Groundwater isotopic investigations in India: What has been learned?

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A large number of isotopic measurements on groundwaters have been made in different parts of the country in connection with several local investigations. These measurements were made over a period of more than three decades. These published data are compiled and reviewed in this article to identify the surface and atmospheric processes and boundary conditions that define the isotopic character of groundwater on regional scale. Based on limited number of available repeat measurements, it is shown that barring specific conditions, seasonal or interannual variability in isotopic character of groundwater is small (<1‰ in the $\delta^{18}O$). This seems to result from processes of selection, mixing and dispersion during groundwater recharge through the unsaturated soil zone. This has enabled treating available single measurements made in different years/seasons as characterizing the local groundwater isotopically. This assumption may not be strictly valid, particularly under conditions of thin soil cover and if the underlying aquifers have secondary porosity comprising of fractures and fissures – regions where residence time of water in the soil column may not be sufficient to homogenize the percolating water before reaching the water table. It is shown that in spite of this limitation, groundwater isotopic data in large contiguous regions exhibit characters that can be explained as due to geographic and climatic control on isotope signature of precipitation and the groundwater recharge process. The data also reveal some interesting features in terms of atmospheric sources of vapours and evapotranspiration recycling.

Keywords: Groundwater, hydrological cycle, interannual variability, isotopes, seasonal variability.

VARIATIONS in stable isotopic compositions of oxygen and hydrogen constituting the water molecule (also referred to as stable water isotopes) have been used in several studies[1,2] to identify water sources for precipitation and for identifying post-precipitation processes during groundwater recharge[3]. This has been possible because stable water isotopes are influenced directly by the atmospheric processes (e.g. water vapour advection, condensation or evaporation) and during groundwater recharge (e.g. selection, evapotranspiration, mixing and dispersion). Often, interpretation of isotope data is complicated because a number of simultaneous processes may affect the evolution of isotope character of particular rain event/s[4] and surface/groundwater body[3].

It is obvious that primary sources of water for rains over India have to be in the Arabian Sea (AS), the Bay of Bengal (BOB) or the Southern Indian Ocean (SOI). Recycling through evapotranspiration of precipitated water over land can also be a significant source of vapour. The relative proportion of each varies not only temporally but also spatially. To identify the source area of precipitated water (i.e. location from which vapour originated) is important for understanding the detailed structure of the regional hydrological cycle. The ratio of precipitation that originates over land to the total precipitation amount is termed as 'continental cycling ratio'. Quantifying the degree of water originated from land is also important because it gives useful information on possible interactions between land surface hydrology and climate[4].

Since stable isotopic compositions of the atmospheric moisture and precipitation and consequently the groundwater are intimately related to the origin of vapour and its fate in the atmosphere and over land, any large-scale modification of the regional hydrological cycle may affect moisture/water balance and isotopic compositions of different reservoirs throughout the region. It is, therefore, necessary to monitor such changes in the isotopic composition of all the components of hydrological cycle, in time and space, as a measure of changing water budget. The present compilation of groundwater stable isotopic measurements is expected to provide a baseline for understanding and monitoring the changing hydrology of India over the next few decades as rapid development and utilization of water resources of the country takes place.

Basics of isotope hydrology

Stable isotope compositions are normally reported as δ values in units of parts per thousand (denoted as ‰) relative to a standard of known composition. The δ values are calculated using: $\delta\ (\text{in}‰) = (R_x/R_s - 1)1000$. Here R denotes the ratio of heavy to light isotope (e.g. $^{18}O/^{16}O$ or D/H) and R_x and R_s are these ratios in the sample and standard respectively. δD and $\delta^{18}O$ values are normally reported relative to SMOW (Standard Mean Ocean Water[5]) or the equivalent VSMOW (Vienna–SMOW[6]) standard.

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In spite of the great complexity in different components of the hydrological cycle, $\delta^{18}O$ and δD in meteoric waters behave in a predictable manner and correlate to define a global meteoric water line (GMWL)[7]. This correlation was further refined[8] as:

$$\delta D = 8.17(\pm 0.07) * \delta^{18}O + 11.27(\pm 0.65)‰ \text{ VSMOW} \quad (1)$$

Deviations of many regional or local meteoric water lines (LMWLs) from GMWL help to identify the climatic and geographical dimensions of hydrological processes and provenance of different water masses.

During exchange process between reservoirs, the process of isotope fractionation can be equilibrium type (e.g. condensation of water drops in the cloud) or non-equilibrium or kinetic type (e.g. diffusion or evaporation from a water body). In general, heavier isotopes preferentially tend to stay with the more condense phase in any fractionation process. The equilibrium fractionation is strongly dependent on temperature whereas the kinetic fractionation is strongly dependent on relative humidity. The kinetic fractionation for ^{18}O is more than that for D. Therefore, during the process of evaporation[9], the relative enrichment of the residual water is more for ^{18}O than for D.

The slope 8 of GMWL corresponds to the ratio of equilibrium fractionation factors of D and ^{18}O at an average 'in cloud' condensation temperature (~25°C), whereas the intercept of 10 arises[3] due to kinetic evaporation of ocean water at an average relative humidity of ~85%. A parameter '*d*-excess' as $d = \delta D - 8*\delta^{18}O$ (‰) has been defined[10] to identify the relative magnitude of kinetic fractionation in different water masses.

Within the cloud, equilibrium fractionation between vapour and the condensing phases preferentially partitions ^{18}O and D into rain or snow. As a result, along the trajectory of the air masses, each rainout preferentially removes the heavy isotopes from the vapour. The remaining vapour then becomes progressively depleted both in ^{18}O and D. Whereas each rainout gives isotopically enriched rain with respect to the remaining vapour, it will be depleted with respect to earlier rainout. In this process, the vapour mass also decreases progressively. This isotope evolution during rainout according to Rayleigh distillation equation has been modelled[3,11].

When part of the rained out vapour is returned to the atmosphere by means of evapotranspiration, the simple Rayleigh distillation equation no longer applies. Transpiration, despite the complex fractionation in leaf water[12,13], returns precipitated water essentially un-fractionated to the atmosphere and reduces the effect of rainout. Unlike transpiration, evaporation usually returns heavy species depleted vapour that is closer to the composition of the atmospheric vapour.

As the evaporation proceeds, the residual water not only enriches in heaver isotopes but also shows progressively lower *d*-excess values due to relatively more enrichment of ^{18}O. The resulting vapour on the other hand shows the opposite effect. The condensation, and consequently rainout, does not significantly alter the *d*-excess as it is an equilibrium process (with slope ~8). Due to the involvement of evaporation, most meteoric and subsurface processes shift the $\delta^{18}O$–δD signatures of water to a position below the LMWL. It is rare to find precipitation or groundwater that plots above the line, i.e. showing higher *d*-excess. But, re-evaporation of precipitated water under low-humidity regions creates vapour masses with isotopic content that plots above the LMWL. If such vapour is re-condensed in any significant quantity before mixing with the larger tropospheric reservoir, the resulting rainwater will also plot above LMWL[3].

A small fraction of rain percolates down through the soil layer eventually to become groundwater. For many groundwaters, their isotopic compositions equal the mean weighted annual composition of precipitation[3,14–16] although significant modification of meteoric signal is also found particularly in arid zones[17,18].

To better understand the processes modifying the meteoric water isotopes in groundwater, a brief description of isotopic characteristics of precipitation over India is presented in the following.

Isotopes in precipitation over India

Weighted annual distribution of $\delta^{18}O$ and *d*-excess of precipitation downloaded and cropped from GNIP data base maintained by IAEA/WMO (available at URL: http://www.isohis.iaea.org) is shown in Figure 1. The $\delta^{18}O$ of precipitation is seen to progressively decrease from +2‰ to –2‰ range along the northern part of the west coast to –2‰ to –6‰ range towards the east coast. In fact, rains over much of India have $\delta^{18}O$ values in the range –2‰ to –6‰. The Himalayan region and the foothills have isotopically lighter precipitation. Qualitatively, the observed distribution has been explained by a dominant source of vapour originating from the Arabian Sea/ Indian Ocean during the SW monsoon and rainout largely along the indicated trajectory (Figure 1 *a*) coupled with such geographical effects as orography in the Himalayan region, differing dominant source regions for SW and NE monsoon seasons, evaporation from falling raindrops and local recycling of precipitated water in certain regions[11]. The effect of heavy rainout along Western Ghats is, however, not discernable. The rainout effect along the Bay of Bengal branch of the SW monsoon can also be identified in the observed isotopic depletion between Kolkata and New Delhi, though altitude effect of the Himalayas could also be a contributing factor. Further insight is provided by the distribution of *d*-excess of the precipitation (Figure 1 *b*). The most striking feature is a large region in Central India with *d*-excess in the 4‰ to 8‰ range. This region

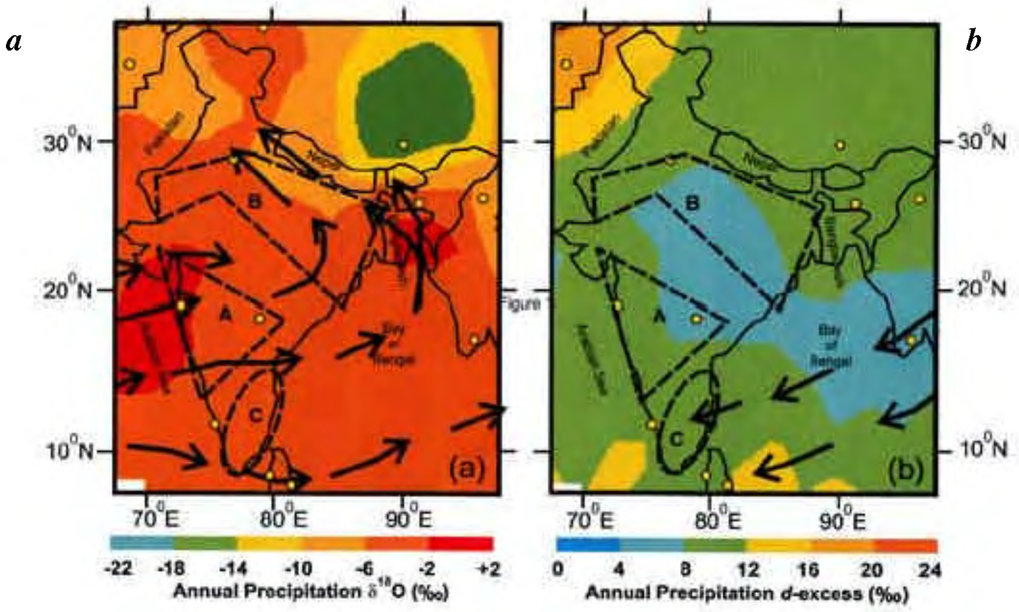

Figure 1. Maps showing distribution of (***a***) amount weighted $\delta^{18}O$ and (***b***) *d*-excess in annual precipitation over India, appropriately cropped from the regional data available at http://isohis.iaea.org. The open circles represent the locations of the GNIP/IAEA network stations for which at least one full year of data was available and has been used in preparation of these maps. The SW summer monsoon and the NE winter monsoon circulations (re-drawn from ref. 39) are superposed over the maps for $\delta^{18}O$ and *d*-excess respectively. The three regions A, B and C have primarily been identified based on distribution of groundwater $\delta^{18}O$ shown in Figure 4 *a*.

Table 1. Equations of LMWLs for different Indian stations based on GNIP data base and other sources

Station	LMWL ($\delta D = a*\delta^{18}O + b$)	Data source
Mumbai (Bombay)	$\delta D = (8.0 \pm 0.3)*\delta^{18}O + (8.4 \pm 0.8)$ [$R^2 = 0.94$]	GNIP
Kozikode	$\delta D = (7.2 \pm 0.2)*\delta^{18}O + (7.6 \pm 0.8)$ [$R^2 = 0.99$]	GNIP
New Delhi	$\delta D = (7.2 \pm 0.1)*\delta^{18}O + (4.6 \pm 0.5)$ [$R^2 = 0.95$]	GNIP
Shillong	$\delta D = (8.0 \pm 0.2)*\delta^{18}O + (11.9 \pm 1.1)$ [$R^2 = 0.98$]	GNIP
Allahabad	$\delta D = (7.5 \pm 0.2)*\delta^{18}O + (4.4 \pm 1.9)$ [$R^2 = 0.99$]	GNIP
Nainital	$\delta D = (7.5 \pm 0.4)*\delta^{18}O + (4.8 \pm 4.0)$ [$R^2 = 0.97$]	Nachiappan *et al.*[18]
North Gujarat	$\delta D = (7.6 \pm 0.6)*\delta^{18}O - (2.9 \pm 2.2)$ [$R^2 = 0.89$]	PRL, Unpublished
Lower Maner Basin	$\delta D = (7.3 \pm 0.1)*\delta^{18}O + (4.0 \pm 1.1)$ [$R^2 = 0.98$]	Kumar *et al.*[27]

overlies areas that have relatively medium (100–150 cm) annual rainfall. On the other hand, the rain-shadow side of the Western Ghats and north western India with rainfall <75 cm (Figure 2 *a*) show *d*-excess of annual precipitation in the range 8–12‰ (Figure 1 *b*).

Equations of LMWLs based on available isotope data of precipitation for the different Indian stations are given in Table 1. It is seen that slopes of the various LMWLs range from 7.2 to 8.0, though intercepts are more variable from –2.9‰ in North Gujarat to +11.9‰ at Shillong. Both these parameters at different stations depend on various factors such as relative humidity during rainy season and contribution of land derived vapour etc. that govern isotope fractionation process. Despite these and the very limited database, it is seen from Table 1 and Figure 2 *a*, that both the slopes and the intercepts of the LMWLs in the country show a qualitative correspondence with the average annual rainfall. In regions of higher average annual rainfall, the LMWL slope is closer to GMWL slope of ~8 and intercept closer to ~10‰. This is because, in general, the average annual rainfall distribution (Figure 2 *a*) is seen to be inversely correlated with the potential evapotranspiration (PET) distribution (Figure 2 *b*), which significantly depends on the relative humidity. Therefore, it is clear that lowering of the slopes, intercepts of the LMWLs, and hence *d*-excess of the local rainwater, are caused by evaporation from the falling raindrops, particularly in the arid regions of the country.

The differing seasonal distributions of isotopes at Mumbai (Bombay) and New Delhi representing two different regions of the Indian monsoon have been explained by differing mechanism of precipitation and moisture source

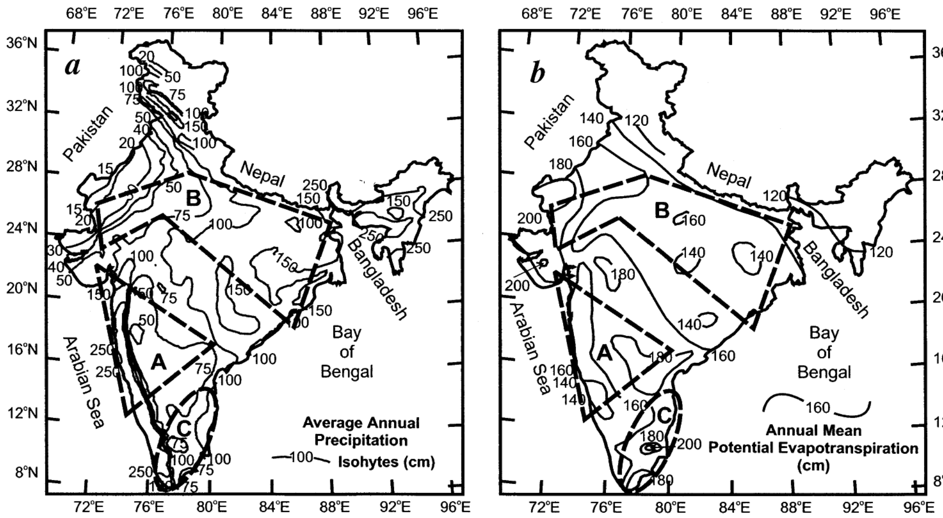

Figure 2. The three regions A, B and C from Figure 4 *a* are superposed on the distributions of average annual (***a***) rainfall (redrawn from ref. 49) and (***b***) potential evapotranspiration (redrawn from ref. 56). It is seen that the two meteorological parameters of a region control the isotopic composition of the precipitation (cf. Figure 1), that is further modified by evaporation from surface and soil water contributing to characteristic isotopic signature of local groundwater (cf. Figure 4 *a*).

regions[19]. The effect of evaporation from falling raindrops also contributes significantly to this seasonally differing pattern at New Delhi[20].

On the regional scale spatial and temporal variability of stable isotope composition of precipitation has been explained in terms of meteorological and pluviometric regime of climatology and atmospheric circulation pattern[21]. The variation of stable isotopes in monsoonal rains of Sri Lanka has also been studied[22].

The very limited database of isotopes in precipitation over India, however, does not permit the isotopic distributions in Figure 1 to reveal all the expected features. It is, therefore, useful to compare and understand the processes revealed by the isotopic distributions based on comparatively larger number (550) of spatially distributed groundwater samples across the country.

Isotopes in groundwater from India

A compilation of published isotopic data on groundwater samples from across India analysed over the last three decades is given in a downloadable tabular form at (URL: http://www.prl.res.in/%7Ewebprl/web/announce/ind-gw.pdf).

Several groundwater measurements for which geographic coordinates could not be ascertained are not included in this table. Such measurements represent <5% of all reported measurements (~600). In case of the multiple measurements for the same groundwater source an average value has been used. Observations (Figure 3) from those few locations, where multiple measurements are available, suggest that temporal variations are likely to be <1‰ in $\delta^{18}O$ of groundwaters that may not be near (<1 km) a large surface water bodies (pond, lake, etc.) and/or not located in areas with thin soil cover or do not have secondary porosity (e.g. joints, fractures and fissures). Geographic distributions of all $\delta^{18}O$ and *d*-excess values included in the present compilation of groundwater isotopic data are shown in Figure 4. Locations of the reported groundwater samples are plotted in Figure 5 *a*. The broad physiographic subdivisions of the country that the sample locations belong to, are shown in Figure 5 *b*. It is evident from Figure 4 and Figure 5 *a* that large parts of the northern India and north-eastern India have so far not been covered by any groundwater isotopic investigation. It is also seen that sample density, even in the covered part of the country, is not uniform as shown in Figure 5 *a*. In fact, several large areas exist without any representative sample pointing to the limitations of the present review. To the extent the areas of sampling gaps exist, the conclusions of this study will remain tentative.

Based on groundwater $\delta^{18}O$ distribution (Figure 4 *a*), the country can be broadly subdivided in three contiguous regions A, B and C with transition areas in between. The region A is approximately triangular in outline and covers most of Maharashtra and parts of the neighbouring states of Karnataka, Andhra Pradesh, Madhya Pradesh, Goa and Gujarat (see Figure 5 *a*). In physiographic terms it comprises the northern section of the Western Ghats and the adjoining northern Deccan Plateau (Figure 5 *b*). The groundwater in this region is characterized by $\delta^{18}O > -2‰$ (Figure 4 *a*) and *d*-excess values <5‰ except in the southern coastal belt where the *d*-excess values lie between 5 and 15‰ (Figure 4 *b*). Outline of the hexalateral region B includes areas in West Bengal, Orissa, Bihar, Madhya Pradesh, Uttar Pradesh, Delhi and parts of Rajasthan and Gujarat

(Figure 5 *a*). The physiography of the area covers parts of the Eastern Plateau, the Ganga Plains, North and South Central Highlands and Western Plains (Figure 5 *b*). The groundwater in this region is characterized by $\delta^{18}O < -4‰$ (Figure 4 *a*), progressively increasing from east coast (Orissa and West Bengal) to <–8‰ towards the North. Groundwaters in much of Rajasthan also exhibit a depleted ($\delta^{18}O < -5‰$) isotope character. The *d*-excess of groundwater in region B, show progressively lower values from

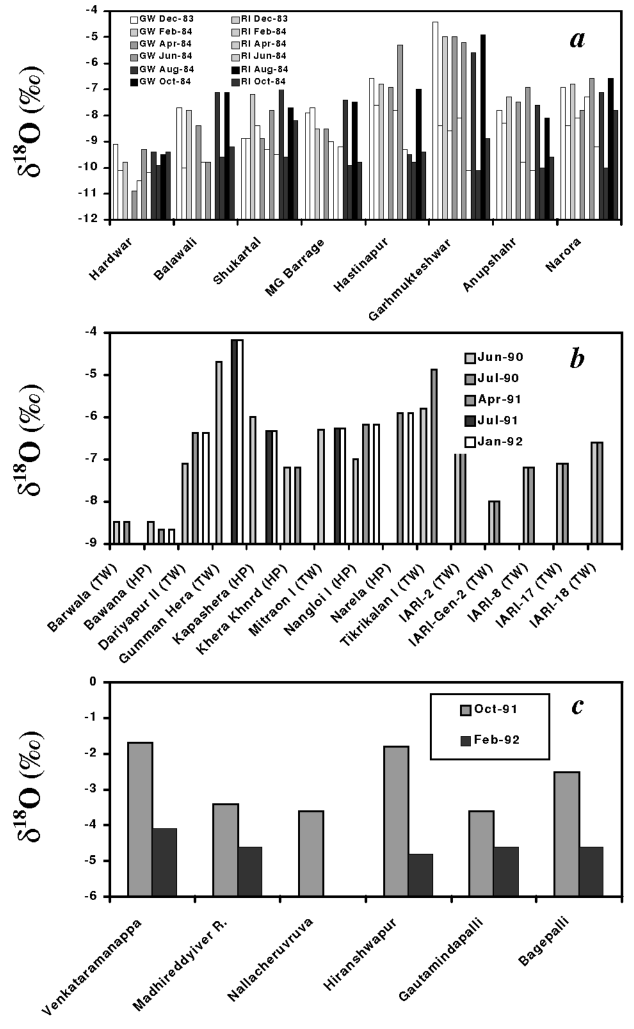

Figure 3. ***a***, Temporal variation of $\delta^{18}O$ in groundwater and river water samples along River Ganga (Hardwar–Narora sector: after ref. 55) indicating: (i) groundwater at a given location has a distinct average isotopic character that does not change much with time; (ii) the river water on the other hand change their seasonal isotope character in such a way that during monsoon spatial distributions tend to disappear (Aug 84) and in post-monsoon season they progressively tend to acquire the isotope character of the local groundwater indicating effluent discharge of groundwater. ***b***, Temporal variation of $\delta^{18}O$ of some groundwater samples in Delhi (after ref. 46) showing that in this region also the average isotopic character of groundwater varies with location but does not change much with time. ***c***, An example showing significant variation in isotope character of groundwater (Kolar District, Karnataka: after ref. 57) in response to recharge following a storm event in hard rock terrain with thin soil cover and fracture and fissures type of secondary porosity.

coastal areas in Orissa, West Bengal towards Delhi and then an increasing trend towards southwest Rajasthan and Gujarat (Figure 4 *b*). The region C is approximately ellipsoidal in outline and covers nearly all of Tamil Nadu, southern Andhra Pradesh, south-eastern Karnataka and southern part of Kerala. In physiographic terms the western part of region C comprises parts of southern Western Ghats, whereas the eastern part of the region C comprises the East Coast Plains. This part of the country also receives significant rain during the NE winter monsoon season. The $\delta^{18}O$ of groundwater in this region is mostly <–3‰ (Figure 4 *a*) and the *d*-excess mostly <5‰ (Figure 4 *b*), except in parts of Tamil Nadu coast and some hill regions around Bangalore, where lower (<–4‰) values of $\delta^{18}O$ are also seen.

Having described the observed gross isotopic characters of groundwater found in different parts of the country, the factors that impart these characteristics are examined in the following.

Discussion

The $\delta^{18}O$–δD regressions of the groundwater samples included in this study are shown in Figure 6 *a*. It is seen that slopes and intercepts of the various regression lines are lower than the GMWL and the LMWLs for which the precipitation data are available (Table 1). The slope of the best fit line to all groundwater data in $\delta^{18}O$–δD plot is 6.6 with an intercept of only 0.3‰. The lowering of groundwater $\delta^{18}O$–δD regression line slope and intercept with respect to the LMWLs indicates that the combined effect of local atmospheric and ground surface processes results in minor to significant evaporation of water before groundwater recharge. This evaporation is additional to transpiration that does not change the slope of the evolving water in the $\delta^{18}O$–δD field.

Based on $\delta^{18}O$ of the three regions A, B and C, the entire dataset is sub-divided in three broad subgroups namely, <–4‰, between –4‰ and –2‰ and >–2‰. It is seen (Figure 6 *a*) that the first two subgroups nearly fit the same regression line, but it is difficult to fit a regression line to the third subgroup, i.e. for samples with $\delta^{18}O > -2‰$. The very large scatter seen for this subgroup is probably due to clubbing together of the differently evolved groundwaters – starting with different average precipitation isotopic values having undergone evaporation to different extents before recharge. This is also evident from Figure 6 *b*, where an approximate decrease in *d*-excess with increase in $\delta^{18}O$ is seen. The groundwaters with $\delta^{18}O > -2‰$ are largely from the region A. In this region, however, samples from the coastal belt and the Western Ghats show *d*-excess values between 5 and 15‰ (Figure 4 *b*) associated with average annual rainfall >250 cm (Figure 2 *a*); whereas the rest of the region A that overlies the rain shadow zone (average annual rainfall <75 cm; Figure 2 *a*) of northern Western

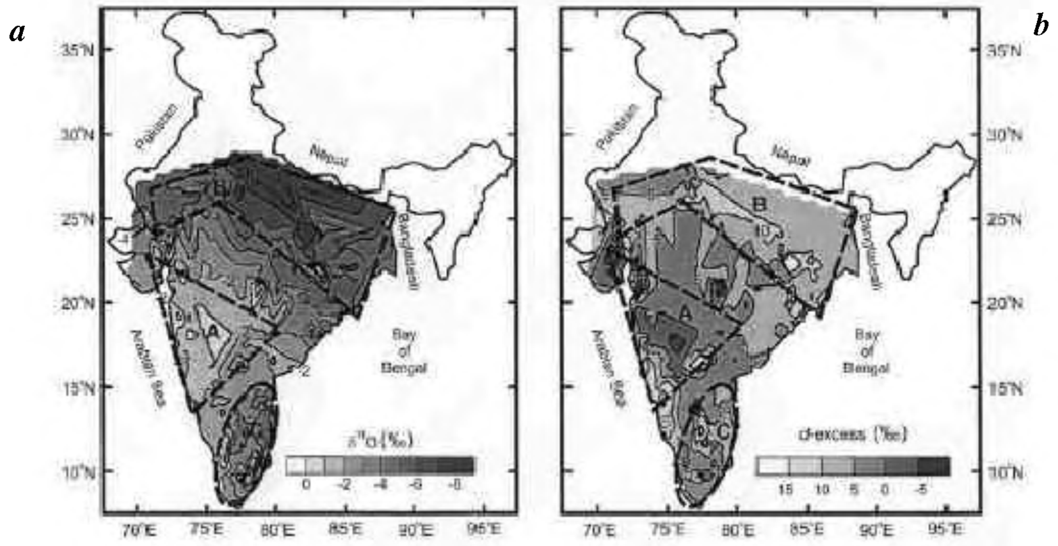

Figure 4. Spatial distribution of (***a***) of $\delta^{18}O$ and (***b***) *d*-excess in groundwater samples based on compilation (available at URL: http://www.prl.res.in/%7Ewebprl/web/announce/ind-gw.pdf) of isotopic measurements. Sampling locations are marked in Figure 5 *a*. At most stations only one measurement is available. For groundwater sources having multiple measurements (<1%) an average value has been used. Based on $\delta^{18}O$ distribution, the country can be broadly subdivided in three contiguous regions A, B and C with transition areas in between.

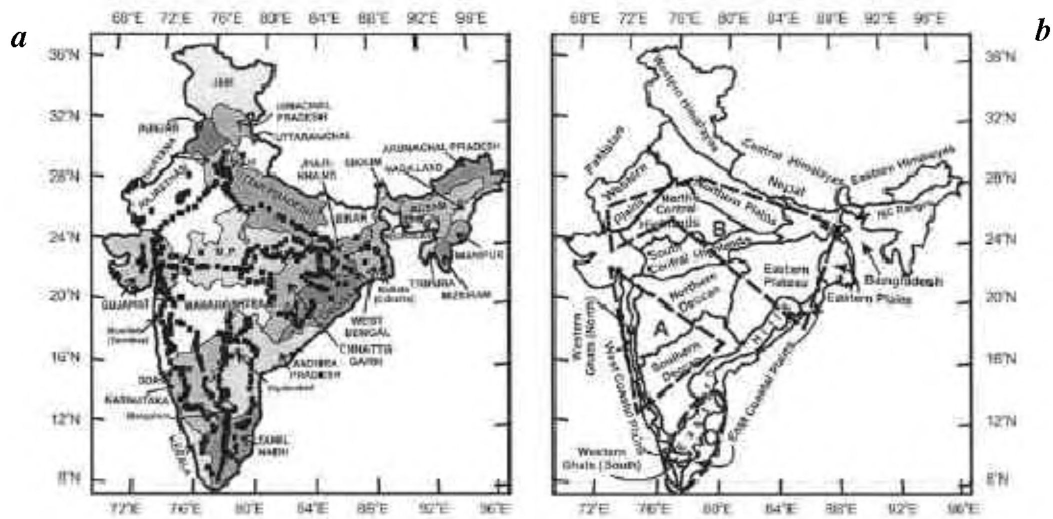

Figure 5. ***a***, Sample locations for which stable isotopic data of groundwater has been used in this study are superposed on a map of India giving names of regions/places that have been referred to in the text. ***b***, The control of physiographic features on isotopic distribution of groundwater is seen by superposition of the regions A, B and C (see Figure 4 *a*) on a physiographic map of India (redrawn from ref. 49).

Ghats and north and south Deccan (Figure 5 *b*) has *d*-excess <5‰. Some parts of the Deccan Plateau and Gujarat show the lowest (<0‰) *d*-excess values (Figure 4 *b*). It is clear from the equations of LMWLs in Table 1, that primary precipitation in these regions may already have had evaporation from falling raindrop. Comparison of Figures 1 *a* and 4 *a* suggests that post-precipitation evaporation from surface water and/or soil moisture in response to high PET of the region (Figure 2 *b*), must contribute to very large lowering of the *d*-excess and the increase in $\delta^{18}O$ of groundwater. The observed absence of rainout related depletion, even in groundwater $\delta^{18}O$ in the region A, expected due to heavy rainout on west coast, can also be attributed to high PET over this region. The presence of heavy black soil rich in montmorillonite having swell and shrink characteristics over the region A (Figure 7 *a*) seems to facilitate evaporation by retarding the infiltration of soil water.

In the region B, $\delta^{18}O$ of groundwaters decrease progressively from the coastal regions in Orissa – West Bengal towards Delhi and the foothills of Himalayas, following the general direction of the Bay of Bengal branch of the SW monsoon (Figure 1 *a*) which is also associated with depressions and cyclonic storms that originate, beginning July, in the northern BOB and move north-westerly in the northern India with highest frequency in August and September (Figures 7 *b* and *c*). Movement of these monsoon depressions overland is associated with heavy rainout of the atmospheric vapours along their tracks. This rainout process leads to decreasing precipitation away from the coastal areas (Figure 2 *a*) and to a gradual decrease in heavy isotope content of precipitation along their tracks. As observed from Figures 1 *a* and 4 *a*, the $\delta^{18}O$ of groundwaters in this segment essentially reflect the characters inherited from the precipitation. The *d*-excess of the groundwaters in this region (Figure 4 *b*) vary between 5 and 15‰, again reflecting inheritance from precipitation (Figure 1 *a*). No significant post-precipitation modification of isotopic composition observed in groundwaters of this section is most likely due to relatively larger fraction of precipitation being recharged to groundwater, facilitated by the relatively higher rainfall (Figure 2 *a*), lower PET (Figure 2 *b*), and lighter alluvial soils (Figure 7 *a*) with comparatively higher permeability. Based on a compilation of studies using tritium tagging of soil moisture for estimating fractional groundwater recharge in the country it has been shown that the highest fractional recharge of groundwater occurs in this part of the country[23].

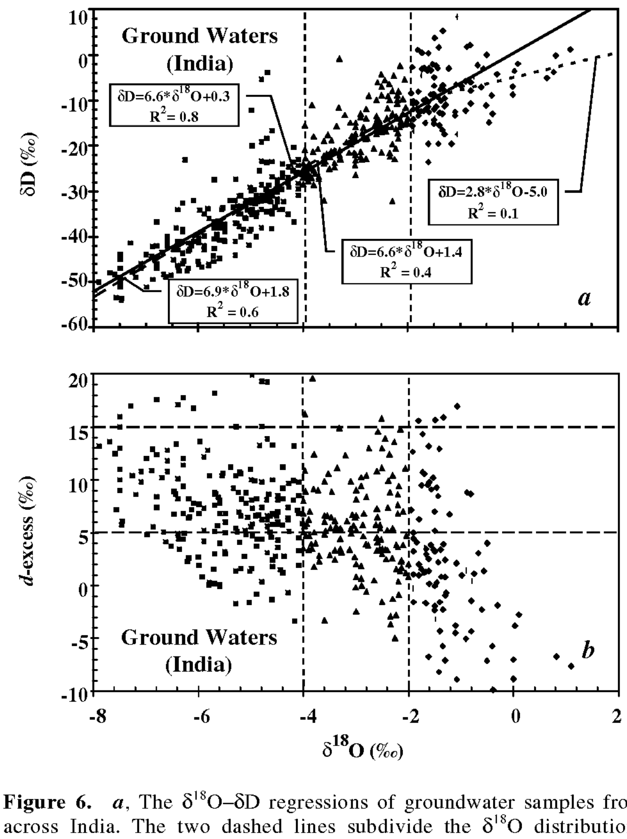

Figure 6. *a*, The $\delta^{18}O$–δD regressions of groundwater samples from across India. The two dashed lines subdivide the $\delta^{18}O$ distributions which are also shown by different symbols. The regression lines for the samples in subdivisions '$\delta^{18}O < -4$‰' and '-4‰ $\delta^{18}O$ -2‰' are not distinguishable from that for the total data set. But no regression line can be drawn through the subdivision '$\delta^{18}O > -2$‰'. ***b***, The *d*-excess vs $\delta^{18}O$ plot shows that all three above subdivisions have samples on both sides of the '15‰ *d*-excess 5‰'; but a progressive increase in proportion of sample with *d*-excess <5‰ is seen with increasing $\delta^{18}O$. Also a progressive decrease in proportion of sample with *d*-excess >15‰ is seen with increasing $\delta^{18}O$.

Beyond Delhi, towards Rajasthan and Gujarat in south west direction in the region B, the $\delta^{18}O$ in groundwaters first increases to > -4‰ and then decreases again to < -6‰, whereas the *d*-excess largely stays within 5–10‰. Due to low rainfall and high PET the soil moisture built even in lighter alluvial soils of the region (Figure 7 *a*) in smaller rain events is almost completely lost by evapotranspiration. Only the big rainfall events that lead to groundwater recharge of a fraction that quickly infiltrates to soil layers. This selection of heavy rainfall events imparts the lowered $\delta^{18}O$ without decreasing the *d*-excess as one moves to progressively desertic parts of Rajasthan.

The region C is the only part of India that receives significant precipitation during both summer SW monsoon and the winter NE monsoons; but the decreasing $\delta^{18}O$ of groundwater is in the direction opposite to the NE monsoon trajectory. Absence of isotopic data on NE monsoon signatures from this region, therefore, constrains the interpretation of groundwater data. The groundwaters in the western part of this region (Figure 4 *a*) showing high $\delta^{18}O$ (> -2‰) and low *d*-excess (< 0‰) obviously reflect the SW monsoon source under the influence of high PET (Figure 2 *b*). The eastern part, on the other hand, shows distinctly lower $\delta^{18}O$ (< -4‰) influenced by a combination of (i) rainout of the SW monsoon and (ii) depleted heavy isotope character of the vapour source of the NE monsoon from the continental areas of central Asia and the oceanic areas of the Bay of Bengal[24]. The *d*-excess values in large part are <5‰ and suggest that a combination of high PET (Figure 2 *b*) and the shallow black soil facilitate significant post-precipitation evaporation before groundwater recharge. Some areas on the eastern hills, however, have a distinct high *d*-excess (>5‰). It has been suggested earlier[24] that high *d*-excess seen in groundwater in this area is inherited from precipitation having a component of kinetically controlled re-evaporated vapour.

The transitional areas, between the three regions A, B and C, obviously have mixed characters. Even so, it is interesting to note a fair resemblance between the distribution of *d*-excess parameter (Figure 4 *b*) and the surface soils (Figure 7 *a*) suggesting that the surface (up to ~1 m) soil permeability may be playing an important role in post-precipitation modification of the primary isotopic signal. Presently, it is not possible to quantitatively test this hypothesis because data on permeability of surface soils is not available. However, compilation of studies using tritium tagging of soil moisture for estimating fractional groundwater recharge in the country[23] lends some support to this.

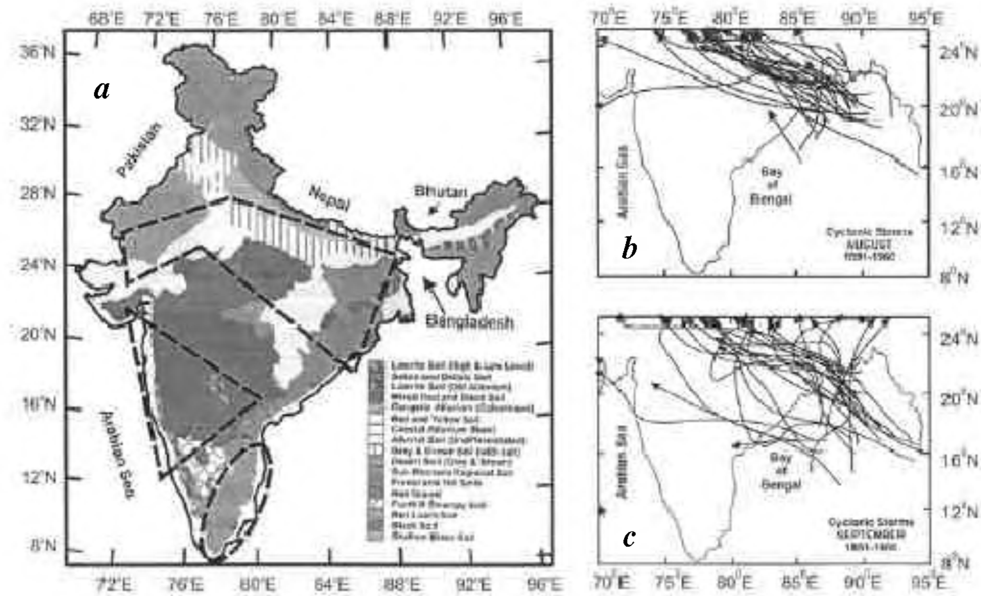

Figure 7. ***a***, The three regions A, B and C from Figure 4 *a* are superposed on the soil map of India (redrawn from ref. 29). It is seen that regions with low permeability surface soils facilitate larger evaporative modification of precipitated water before groundwater recharge. The significant variations in *d*-excess distribution (Figure 4 *b*) in regions A, B and C are seen to be influenced by the surface soil characteristics and the PET (Figure 2 *b*). ***b*** and ***c***, Tracks of cyclonic storms (redrawn from ref. 48) that originate, beginning July, in northern BOB and move north-westerly in northern India with highest frequency in August and September are shown respectively in (***b***) and (***c***).

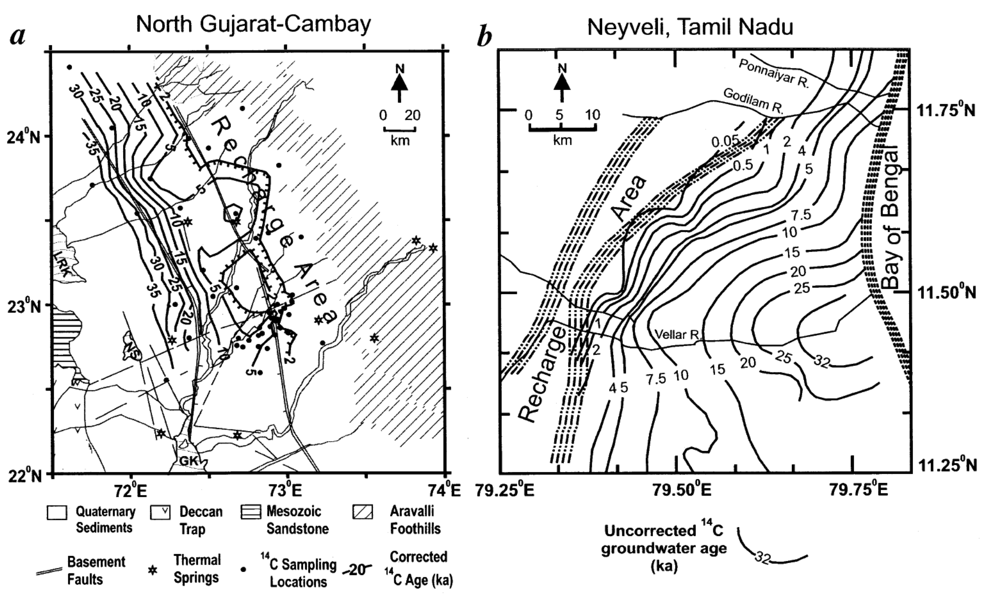

Figure 8. Two examples of radiocarbon dating of regional aquifer-systems in India. ***a***, North Gujarat–Cambay region (redrawn from ref. 26). ***b***, Neyveli region in Tamil Nadu (redrawn from ref. 25). In both cases radiocarbon contours indicate slow flushing rate of regional aquifers and the isotopic compositions of water dating back to the last Interglacial period indicated dry-arid climate compared to the present.

In the foregoing, the focus was only on the groundwater isotopic data of shallow unconfined aquifers. There have also been two important studies from India[25,26] employing radiocarbon dating (Figures 8 *a* and *b*) of groundwater. These indicated that in regional alluvial aquifer systems, with several confined aquifers, the movement of groundwater away from the recharge area is extremely slow (<10 m/yr). It was also shown that in spite of considerable mixing and dispersion accompanying movement, groundwaters recharged over thousands of years ago and having moved tens to hundreds of kilometers away, still retains some of their characters acquired at the time of groundwater recharge. The isotopic characters of groundwater in the Neyveli region[25] and the EC and fluoride content in case of North Gujarat[26] aquifers have been identified as differentiating the groundwater recharge that occurred at the time around the last glacial maxima about 20 thousand years ago from the present day recharge.

Summary and conclusions

Available data of isotopic measurements of shallow unconfined groundwater samples from different parts of the country and measured by different laboratories have been compiled and distribution of $\delta^{18}O$ and *d*-excess parameters have been studied in relation to distributions of (i) sources of primary precipitation; (ii) available distribution of isotopes in primary precipitation; (iii) physiographic features; (iv) annual precipitation amount; (v) annual mean potential evapotranspiration; and (vi) surface soils.

Despite limitations of data availability, the following conclusions seem justified:

- Temporal variations in groundwater sources that may not be near (<1 km) a large surface water body (pond, lake, etc.) and/or not located in areas with thin soil cover or do not have secondary porosity (e.g. joints, fractures and fissures) are unlikely to be >1‰ in $\delta^{18}O$.
- Based on $\delta^{18}O$ distributions of groundwater, the country can be broadly subdivided in three contiguous regions A ($\delta^{18}O > -2$‰), B ($\delta^{18}O < -4$‰) and C ($\delta^{18}O$ around –3‰ to –4‰) with transition areas in between.
- The slope and intercept of the $\delta^{18}O$–δD regression line for all groundwater samples is lower than the GMWL or the LMWLs, indicating minor to significant evaporation of precipitated water before groundwater recharge.
- Pre-recharge modification of the isotopic character of precipitated water is caused by a variety of surface and atmospheric processes (evapo-transpiration, recycling, infiltration and selection) as also the boundary conditions (surface soils, physiographic features, proximity to surface water). One or more factors may be dominant in different geographical regions.
- In coastal parts of the region A, dominated by heavy rainfall from the Arabian Sea branch of the SW monsoon, groundwaters largely reflect isotopic characters of the rainfall. But on the rain shadow side of the Western Ghats, with high PET and low permeability black soil, signatures of significant pre-recharge evaporative enrichment of heavy isotopes are evident.
- In contrast, the groundwater in region B largely retains the isotope character of precipitation acquired from the Bay of Bengal Branch of the SW monsoon. This is facilitated by a combination of factors such as relatively larger rainfall, lower PET, more permeable soil cover and selection effect, particularly in the desertic areas.
- In the region C, with a dual monsoon system, groundwaters in coastal areas retain isotopic signatures of Arabian Sea branch of the SW monsoon on the west coast and of NE winter monsoon on the east coast. In the interior areas, high PET and low permeability soil cover lead to evaporative enrichment of heavy isotopes except on Eastern Hills.
- In regional alluvial aquifer systems, groundwaters recharged over thousands of years ago and having moved tens to hundreds of kilometers away, still retain some of their characters acquired at the time of groundwater recharge.

Epilogue

The 550-odd groundwater samples that form the basis of this paper were analysed over a period of more than three decades. Even with these limited data, it has been possible to extract the process related information concerning the hydrological cycle components over India, though only qualitatively. The present exercise has shown that hydrological processes and interactions between various components do leave identifiable signatures in isotopic variations of water constituents. Extracting quantified process related information from isotopic signatures however, requires that thousands of measurements from different hydrological reservoirs be made in a short time of few years and data interpreted in conjunction with conventional measurements of meteorological and geographical parameters, river discharges, groundwater pumping, shallow subsurface geology, etc. Over the vast country, this may seem like a Herculean task, but this is accomplishable if multidisciplinary researchers join hands and minds passionately. Only then can this activity provide improved understanding of the hydrological cycle and a database for large scale development planning of water resources in the country.

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MEETINGS/SYMPOSIA/SEMINARS

Third National Conference on Nonlinear Systems and Dynamics (NCNSD–2006)

Date: 6–8 February 2006
Place: Chennai

Topics include: Classical deterministic chaos; Hamiltonian and quantum chaos; Control of chaos and synchronization; Turbulence; Nonlinear optics; Nonlinearity in magnetohydrodynamics, plasma and astrophysics; Nonlinear phenomena in engineering and social sciences; Integrable systems and solitons; Self-organized criticality; Spatio-temporal pattern formation; Fractal geometry; Bifurcation theory; Time series analysis and other mathematical approaches; Nonlinear phenomena in medical and biological sciences.

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National Conference on Earthquake Analysis and Design of Structures (EQADS-06)

Date: 2–3 February 2006
Place: Coimbatore

Topics include: Engineering seismology; Modeling and analysis of building structures; Design and construction; Application of software packages for analysis and design; Recent trends and modern methods; Health monitoring; Case studies; Retrofitting materials principles and techniques; Soil structure interaction; Issues in seismic awareness and education.

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