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Correlation of conductivity and stable isotope ^{18}O for the assessment of water origin in river system

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Abstract

When working on wetlands, or other surface and subsurface water systems with multiple water sources, it is not always easy to identify the mixing between the different waters. Here, we have tried to adapt an easy technique, i.e., conductivity, but regularly standardised against stable natural isotope ^{18}O, to immediately give a glimpse on the field site of the percentage the two kinds of water. In certain cases, this method is also valid to discriminate a third source of water. The first experimental site to be described is in a meander of the Garonne river in south-west France, where there exists an interesting case of active paleo-channels. The second site is located in North India, in the Himalayas mountains, Garhwal, at the source of the Ganges river. Here, the samples were taken to discriminate between snow and glacier melt.

Keywords: Wetland; Conductivity; Stable isotope; Oxygen 18

1. Introduction

Methodologies based on the use of naturally occurring isotopes have a large spectrum of applications for hydrological problems encountered in water resources research. The production and behaviour of these stable isotopes in the hydrological cycle are controlled by various processes, and observations of their concentration distribution (in time and space) in a given system enable inferences to be made concerning the system under study. Consequently, they have the distinct advantage of facilitating the study of water movement and related hydrological processes on a much larger temporal/spatial scale than is possible with intentionally injected tracers, which are often employed for studying site-specific local scale problems (Yurtsever, 1995).

The ^{18}O intrinsic meteoric tracer has been useful in the identification of water sources in headwater catchments (Hardegree et al., 1995). High analytical costs and intensive sample preparation make the use of stable isotope tracers impractical in environments such as wetlands which are characterised by rapid changes in water table elevation.

In these types of dynamic environments, a more rapid assessment of physical/chemical characteristics is needed to provide insight on water origins and mixing. White et al. (1987) used in situ temperature measurements to identify the area of surface

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water–ground water mixing. Groundwater electrolytes have long been used to calculate the mixing of water. However, in riparian zones, these kinds of result are often difficult to interpret. Some authors have shown that for instance, chloride and oxygen 18 have different sensitivities (Marc et al., 1995). Canadian researchers (Azetzu-Scoot and Tan, 1997) have studied the correlation between the salinity and oxygen 18 content in the surface layer of these high latitude waters, to study the distribution of sea ice melt water and meteoric water (rain, snow).

Conductivity is certainly the best approach to have an immediate assessment of the water composition of piezometers. During the summer baseflow, it has been also possible to detect the output of phreatic water in the river water by passing the conductivity cell under the water along the bank. At the maximum of the signal, river water samples at about 30 cm depth have been taken for isotope measurements, which have confirmed the high content of phreatic water. This is an advantage of the immediate technique, which gives enough information for making an intelligent sampling.

In this study, the objective was to correlate conductivity with oxygen 18 analysis of water origins in two sites: the Garonne river in France and the high tributaries of the Ganges in Himalayas. In the first site, the aim was to analyse the progressive elution of groundwater in a gravel bar by the penetrating river water. The existence of active paleo-channels identified by dye injections (Bernard et al., 1994), at a lower elevation than the surface river water, give rise to a complicated system with variable mixing areas in the subsurface. To understand this system, samples were also taken around the gravel bar: the riparian wood land and the poplar plantation. In the second example, we have studied high altitude meteoric waters. About 30 to 50% of the total annual water yield of the rivers in this area of Northern India is provided by the snow and glacier melt runoff (Singh and Quick, 1993). But in spite of their prime importance for the management of water resources, including irrigation, only few seasonal snow melt runoff forecasting studies have been carried out (Singh and Quick, 1993; Singh et al., 1997). The aim of this second study was to find an easy way to differentiate between glacier melt and snow melt in surface water.

2. Materials and method

2.1. Site description

The first study site is located on a 2 km long gravel bar along the Garonne river, a 7th order

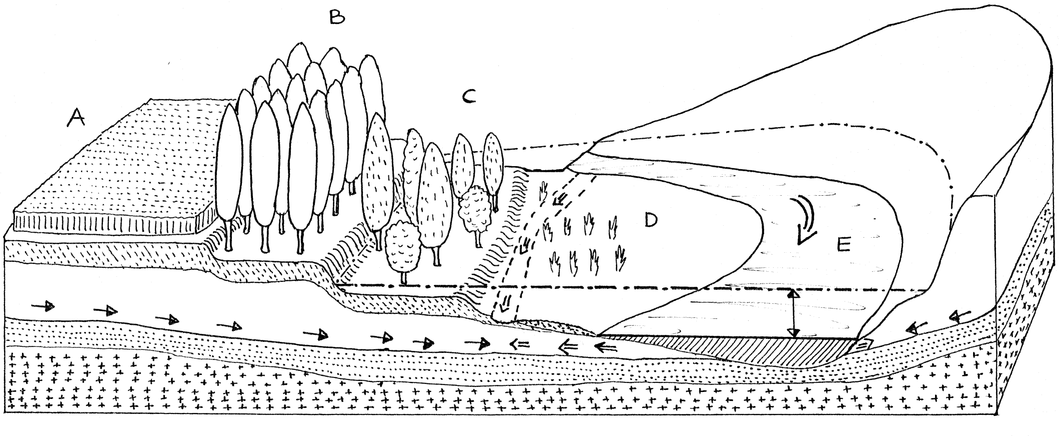

Fig. 1. Schematic view of the Garonne river meander, in France. From up to down, we have first the agricultural field area (A), where the ground reference is sampled from a well, the poplar plantation (B), equipped with wide piezometers, the natural riparian forest (C) also equipped with wide piezometers, then the gravel bar (D) with small piezometers and the river bed (E). The dotted lines on the gravel bar show the old channel where the river water enters the subsurface. The single arrow represents the schematic phreatic water circulation and the double arrow the river water flow. The horizontal alternate line shows the average level of the annual floods.

stream, about 50 km downstream of Toulouse, France. The position of the site is about 43°53′N and 1°12′E, at a altitude of 90 m. Subsurface water was collected in a series of 30 piezometers (1.5 to 2.5 m PVC or PE pipes, 2 cm wide and perforated at the end) positioned along three transects. In the upper banks which are occupied by a natural riparian vegetation and a poplar plantation (see Fig. 1), 18 piezometers (5 to 6 m long, 63 to 100 mm wide PVC pipes) were used to monitor chemistry of ground water entering the gravel bar.

The second site is far most east, in the Indian Himalayas area called Garhwal, in the Kumaon range, North of the Uttar Pradesh (about 350 km NE from New-Delhi, see Fig. 2). The three main effluents of the Ganges have the position and elevation at three respective villages: Gangotri (31°01′N and 78°56′E, altitude 3140 m), Kedarnath (30°44N and 79°04E, altitude 3584 m) and Badrinath (30°45N and 79°30E, altitude 3122 m). The stream water was collected just before the Monsoon. Here, two samplings were also performed, one for the conductivity and pH measurements, and the second for the isotopic analysis. Sixteen sites were sampled, mainly in the first valley, Bhagirati river between Gangotri and the main glacier at Gaumukh (3900 m). This valley now protected by the Indian Ministry of Environment and Forest, is characterised by abundant conifer forest of deodar until 3300 m high, followed by birch and small willow up to 3800 m. Glaciers, like the Bhagirathi bamak with 28 km long, take the snow up the 6500 to 7075 m peaks range, whereas, the limit of

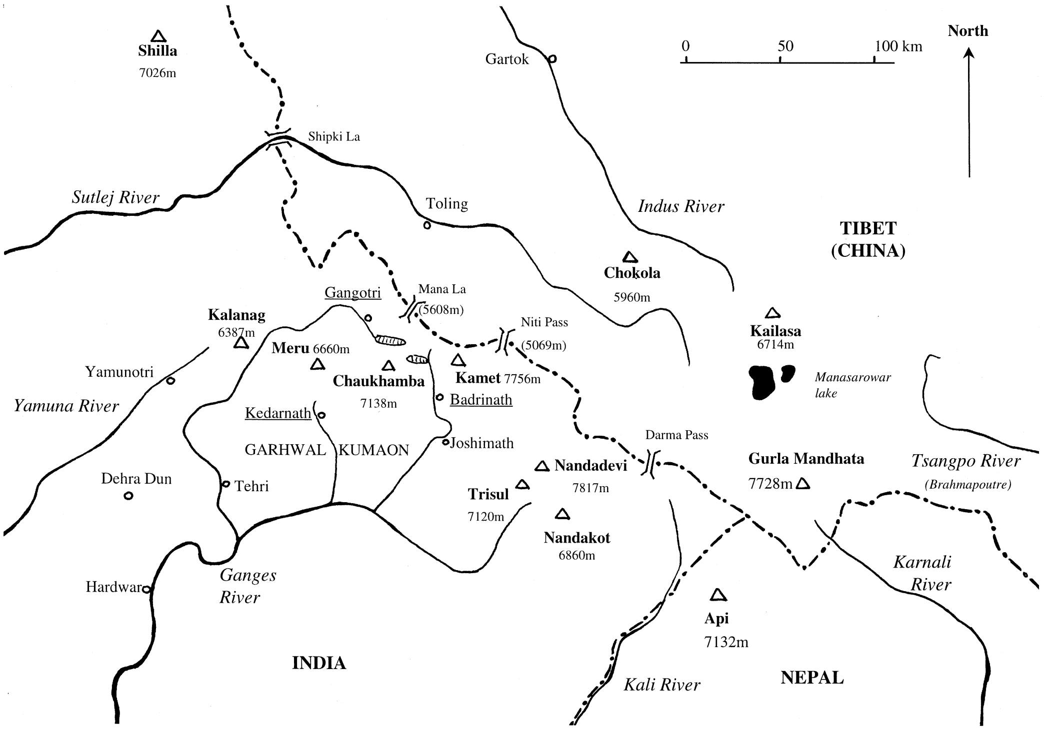

Fig. 2. General view of the hydrography of the central Himalayas, including the study area. The Yamuna, Kali and Karnali rivers are affluent of the Ganges. The Brahmapoutre passes around the whole mountain range by the East and then meets the Ganges close to its delta in the Indian ocean. The Indus also passed around the Himalayas range by the West and than goes south to the Arabian sea. The case of the Sutlej is quite unique: it crosses directly through the Himalayas range, as this river existed before the Himalayas were formed. After this shortcut, it joins the Indus river. This Himalayan central area does not contain the 8000 m peaks or the longest glacier (in the Karakorum range, the Siachen glacier is 72 km long), but it is unique for its water distribution. Notice how all these rivers emerge from the Kailash range which has been considered for thousands of years as the gravity centre of the range, and even now it is difficult to find a precise map of the area.

eternal snow is about 4500 m. The second valley, in Kedarnath, the river is called Mandakini, and the climate is very much influenced by the Monsoon. The wet subtropical forest extends to 2800 m, above this elevation the forest is progressively replaced by alpine meadows. The glacier system is less well developed. The last valley of Badrinath is an old trek way to reach Tibet through the Mana pass (5600 m). The river is named Alaknanda, and as in the first valley, is powered by imposing glaciers like the Bhagirath Kharak bamak 18 km long. In this windy valley, there is no dense forest, just some bush and meadows.

2.2. Sampling and analytical methods

To analyse the mixing of river water and ground water in the Garonne system, we obtained water samples from the piezometers installed in the gravel bar from August 1997 to April 1998. Water table elevation for each well was recorded before pumping. Several well volumes were pumped and discarded before taking the water samples. In each sample, temperature, conductivity, and pH using a portable Ionmeter (Consort C531) were recorded. On four dates (9/7/97, 11/9/97, 14/11/97 and 9/4/98), we also obtained water samples for analysis of ^{18}O. These samples were collected in 10 ml glass vials with tight caps and were sent to the Biogeochemical Isotopic laboratory in Paris, France for isotopic analysis using an Optima spectrometer from Micromass, equipped with a Isoprep off-line gas production. Results for ^{18}O are expressed in: $\delta\,^{18}\mathrm{O}\ (‰) = (R\ \mathrm{sample}/R\ \mathrm{standard} - 1) \times 1000$ the standard being the Standard Mean Ocean Water (SMOW), which give a ratio of Oxygen 18/Oxygen 16 equal to 2.005×10^{-3}.

For the Garonne mixing zone, we also measured electrochemistry and stable isotopic composition of the end members: one, the Garonne river itself at the upper end of the gravel bar (Fig. 1) and two, phreatic water from an agricultural well (CM3) located about 1 km from the river.

The continuous river stage were obtained from a water station a few kilometers upstream of the study site. Water table elevation was continuously measured using a limnigraph installed in the poplar plantation. Precipitation inputs were supplied by a meteorological station in a nearby village of Monbéqui.

For the second site in the Himalayas, surface water were collected in June 97 before the Monsoon. Our aim here was to find an easy technique to discriminate the water origin of the river: snow melt from the winter precipitation or glacier melt from

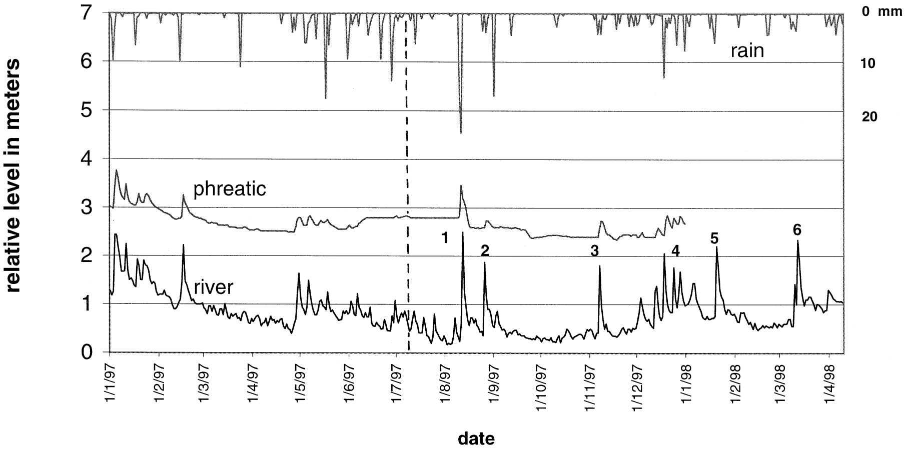

Fig. 3. Rain, phreatic and river water levels in the Monbéqui field site (Garonna river). Relative water levels are given in meters, except for the rain in millimeters where the results have been plotted in reverse (peaks down) for a better viewing of the correspondence among peaks. The vertical dashed line indicates the beginning of the electro-chemical sampling, the end of the graph at the right side corresponds also to the end of the study.

older events. Here, paired sampling was also used: one for the electrochemical measurements and one for the isotope analysis. The same methods describe above were employed.

3. Results

3.1. Garonna site

Fig. 3 summarises the variation of the three water sources for site one, the plotted curves begin on January 1 for having a better overview of hydrodynamics. Six floods during this period problems are well defined, respectively, on 12/08/97 (2m50), 26/08/97 (1m87), 07/11/97 (1m80), a series of six peak from the 3/12/97 to 5/01/98 with a maximum on 18/12/97 (2m06), 20/01/98 (2m21) and 12/03/98 (2m34). Technical problems with the limnigraph lead to some data missing at the end of the study. The phreatic levels follow the shape of the surface hydrograph but with less variation and amplitude.

According to the conductivity measurements, phreatic water and river water are distinct throughout the study (see Fig. 4a). The phreatic water (mean value 860 μS) is always about 3 times more charged

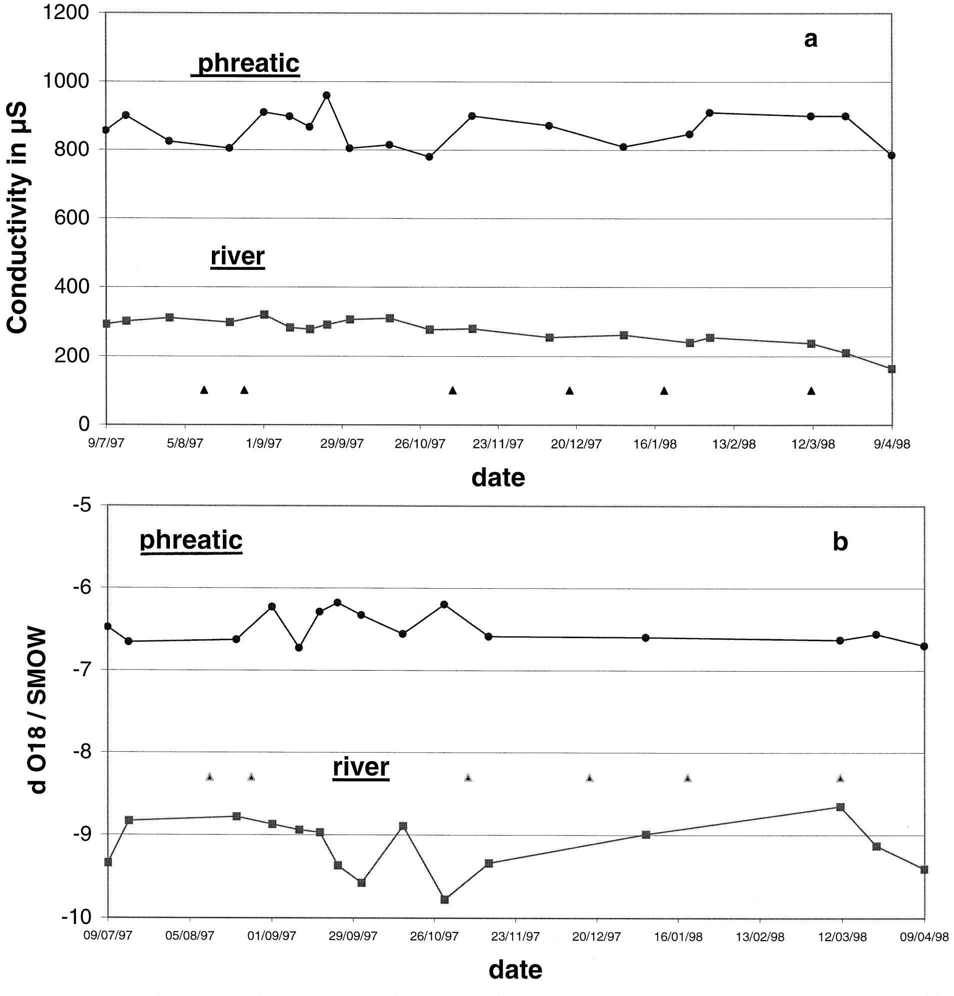

Fig. 4. Variation of the phreatic (upper curve) and Garonne (down curve) water characteristics as seen from conductivity (a) and Oxygen 18 (b) over the study period. The added triangle on both curves indicates the main floods, as represented in Fig. 3.

Table 1

Type of measurement	Kind of water	Mean value	Std. dev.	In percent	Number of points
Conductivity in µS	phreatic water	860.3	49.8	5.8	19
	river water	272.1	39.0	14.3	19
$\delta\,^{18}$O SMOW	phreatic water	−6.49	0.19	2.9	15
	river water	−9.15	0.34	3.7	15

in ions than the river water (mean value 272 µS), due to high agricultural utilisation of the land (corn, sunflower, orchard). The river water chemistry is especially stable with time; the direct repercussion of the six floods, marked by the six black triangles, is not seen.

In Fig. 4b, these two waters are analysed for their Oxygen 18 content. The ^{18}O content of phreatic water has a mean value of $\delta = -6.45$, relatively close to local meteoric water ($\delta = -5.9$ to -6.8). The shape of this curve is quite similar to the one obtained by conductivity. In contrast, the river water coming from higher altitude areas and more continental ‘‘back land’’, is much more depleted in heavy isotopes (mean value $\delta = -9.07$). The isotope data indicate small variations which are not apparent in the conductivity data. For a real comparison, the results of these curves are summarised in Table 1, where the standard variation of the mean value is expressed as a percentage.

Stable oxygen isotopes give more precise results than conductivity. In each case, the phreatic water has the lower coefficient of variation. The apparent high variation in river water is due in fact to a general decrease in conductivity throughout the study period.

The correlation between the values of conductivity and oxygen 18 for the gravel bar have been taken at four time periods, with an increasing number of points, and a better correlation coefficient. We get, respectively, $R^2 = 0.859$ for 9 points (on 09/07/97), $R^2 = 0.863$ for 14 points (on 11/09/97), $R^2 = 0.903$

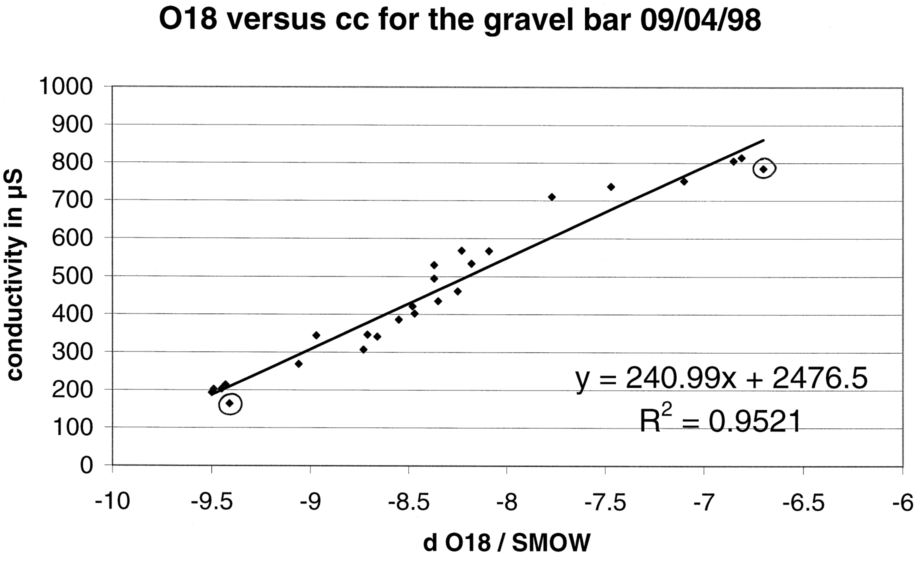

Fig. 5. Correlation curve between conductivity and oxygen 18 for the subsurface water samples taken in the gravel bar of Monbéqui along the Garonne river on the 9/04/98. The two circle points represent the reference water: river water (190 µS, $\delta = -9.4$) and phreatic water (790 µS, $\delta = -6.8$). The associated probability for the 26 points was < 0.0001.

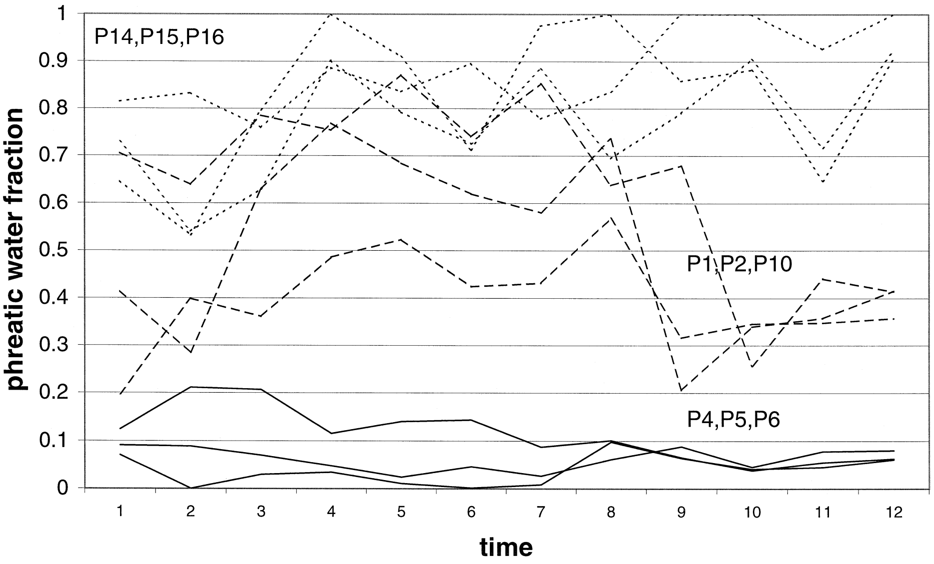

Fig. 6. Evidence of the repartition of the piezometers of the Monbéqui gravel bar in three distinct groups (mainly ground water: P14 to P16, mainly river water: P4 to P6 and one fluctuating group: P1, P2 and P10) as seen from the percentage of groundwater calculated with the conductivity values.

for 15 points (on 14/11/97) and $R^2 = 0.952$ for 26 points. This last result is shown in Fig. 5. Even if the hydrological behaviour of the gravel bar is complicated because of the multiple water sources, conductivity gives a good and rapid glimpse of the subsurface water mixing. In the riparian forest and poplar plantation, some water samples display higher conductivity values in conductance than our reference well (CM3) for 100% of phreatic water.

In the gravel bar, the intensive conductivity measurements (over 300) could help us classify the piezometers into three areas. The first area depends

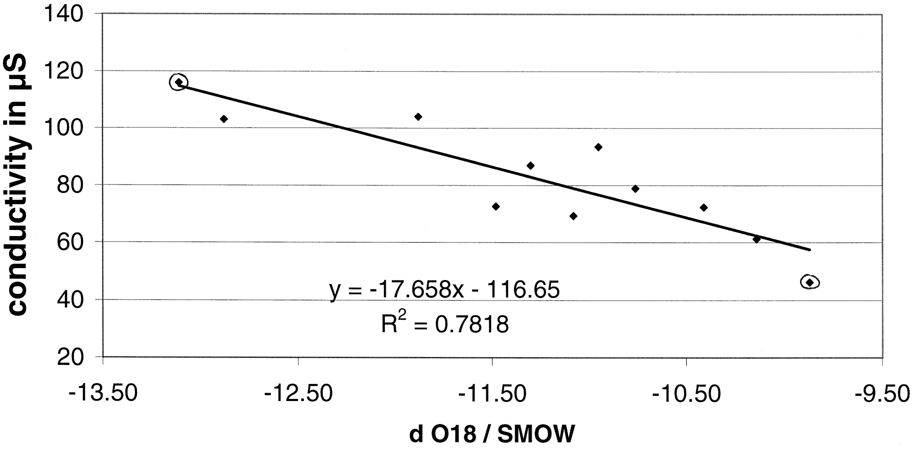

Fig. 7. Correlation of conductivity and oxygen 18 for the surface water in the Bhagirathi high valley in the Indian Himalayas. The two reference waters are circle: snow melt (46.3 µS, $\delta = -9.87$) and glacier melt (116 µS, $\delta = -13.11$). The associated probability for the 12 points was < 0.0001.

mainly on the river water entry, the second area, just on the foot of the hillside along the riparian forest, show characteristics of ground water. In the middle, along the old channel, this third area receives both kind of waters, because the elevation of upper part of this channel is lower than river level, even during the summer lowest water level. The extent of this mixing area and the proportion of the components depend mainly on the Garonne level and the previous events. In Fig. 6, the data of some characteristic piezometers, as a function of time, are given in percentage of ground water as calculated from the conductivity measurements.

3.2. Himalayan site

For the water samples from the Gangotri high valley in the Himalayas, the conductivity and oxygen 18 measurements discriminate well the water melt origins (Fig. 7). The ice melt is more depleted in heavy isotopes (more negative δ values) because they incorporate higher altitude snow, which is isotopically light, due to the fractionation during condensation at colder temperatures (Moser and Stichler, 1980). The snow melt conductivity is very close to the rain value (see Table 2), whereas the glacier is more charged in ions certainly due to the long storage and contact with ground. Even the pH measurements are useful to differentiate ice from snow/rain. From the isotopic measurements, we can roughly estimate, that at the level of the Gangotri village, the composition of the Bhagirathi river is 90% glacier melt, so from old meteorological events and 10% snow melt from the last winter. This reflects the presence of the bigger glaciers of the district and remaining small snow cover due to the hot weather.

Table 2
Ice and snow references were taken in the Gangotri valley. $\delta^{18}O$ values are given by reference to the SMOW, the conductivity values are expressed in microsiemens. Turbidity is only relative to the seen particles after sedimentation.

Origin	$\delta^{18}O$	Conductivity	pH	Turbidity
Ice melt reference	−13.11	116.0	6.05	xxx
Snow melt reference	−9.87	46.3	6.75	x
Rain in Kedarnath	−0.22	43.4	6.65	o
River at Gangotri	−12.88	103.0	6.00	xx
River at Kedarnath	−11.61	70.4	6.80	xx
River at Badrinath	−12.99	73.1	6.50	xx

4. Discussion

Studying water mixing is not always simple because the boundaries between surface water and groundwater are not well defined (Vervier et al., 1992; Fraser and Williams, 1998). Nevertheless, some interesting information can be extracted from the above data. For the Garonne field site, the chemical data from the water samples taken under the riparian forest and in the poplar plantation suggest that peaks in water table elevation are not due to the penetration of surface water (except during high floods). This affirmation is also confirmed by the fact that local heavy rains do not generate the phreatic water table elevation if at the same time there is no increase in river stage (see Fig. 3). In fact, the river level seems to regulate the phreatic water output.

It was surprising that floods have little influence on the water chemistry characteristics. It seems that the change in water quality is quite rapid, and a few days later, the system returns to initial conditions. During the peak of a flood (12/03/98), the oxygen 18 amount was higher (δ value less negative). This is in agreement with isotopic composition of the rain. Even the conductivity value dropped from 278 μS in the morning to 238 μS in the evening. Some people have studied the relationship between isotopic composition of the stream water and stream discharge (Bariac et al., 1995). They found a hysteresis loop relationship between the rising and the falling limbs. After the signal returns to normal, which shows the rapid turnover during flood, and also the complex influence during these water variations. The same authors also found two regression lines when they plot the oxygen 18 value and the concentration in chloride: one for each limb.

The interest of coupling two techniques is to use their different sensitivities. Isotopic analysis alone is not able to distinguish between groundwater (mean value $\delta = -6.5$) and rain ($\delta = -5.9$ to -6.8). However, the conductivity of these waters is very different: 860 μS and 70 μS, respectively, allowing to distinguish this third source of water: rain. For the

Himalayas data, this representation is also valid, but the sensitivity of the techniques is reversed. Here snow melt and rain are very close as seen by conductivity (respectively 46 and 43 μS), whereas the isotopic composition is very different (respectively $\delta = -9.9$ and $\delta = -0.2$).

The problem with the sampling in the Himalayas river water is the high content of insoluble matter, especially from the glacier outlet (see apparent turbidity in Table 2). This is certainly one parameter which could explain the lower correlation of the right part of the regression line in Fig. 7 and the worst correlation coefficient, in comparison to the Garonna river data set. The specific coffee colour of these charged rivers (they become transparent only in winter) was surprising in the beginning, but is very useful to follow the mixing of two confluences, since they have each their own nuances. I was surprised to see that even the ice could include mineral particles of the soil, showing how the river and glacier still erode these young mountains. This mineral inclusion in ice and also the possible deposit on snow are important factors in their melting chemistry (Singh and Kumar, 1996). Regardless of the colour, this charged water has high purity and low biological oxygen demand (Agarwal, 1997).

The three high altitude rivers present their own electrochemical characteristics (Table 2). This reflects the difference due to local climate and vegetation. Like the Bhagirathi river, the Alaknanda river also has a very high percentage of glacier melt water, as seen from the oxygen 18 value, but is less charged with ions. The Mandakini river derives about half of its flow from the two sources, as seen from the isotopic data, which represent well the lower elevation glacier system.

5. Conclusion

The results from the two study sites show the usefulness of coupling two analytical techniques. A portable instrument is quite useful for adjusting the sampling frequency. This saves time and money since stable isotopic analysis is long and expensive. When used together, these two techniques allow discrimination of a third source of water. This work is being continued to determine how these variations in water origin and level affect the riparian vegetation settlement and development.

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