.unh.edu/html/Stn.html)

River	Length (km)	Drainage basin area (km^2)	Water discharge (m^3 s^{-1}) min. < mean < max.	Mean specific discharge (l s^{-1} km^{-2})
Ganga	2295	941 400	1200 <12 000 < 65 000	12·7
Brahmaputra	2750	554 500	3000 < 21 000 < 59 000	37·9
Mahanadi	820	115 000	600 < 1800 < 3800	15·7
Godavari	1465	305 500	7 < 1900 < 34 500	6·2
Krishna	1170	252 000	0 < 1400 < 16 500	5·5
Cauvery	730	75 000	5 < 300 < 800[a]	4·0
Nethavrati	148	4200[a]	380[a]	90·0
Narmada	1175	94 000	10 < 900 < 11 200	9·6
Tapti	645	60 500	2 < 500 < 9800	8·3

[a] Shankar and Manjunatha (1994).

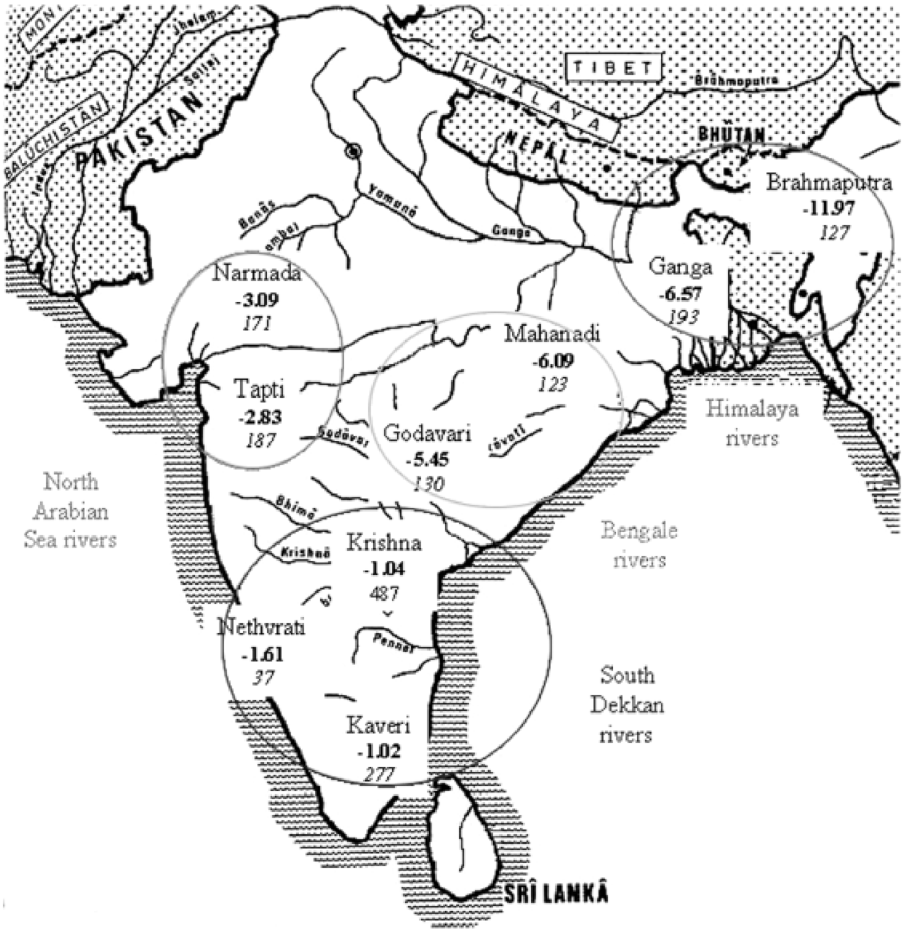

Figure 1. General position of the nine studied rivers in India. Under each river name, the $\delta^{18}O$ is given in dark and the conductivity value in italic. These results suggest the following groups: Himalayan river (Brahmaputra: BP), Bengal rivers (Ganga: GG, Mahanadi: MD, and Godavari: GD), Deccan rivers (Krishna: KR, Cauvery: CV and Nethravati: NR) and Arabian see rivers (Tapti: TP and Narmada: ND)

Analytical methods

The stable isotope composition of water is reported with reference to the Vienna standard mean ocean water (V-SMOW)/standard light Antarctic precipitation, in parts per thousand, defined by

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

and

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

The pH and conductivity were measured with an ionmeter (Consort C531). Major anions (chloride, sulphate, nitrate) were measured by ionic chromatography and the alkalinity was determined by Gran titration. Major cations (calcium, magnesium, sodium and potassium) were measured by atomic absorption spectrometry.

Characteristics of the different river basins

The River Ganga basin, the largest river in India, covers approximately 25% of the country's area; it is bound by the Himalayas in the north and the Vindhyan Ranges in the south. The Ganga has its source in the glaciers of the Greater Himalayas, which forms the frontier between India and Tibet in northwestern Uttar Pradesh. The Yamuna, the Ghagra, Gandak and Kosi are the main tributaries of the Ganga in the north and are fed by snow/glacier melting and summer monsoon rainfall. However, in the southern dry part, the small tributaries Chambal and Son are not perennial. The low water period is from January to March in the Himalayan valley and extends to January to May in the low-altitude plain. The high water period is centred in August. The water sampling was done in Patna after the confluence with the River Gandak on 12 August.

Rising in Tibet, the Brahmaputra flows east and then to the south to Arunachal Pradesh after cutting across the great Himalayan range and dropping rapidly in elevation. In these cold, high lands, the river presents a long low water regime between January and May. It continues to fall through gorges in Arunachal Pradesh until finally entering the wet Assam Valley. Many of these valleys display average annual rainfall of around 3000 mm. The Brahmaputra meanders westward, displaying a high water period from July to September, and joins the Ganga in Bangladesh. The water sampling was performed at Gawahati on 13 August.

The River Mahanadi, rising in the centre-west of India (Madhya Pradesh), is an important river in the state of Orissa. In the upper drainage basin of the Mahanadi, which is centred on the Chhattisgarh Plain, periodic droughts contrast with the situation in the delta region, where floods may damage crops in what is known as the rice bowl of Orissa. The water sampling was performed at Cuttack on 15 August.

The Godavari basin is the third largest Indian basin after the Ganges and Brahmaputra. The source of the Godavari is located northeast of Bombay (Mumbai) in the state of Maharashtra; it flows southeast across the whole of the Deccan Plateau over 1465 km to its mouth on the Andhra Pradesh coast. Its delta on the east coast is also one of the country's main rice-growing areas. Despite the large catchment area, its discharge is moderate because of the medium levels of annual rainfall (700–1000 mm). The low water period is from the end of December to early June, and the high water period is around August–September. The water sampling was performed at Rajahmundry on 16 August.

The River Krishna is the next longest south Indian river after the Godavari. It rises in the central Western Ghats and flows eastward into the Bay of Bengal. As the inland is relatively dry (700 to 250 mm), the discharge is low, with a hydrograph similar to the Godavari. The water sampling was performed at Vijayawada on 17 August.

The source of the Cauvery is in the southern part of the Western Ghats, in the state of Karnataka, near the Nilgiri (2637 m) and the Anai Mudi (2696 m) peaks. The waters of the river are a source of irrigation, and about 95% of the Cauvery is diverted for agricultural use before it empties into the Bay of Bengal. The water sampling was done near Tiruchchirappalli on 18 August.

Owing to the altitude of Western Ghats, the coastal hills are the wettest area of India after Assam. Annual rainfall of up to 6500 mm has been recorded. The mainly small rivers have limited drainage basin areas and flow from west to east. One of the main rivers of Karnataka is the River Nethravati, which originates near the Kudremukh peak (1893 m). The water sampling was done at Panemangalore on 22 August.

The Narmada and the Tapti are the only major rivers that flow into the Arabian Sea. The Narmada rises in Madhya Pradesh and crosses the state, passing swiftly through a narrow valley between the Vindhyan Range and spurs of the Satpura Range. It flows into the Gulf of Khambhat (or Cambay). The shorter Tapti follows a generally parallel course, between 80 and 160 km to the south of the Narmada, flowing through the states of Maharashtra and Gujarat on its way to the Gulf of Khambhat. These rivers display low water discharge from November to June and high water discharge in August. The water sampling was done at Surat and at Bharuch respectively on 10 August.

RESULTS

The ^{18}O and deuterium isotope results are reported in Table II and Figure 1. The values range from −12 to −1‰ for δ^{18}O and −85 to −6‰ for δ^2H. A northwest–southeast trend across the continent can be observed, parallel to the Himalayan range until the southern end of Deccan. Going from the more depleted (more negative values) in heavy isotopes to the less depleted, we have first the Himalayan rivers with the River Brahmaputra having a δ^{18}O value of around −12·0‰. This extremely negative value reveals the high content of glacier and snow which is typical for a high-altitude river. The Ganga, with its numerous active low-altitude tributaries, in this sampling season displays a moderate δ^{18}O value of around −6·6‰; a more negative value has been reported upstream. The next group, which includes the Mahanadi and the Godavari rivers, referred to as the Bengal rivers group, has a value of around −6‰. These rivers are less depleted in ^{18}O than the Himalayan rivers because they are only rain fed. The next group, referred to as the north Arabian Sea river group, comprises the Narmada and Tapti rivers and has a δ^{18}O value of around −3‰. The Deccan river group, comprising the Krishna, Cauvery and Nethravati, has water that is supplied by coastal rainfall, as they are much less depleted, with a δ^{18}O value of around −1‰. The δ^{18}O and δ^2H relationship is plotted in Figure 2a in comparison with the global meteoric water line (GMWL). Two points fall close to this line, those of the Brahmaputra and the Nethravati rivers. The mean slope of these nine points is about 7·1 ($\delta^2\text{H} = 7{\cdot}09\delta^{18}\text{O} - 1{\cdot}17$ with $r^2 = 0{\cdot}99$).

The deuterium excess is also calculated and the value is given in Table II. It provides a measure of non-equilibrium effects because it is the difference between measured δ^2H and the expected equilibrium value of δ^2H based on measured δ^{18}O. Only the Brahmaputra is close to the theoretical value of 10 for the deuterium excess, followed by the River Nethravati (6·4). The Krishna and the Cauvery rivers display lower values with negative values, possibly due to the evaporation process. The deuterium excess of all the other rivers ranges between 1·5 and 5. This result is supported by the very good relationship between the deuterium excess and the chloride concentration (Figure 2b). Indeed, when there are no or negligible evaporitic rocks in the drainage basin, one can assume that all chloride measured in the river waters is supplied by atmospheric precipitation (except if there is significant chloride pollution) and originates mainly from seawater (Stallard and Edmond, 1983; Probst *et al.*, 1994). The chloride concentration increases in going from rainwater (some micrograms per litre) to river water (some milligrams per litre) simply by virtue of the evapotranspiration process. Consequently, when there are no important anthropogenic inputs of chloride and no evaporitic rocks, one can consider that chloride concentration in river water is a good indicator of the evapotranspiration intensity. As seen in Figure 2b, the Krishna and the Cauvery, which have the lowest deuterium excess, exhibit the highest chloride concentrations. The good linear relationship between sodium and chloride concentration (Figure 2c) shows that the ratio Na/Cl does not change from one river to another, even if their ratio is very high (1·4 mg mg^{-1}) compared with seawater (0·56 mg mg^{-1}), showing that there are no significant inputs of

Table II. Isotopic and electro-chemical properties of the major Indian river water sampled during August 2001

River	δ^{18}O (‰)	δ^2H (‰)	D excess[a]	pH	Conductivity (μS cm^{-1})
Ganga	−6·57	−47·56	5·03	8·1	193
Brahmaputra	−11·97	−85·35	10·43	8·0	127
Mahanadi	−6·09	−46·54	2·22	8·0	123
Godavari	−5·45	−40·41	3·19	8·1	130
Krishna	−1·04	−12·20	−3·90	8·5	497
Cauvery	−1·02	−9·71	−1·52	8·7	277
Nethavrati	−1·61	−6·45	6·42	7·7	37
Narmada	−3·09	−22·48	2·23	8·1	171
Tapti	−2·83	−21·14	1·54	8·0	187

[a] Difference between measured δ^2H and expected equilibrium value of δ^2H based on measured δ^{18}O.

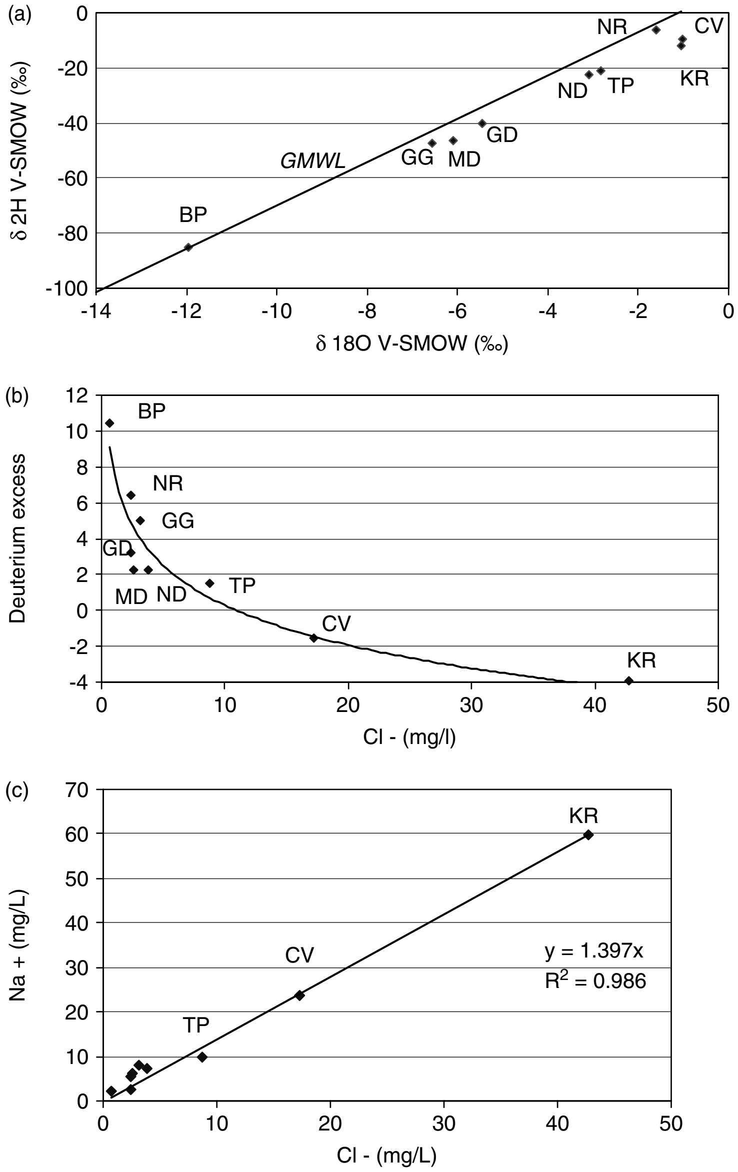

Figure 2. (a) Relation between δ^{18}O and δ^{2}H for the June sampling of the rivers. (b) Relationship between the deuterium excess and the chloride concentration. (c) Relation between chloride and sodium. The abbreviations for the river names are the same as in Figure 1

chloride from anthropogenic activities. Na/Cl ratios of all the major Indian rivers have ratios greater than the typical ratio for sea salt (i.e. 0·56 mg mg^{-1}). These rivers could derive a dominant portion of the Na from silicate weathering (Dalai *et al.*, 2002b). High Na/Cl ratios are also observed for most large river basins of the world on account of the weathering of silicate rocks (Probst *et al.*, 1994; Boeglin and Probst, 1998; Mortatti and Probst, 2003). Nevertheless, a small portion of Na could come from sea salt and halite deposits along the river catchments.

The Krishna and Cauvery rivers present the highest ionic charges, as seen from the conductivity values and the total dissolved solids (TDS). This is mainly due to the high concentrations of chloride, sulphate and

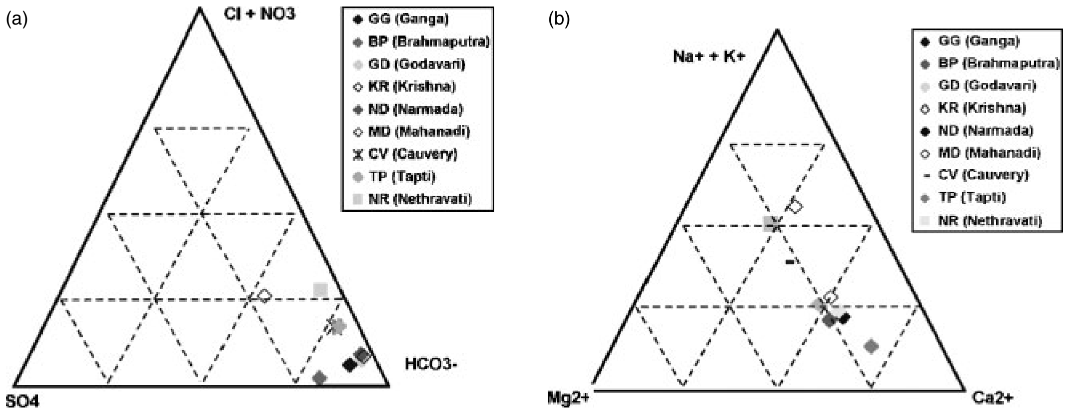

Figure 3. Ternary diagrams showing the anionic (a) and cationic (b) chemical compositions of the different Indian river waters

Table III. Physico-chemical characteristics (mg l^{-1}) of the major Indian river water sampled during August 2001

River	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	TDS
Ganges	3·10	2·36	7·56	116·08	7·98	3·08	5·56	23·88	174
Brahmaputra	0·64	0·75	11·19	67·36	2·31	2·30	2·87	17·65	109
Mahanadi	2·58	2·03	1·54	72·22	6·31	1·88	3·41	12·79	108
Godavari	2·43	1·85	2·29	75·66	5·58	1·70	3·55	14·50	112
Krishna	42·72	1·33	50·85	170·92	59·67	4·10	12·49	31·17	380
Cauvery	17·28	0·13	9·35	146·10	23·35	23·35	10·90	21·20	238
Nethavrati	2·37	0·60	0·72	12·66	2·62	0·54	0·95	1·41	26
Narmada	3·84	3·69	2·71	106·10	7·13	1·66	5·71	19·60	157
Tapti	8·75	5·08	4·84	98·82	9·71	1·47	6·26	18·91	160

sodium, which are very much higher than for the other rivers (see Table III). The ternary diagrams of the anionic (Figure 3a) and cationic (Figure 3b) composition show that the chemical composition of the northern river waters is close respectively to the calcium + magnesium pole and to alkalinity pole which correspond to the natural weathering of silicate and carbonate rocks. Whereas, the rivers from the southern Deccan exhibit higher proportions of chloride and sodium, showing the greater influence of the rainwaters originating from the seawaters and of the silicate weathering. These diagrams shows that all river waters have about the same percentage of magnesium (20–25%), potassium (2–5%) and nitrate (1–4%), but differ in their sodium versus calcium proportions and chloride + sulphate versus alkalinity proportions.

DISCUSSION

Rainfall gradient over India

If we look at the mean isotopic variation of rainfall over India as seen from the GNIP data set (Yurtsever and Gat, 1981; Araguas-Araguas *et al.* 2000, Gupta and Deshpande, 2003), one can distinguish four main areas corresponding to a general northwest–southeast gradient: (i) the west coast and the southern part of Deccan with $\delta^{18}O$ values between 0 and −2‰; (ii) the Thar Desert, the central part of Deccan and the east coast with values between −3 and −5‰; (iii) the lower Ganga and Brahmaputra valleys, with values around −6 to −7‰; (iv) the Himalayan ranges, from −8‰ to −15‰. This description can be complemented by different values from the literature reporting the isotopic composition of Himalayan rivers (Yamuna −10‰

(Dalai *et al.*, 2002a), Ganga −12 to −14‰ (Ramesh and Sarin, 1992; Lambs, 2000), Sutlej −14‰ and Indus −16‰) and glaciers (from −12 to −18‰ on the Indian side and −17 to −25‰ on the Tibetan side (Pande *et al.*, 2000)). A clear gradient can be seen when the river catchment is higher and deeper inside the Tibetan side. Yadav (1997) measured −3·2 to −6·4‰ in Rajasthan rain and −3·6 to −5·4‰ in small rivers in July. Our isotopic measurements on the Indian rivers are in accordance with this general compilation of the rainfall over India. For the Deccan river group, the river waters range between −1 and −1·6‰ against the mean rainfall between 0 and −2‰. For the Arabian Sea group the average value is −3‰, and for the Bengal river group the values range between −5·5 and −6‰ against the mean rainfall range between −3 and −5‰. The Ganga isotopic value (−6·5‰) is in accordance with the mean rainfall isotopic values (−6 to −7‰) and the groundwater measurement in Allahabad of −6·4‰ (Lambs, 2004). The more depleted value found for the Brahmaputra (−12‰) represents mainly snow and ice melt. For the same river, during April and December, Ramesh and Sarin (1992) found the δ^2H values of −65‰ and −37‰, which correspond to δ^{18}O values of about −5·7‰ and −9·7‰ respectively, revealing a higher contribution of the lower altitude tributaries. This example shows that the isotopic general northwest–southeast gradient of the rainfall, due to continental and altitude effects, cannot in fact be applied to the river water. First, all riverbeds are not parallel to this gradient orientation. The Narmada and Tapti rivers flow perpendicular to this gradient, consequently their isotopic composition is the sum of contributions from different tributaries. However, the inland influence is smaller due to lower precipitation. For large rivers, like the Ganga, which effectively flows along this gradient, the influence from the northern tributaries (a Himalayan river, very depleted in heavy isotopes) and the southern tributaries (central Indian rivers, less depleted) is very contrasting. Second, the influence of the monsoon must be considered. In the north of India, air masses carrying large amounts of moisture move in a northwesterly direction from the northern Bay of Bengal during the monsoon season and shed a significant fraction of their moisture during their transit in spells of heavy rainfalls. Such rainfalls reaching the northwestern Himalayan region are depleted isotopically with low δ values (Dalai *et al.*, 2002a). Third, the monsoon clouds are blocked by the high Himalayan ranges, and catchment areas of the Trans-Himalayan rivers receive less precipitation, mainly in the form of snow, which explains their low isotopic values.

Comparison with river water isotopic data

The Himalayan rivers have been studied mainly in their mountain catchments. Curiously stable isotope data for Indian rivers (^{18}O and deuterium) were missing in the international literature before the 1990s. The pioneering work done by Ramesh and Sarin (sampling in 1982) and the one reported through the IAEA (sampling in 1981 and 1983) were published respectively 10 years later (Ramesh and Sarin, 1992) and 20 years later (Rozanski *et al.*, 2001).

The data compilation of these complementary samplings could give us an idea of the seasonal variation of δ^{18}O in the Himalayan rivers (see Figure 4). The more numerous data of the River Indus have been added for a better visualization, since the headwater basins of these rivers are very close (Lambs, 2000). Less-negative values are observed from April/May to August, which correspond to high discharge in river from the monsoon rains. The beginning of the monsoon is also a warmer period in the Ganga plain and basin, and the rainwater mixed with snowmelt could explain the isotopic variation observed during this season. Moreover, the variability of the intensity and the beginning of the monsoon (±2 weeks) for each year gives a relatively high interannual variation. The more negative values are found during fall, coming from glacier melt, their isotopic signature (δ^{18}O ≈ -13‰) being less hidden by the other sources of water. This seasonal effect is in contrast to what can be observed for other mountain rivers, like the Rhine or the Danube in Europe, or even rivers in cold areas, like the St Lawrence in Canada, where the more negative values are found in summer (Rozanski *et al.*, 2001).

The δ^{18}O–δ^2H relationship

Understanding the relationship between δ^{18}O and δ^2H in rain and surface waters helps to assess the role of evapotranspiration in altering their isotopic composition. Table IV reports the relationship between δ^2H and

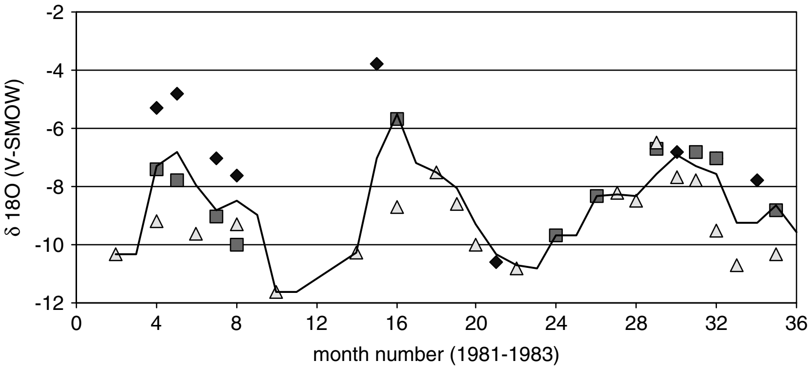

Figure 4. Visualization of the seasonal effects of the $\delta^{18}O$ for the Himalayan rivers (Ganga: rhombus; Brahmaputra: square; Indus: triangle) as obtained by combining the data of Rozanski *et al.* (2001), 35 points for the 1981–83 period, and the data of Ramesh and Sarin (1992), four points to complete the missing data in 1982. The solid line is the moving mean calculated from the mean value of each month

Table IV. Isotopic studies about the rainfall in India and closed country

Slope ($\delta^2H/\delta^{18}O$)	Deuterium excess	Location	Reference
$6{\cdot}9 \pm 0{\cdot}1$	$2{\cdot}1 \pm 0{\cdot}8$	Gangetic plains	Bhattacharya *et al.* (1985)
$7{\cdot}2 \pm 0{\cdot}1$	$5{\cdot}1 \pm 0{\cdot}1$	North India	Ramesh and Sarin (1992)
$7{\cdot}80 \pm 0{\cdot}05$	$7{\cdot}2 \pm 0{\cdot}4$	New Delhi (monsoon)	Dalai *et al.* (2002a)
7·5	10·0	River Indus basin	Karim and Veizer (2002)
7·28	11·56	Kabul	Karim and Veizer (2002)
7·3	7·6	Sri Lanka (wet zone)	Song *et al.* (1999)
6·5	2·0	Sri Lanka (dry zone)	Song *et al.* (1999)

$\delta^{18}O$ for rainfall over stations in India and in neighbouring countries, which can be considered as the local meteoric water line.

The general slope is around $7{\cdot}1 \pm 0{\cdot}2$, with lower values for the dry areas. In contrast, during the summer monsoon the slope (7·8) is closer to the GMWL, defined first by Craig (1961) and then completed by Rozanski *et al.* (1993), i.e. $\delta^2H = 8{\cdot}17\delta^{18}O + 10{\cdot}3$.

In general, the river meteoric water line slope is in the range of about 7 to 8·5, as per the equation, and is within the normal range for precipitation, whereas slopes in the range 6–7 as per the equation may indeed reflect substantial amounts of post-rainfall evapotranspiration (Kendall and Coplen, 2001). The slope also varies with the altitude. Pande *et al.* (2000) found a slope of 9·12 for the headwaters of the Indus, and Ramesh and Sarin (1992) found a slope of 7·45 in the headwaters of the Ganga and 6·08 for the lowland Ganga. Even for the latter slope, if we separate the data from March and from October we get a seasonal effect with slopes of 5·51 and 6·95 respectively. Furthermore, Dalai *et al.* (2002a) found different slopes for the Yamuna (the main tributary of the Ganga), of 5·61 in June and 6·34 in October.

In Figure 2a, $\delta^{18}O$ versus δ^2H values of the Brahmaputra and the Nethravati rivers fall close to the GMWL, indicating that there is no evaporation process going on in these rivers. For the other rivers we observe that the greater the distance from the GMWL, the greater is the evapotranspiration. Therefore, the Cauvery and Krishna rivers are the most affected by evapotranspiration processes. In March 2001, the River Ganga displays a $\delta^{18}O$ value of $-7{\cdot}0‰$ in the foothills of the Himalayas in the city of Hardwar, and this value drops to $-4{\cdot}2‰$ at Allahabad, 700 km downstream (Lambs, 2004). The fact that the River Yamuna joins the Ganga downstream of Allahabad and displays about the same value ($-4{\cdot}1‰$) removes the possibility of the influence of tributaries. Furthermore, the fact that the local groundwater has a low $\delta^{18}O$ value of about $-6{\cdot}4‰$ explains that this is due to evapotranspiration during the low water and warm period.

Deuterium excess

Low humidity conditions in the source region enhance kinetic evapotranspiration, resulting in a lower slope of the $\delta^{18}O$–$\delta^{2}H$ regression line (<8) and a higher deuterium excess in the resulting precipitation (Clark and Fritz, 1997). In contrast, precipitation resulting from a source at high humidity defines a $\delta^{18}O$–$\delta^{2}H$ regression line closer to the GMWL (slope of 8) and has deuterium excess (*d* value) close to 10. For precipitation at New Delhi, Araguas *et al.* (1998) observed a long-term annual average *d* value a little lower at 8·5‰. The deuterium excess from our rivers ranges from 10 to −2‰. Dalai *et al.* (2002a) found a deuterium excess ranging from 17 to 5‰ for the River Yamuna and its tributaries, and also found a negative correlation between $\delta^{18}O$ and the *d* value. This trend could result from different mixing proportions of water from two end members, i.e. snow/glacier melt and precipitation. Glacier melt for the River Brahmaputra gives a higher *d* value (Dalai *et al.*, 2002a). Effectively, only the Brahmaputra is close to the theoretical value of 10; this previous report's effect could compensate for an evapotranspiration process observed at a lower and hotter altitude. All the other rivers have lower deuterium excess values, from +6 to −4‰, which shows a progressive evapotranspiration process from north to south. Araguas *et al.* (1998) have shown that partial evaporation of raindrops below the cloud base, under conditions of low relative humidity, light rainfall and higher temperature, could substantially reduce deuterium excess collected at ground level. The rivers displaying the more negative deuterium excess, i.e. the Krishna and Cauvery, are also the more concentrated, which could indicate a more significant evaporation of the water. The fact that the River Krishna displays chloride and sulphate concentrations above 25 mg l^{-1} could also be due to water pollution. This can also be seen with the specific discharge obtained by dividing the mean discharge from the drainage basin area (see Table I). The Brahmaputra displays a higher value (38 $l\ s^{-1}\ km^{-2}$), whereas the other northern rivers present values around 10 $l\ s^{-1}\ km^{-2}$, a value also found for other tropical rivers. The five southern rivers display lower specific discharges, at around 5 $l\ s^{-1}\ km^{-2}$. In the middle of the Deccan, there is a lack of precipitation, and even in the central part the rainfall is as low as in the Thar Desert (less than 250 mm $year^{-1}$). In contrast, the Deccan coasts, mainly on the west side, are very wet. This explains why the River Nethravati is the only southern river with a high deuterium excess.

CONCLUSIONS

The Indian subcontinent displays a wide range of oxygen and deuterium isotopic values, with a northwest–southeast-trending isotopic gradient parallel to the Himalayan range; the heavy isotope depletion increases with continental and altitude effects. There is a pronounced seasonal effect due to the multiple origin of waters (mainly for the Himalayan rivers) and the influence of the monsoon. During the hot season (i.e. pre-monsoon) and low water flow conditions, significant evapotranspiration could exist, as seen from the deuterium excess. During the wet summer monsoon, the high entry of seawater masses reduced the evapotranspiration processes. The high chloride concentrations of the Krishna and Kavery rivers from southern Deccan could confirm this result.

More samples are necessary to complete this pioneering work on Indian rivers. Better understanding of the water characteristics and origins will help to improve the management of the substantial water needs (potable water, irrigation, industry) of this expanding country.

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