Interactions between groundwater and surface water at river banks and the confluence of rivers

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Abstract

Riparian vegetation depends on hydrological resources and has to adapt to changes in water levels and soil moisture conditions. The origin and mixing of water in the streamside corridor were studied in detail. The development of riparian woodland often reflects the evolution of hydrological events. River water levels and topography are certainly the main causes of the exchange between groundwater and river water through the riverbank. Stable isotopes, such as ^{18}O, are useful tools that allow water movement to be traced. Two main water sources are typically present: (i) river water, depleted of heavy isotopes, originating upstream, and (ii) groundwater, which comes mainly from the local rainfall. On the Garonne River bank field site downstream of Toulouse, the mixing of these two waters is variable, and depends mainly on the river level and the geographical position. The output of the groundwater into the river water is not diffuse on a large scale, but localised at few places.

At the confluence of two rivers, the water-mixing area is more complex because of the presence of a third source of water. In this situation, groundwater supports the hydrologic pressure of both rivers until they merge, this pressure could influence its outflow. Two cases will be presented. The first is the confluence of the Garonne and the Ariège Rivers in the south-west of France, both rivers coming from the slopes of the Pyrénées mountains. Localised groundwater outputs have been detected about 200 m before the confluence. The second case presented is the confluence of the Ganges and the Yamuna Rivers in the north of India, downstream of the city of Allahabad. These rivers are the two main tributaries of the Ganges, and both originate in the Himalayas. A strong stream of groundwater output was measured at the point of confluence.

Keywords: River/ground water; Wetland; Stable isotope; Oxygen 18; River confluence

1. Introduction

Streams are not only the terminal points of groundwater flow and the start of the surface water system, but they are also critical components of the riparian and riverine ecology (Woessner, 2000). In these dynamic systems, trees are the memorials of past events. The development and the modification of riparian woodland often reflect the evolution of hydrological events (Tabacchi et al., 2000). The fluvial plain is, in fact, a point of complex interaction between streams and the groundwater system (Lambs, 2000). Stream and riparian ecologists have cited the importance of the mixing of stream water and groundwater, and refer to the zone in which this

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occurs as the hyporheic zone. Mixing of surface water and groundwater takes place within the upper layers of the channel sediments. Such near-channel exchange occurs at many scales, from centimetres to tens of metres depending on the bed geometry and the hydraulic-potential strengths. Pool and riffle sequences characterize many high-gradient streams. It has often been found that surface water enters channel sediments at the head of riffles and exits at the riffle base in pools. Water may also circulate out of the stream as it enters the riffles, flow through the adjacent banks and back into the down-gradient pools (Woessner, 2000).

The physical characteristics of groundwater and surface water have been considered to be distinctive, although more recent studies have described surface water as a 'perched groundwater aquifer', in recognition of the isotopic history of both components. Despite this, it is generally considered that groundwater is characterized by stable flow, even temperature and a stable chemical composition that reflects the underlying aquifer geology. In applied hydrology, the role of groundwater in sustaining low flows has provided the focus for recent research (Sear et al., 1999).

Stable isotopes, such as ^{18}O, are useful tools that allow water movement to be traced. Two main water sources are typically present: (i) river water, depleted of heavy isotopes, originating in the mountains, and (ii) groundwater, which gives for temperate climate an annual average of the local rainfall. The study of water mixing assists an understanding of the availability of water in riparian soils. River water levels and topographical details are certainly the main causes of the inflow of groundwater through the river bank (Lambs, 2000; Lambs et al., 2002). In this paper, we will describe in more detail these water movements along gravel bars and show evidence that groundwater passes into the river from a relatively small area of the gravel bar. The high flux observed at the end of this gravel bar prompts the question: how does groundwater flow within the land between two rivers?

Studies are reported of the interaction of groundwater and surface water flows at the confluence of two rivers. The first is the confluence of the Garonne and the Ariège Rivers in the south-west of France. These are the two main tributaries of the Garonne, rising in the Pyrénées about 80 km away. They meet just upstream of the city of Toulouse. The second case is the confluence of the Ganges and the Yamuna Rivers in the north of India, just downstream of the city of Allahabad. These rivers are also the main tributaries of the Ganges, originating a few hundred kilometres away in the Himalayas. An old legend claims that at the point of this confluence a third, invisible, river flows-almost certainly a groundwater output.

2. Materials and methods

2.1. Sampling techniques

Characterization of the exchange of groundwater with river water has been accomplished by measuring water levels in wells and piezometers, and comparing water and stream geochemistry, as proposed by Woessner (2000) In view of the detection of groundwater output, during the low river water period, we measured the variation in the temperature of the river water along the bank, using approaches reported by White et al. (1987) and Silliman et al. (1995). For this purpose, the temperature sensor of the portable ionometer (Consort C531) was fixed on a beam, lowered into the river water to a depth of about 30 cm and moved along the river bank. This sensor has a more rapid response to change than the conductivity cell and is less influenced by movement or stream velocity. When a change in temperature was detected, a water sample was taken for measurement of conductivity, pH or isotope ratios. Notes were taken of interesting details as appropriate: these include the presence of riffles and pools, changes in vegetation (succession from poplar to willow can reveal the presence of groundwater), water drainage between gravel just after the riffle, and so on.

2.2. Site description

The first site, Monbéqui, is located in the south-west of France along the right bank, on the east side, of the Garonne river, a few kilometres downstream of Verdun (Tarn and Garonne). The Monbéqui village itself and the main road are on a high terrace (altitude 100 m) where they are safe from flooding. The middle terrace, which is 2.5 km wide (altitude 91–92 m), is used for agricultural purposes and is flooded only rarely (every 30–50 years). There are numerous agricultural wells, which have been used to study the groundwater characteristics and to find a well suitable for use as a reference well. The lower terrace (altitude 89–91 m), which is a few hundred metres wide, is flooded about every 5 years and is devoted to poplar plantations. The river banks themselves (altitude 86–88 m), which are 10–100 m wide and about 2 km long, are flooded at least once a year and are occupied by riparian vegetation, mainly black poplar and white willow. The geographical location is about 43°53′N and 1°12′E. The slope of the river is about 0.8 m/km. The down-stream part of this area and the gravel bank are illustrated in Fig. 1. From

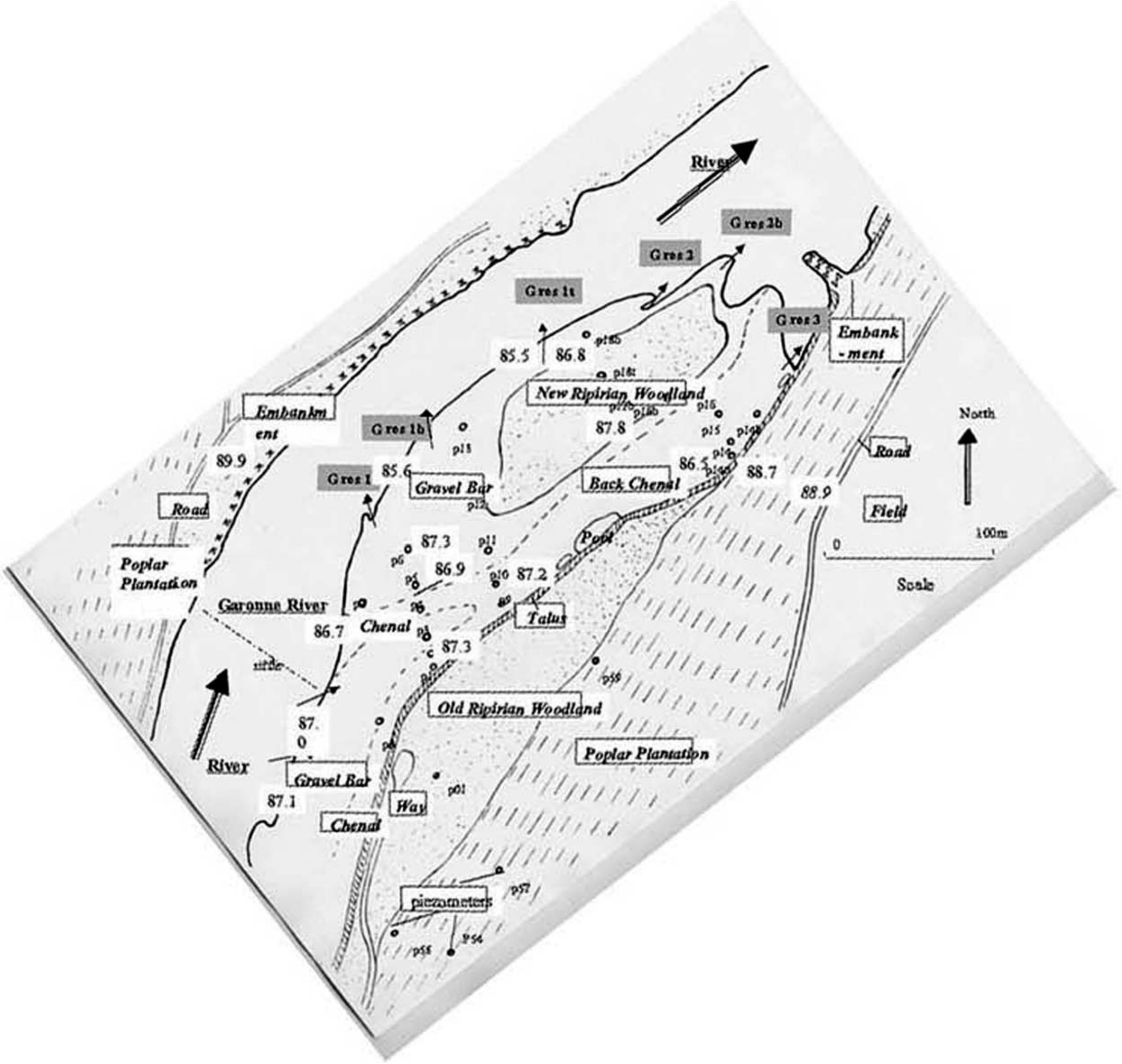

Fig. 1. General view of Garonne river meander near Monbéqui, S.W. France. The nature of the land use is given in the framed white rectangles. Some elevations (in metres above sea level) are reported in smaller white rectangles to give an idea of the profile section of this field site. The possible water input (river water into groundwater, two before the riffle) and output (groundwater into the river water, six after the riffle, numbered in a grey rectangle) are indicated by black arrows. The figure is completed with the position of the numerous piezometers (black circles with numbers) used in this study.

1997 to 1999, the characteristics of the river water and groundwater (temperature, conductivity, ^{18}O ratio) were studied. The piezometers on the gravel bar were sampled approximately once a week, while the riparian forest, the poplar plantation (Lambs, 2000; Lambs and Berthelot, 2002) and the agricultural wells of the middle terrace were sampled less frequently.

On three occasions (30 October 1997, 14 November 1997 and 22 January 1998), while there was low water in the Garonne, the water height, the temperature, the pH and the conductivity were measured in the piezometers as well as along the Garonne river bank to follow in detail the discharge of groundwater into the river.

The second site is upstream, about 10 km before Toulouse at the confluence of the Garonne and the Ariège rivers (see Fig. 2). The location is 43°30′N and 1°24′E, at an elevation of 145 m. The Garonne river has its source in the central Pyrénées in the north of Spain, near Mt Aneto (3404 m) and Mt Maladeta (3312 m), and enters the south-west of France through the Val d'Aran valley. It flows for about 150 km of its entire length of 565 km before reaching Toulouse. After joining the Ariège, the mean discharge is about 200 m^3/s, but during low water the discharge can be as low as 40 m^3/s, and during flood it can reach up to 3000 m^3/s, as in June 2000. The Ariège river is the main high-altitude tributary of the Garonne river. It is 170 km long, and has its source in the eastern Pyrénées. Its mean discharge is about 70 m^3/s.

These rivers were sampled in February 2000, in addition to two reference locations: the Garonne

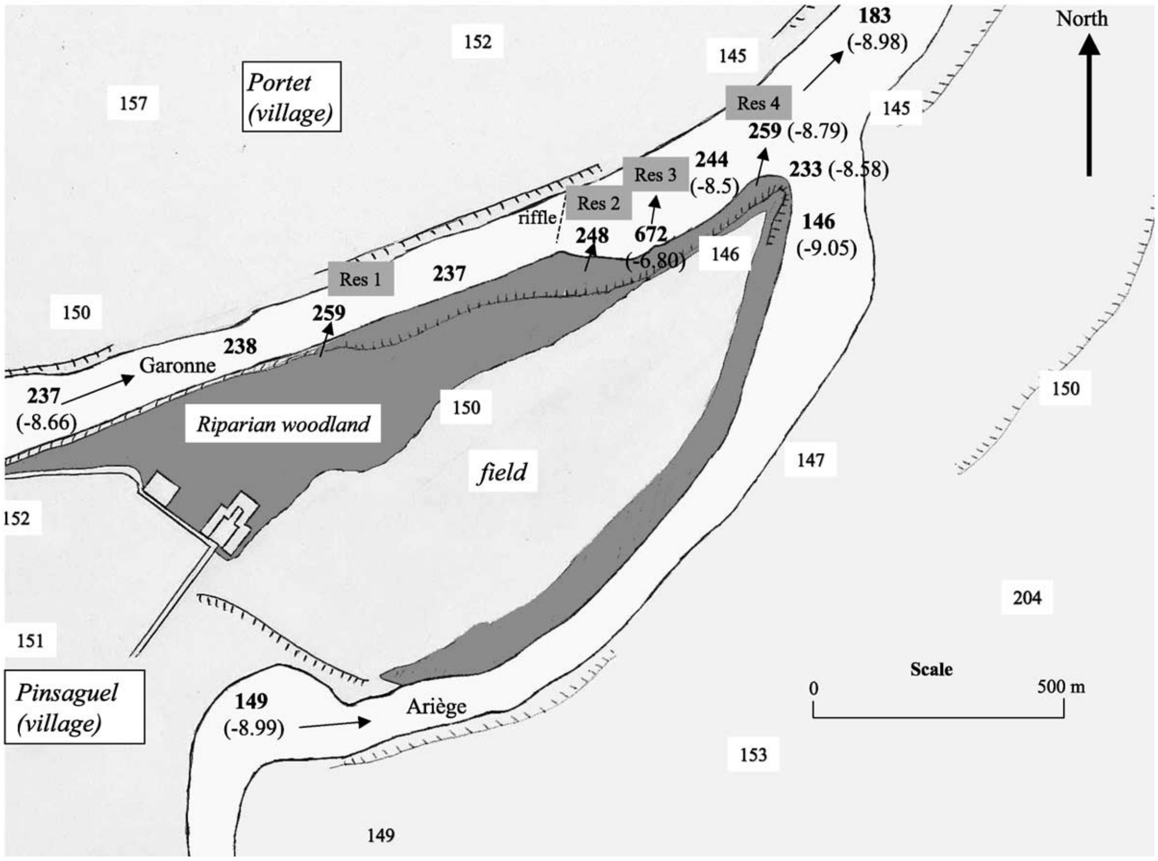

Fig. 2. Schematic representation of the confluence of the Garonne and Ariège Rivers a few kilometer upstream of Toulouse, S.W. France. The main altitude of the ground is given in metres above sea level (white rectangle). The possible water outputs into the river water are indicated by black arrows and numbered from Res 1 to Res 4 with grey rectangles. Surface water characteristics on 13 September 2001 are given: resistivity in bold type, and ^{18}O isotopic content in brackets.

and groundwater at Verdun plus a smaller tributary, the Save river (see Table 2). This confluence itself was studied in September 2001 at the low-water period. The slope is about 1.2 m/km in this section of the Garonne, but at the point of the confluence, the local slope is only 0.4 m/km, which explains the presence of the large gravel bar and the riparian vegetation just downstream. No piezometers were installed. The study was conducted on 13 September 2001 when the flow in the river was 46 m^3/s (in this year, the low water period began in August (6 August 2001, 52 m^3/s) and continued until mid November (12 November 2001, 51 m^3/s). One and a half kilometres of the Garonne's right bank was searched on foot up to the confluence, as well the first 50 m on the Ariège side, the access being very difficult. The riffle and pool were noticed as well as the change in vegetation (willows), and water was sampled all along the bank to locate places where the temperature and conductivity changed. At the confluence point, different depths were tested (up to 1 m deep). Interesting points were sampled for their ^{18}O and deuterium contents.

The third site is located in North India, in Uttar Pradesh at the confluence of the Ganges and Yamuna rivers, just downstream of the city of Allahabad (see Fig. 3). The geographic position is 25°26′N and 81° 54′E, and the altitude is 94 m. The 2700 km-long Ganges is formed by the junction of three headstreams, the Bhagirathi, the Mandakini and the Alaknanda, in the Uttaranchal district, near the Indian high peaks Nanda Devi (7817 m) and Kamet (7756 m). Sampling of these rivers was

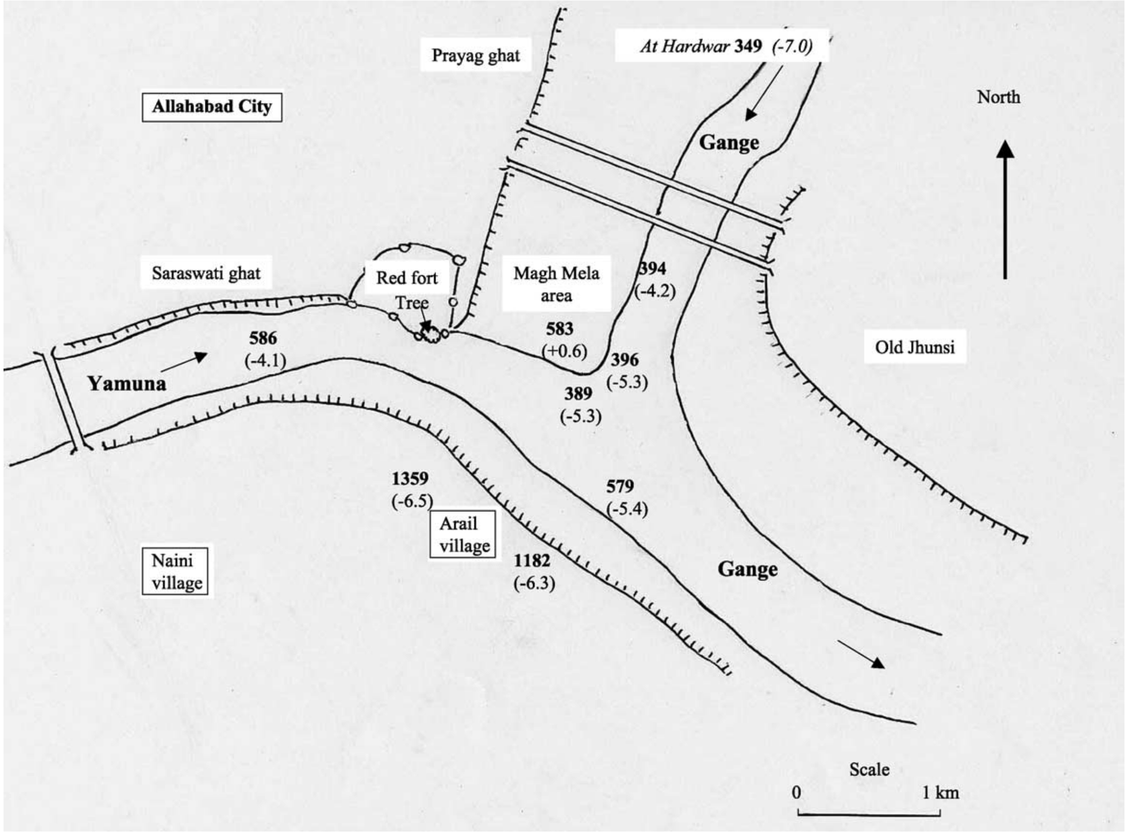

Fig. 3. Schematic representation of the confluence of the Yamuna and Ganges Rivers at Allahabad, UP, India. Sampled water characteristics on 16 March 2001 are given: resistivity in bold type, and ^{18}O isotopic content in brackets. The two samplings around the Arail village correspond to groundwater taken from wells. People are coming to the Magh Mela area to bathe near the confluence. The values just reported behind are coming from a small flask in the sand bank.

performed in 1997 (Lambs, 2000). After travelling more than 200 km, the Ganges reaches the city of Haridwar (altitude 310 m), where it breaks through the low Siwalik Range and begins its generally south-easterly flow across the Gangetic plain. At Haridwar, a sampling of the Ganges was done just a few days before the sampling in Allahabad (March 2001). Between Haridwar and Allahabad, a distance of nearly 800 km, the river follows a winding course (the slope is about 0.3 m/km) made unnavigable by shoals and rapids. At Allahabad (altitude 94 m), the Ganges is joined by the Yamuna River from the south-west, then flows east towards the Bangladesh border, where its mean discharge is about 14,000 m^3/s. The Yamuna river is 1370 km long; it originates in the Kumaon district of the western Himalayas, and is the major tributary of the Ganges. The confluence area of the Ganges and the Yamuna rivers was sampled in March 2001 during the low-water period. There is no vegetation directly on the bank, because of the floods brought by the monsoon rain in July–August.

The huge sand-lime banks at this confluence are an important area of pilgrimage (Magh Khumba Mela) where millions of people come to bathe at the peak moment. For this reason, no scientific equipment was used. Water samples were taken in duplicate in 10 ml glass vials, one for pH and conductivity measurements, the second for the isotopic content. The confluence point and surrounding river banks were surveyed by walking in shallow water (20–60 cm) and the water confluence was taken where an increase of temperature was felt. A sample of each river was taken a few hundred metres upstream and downstream of the confluence. Groundwater samples were taken using two hand pumps (closed well) at village wells. These were taken as the reference of the local groundwater.

2.3. Analytical methods

Surface water as well as groundwater obtained from piezometers or wells was collected in 40 ml flasks The temperature and conductivity were measured with a portable Ionmeter (Consort C531) directly at the site (except in India). When needed, a second sample was collected in 10 ml glass vials with secure caps for isotopic analysis. The stable isotope composition of water is reported with reference to the Standard Mean Ocean Water (V-SMOW/V-SLAP), in parts per thousand. The definition for oxygen is:

$$\delta^{18}\mathrm{O}_{\text{V-SMOW}}\ (‰) = ((^{18}\mathrm{O}/^{16}\mathrm{O}_{\text{sample}})/(^{18}\mathrm{O}/^{16}\mathrm{O}_{\text{standard}}) - 1) * 1000;$$

and for deuterium:

$$\delta^{2}\mathrm{H}_{\text{V-SMOW}}\ (‰) = ((^{2}\mathrm{H}/^{1}\mathrm{H}_{\text{sample}})/(^{2}\mathrm{H}/^{1}\mathrm{H}_{\text{standard}}) - 1) * 1000.$$

3. Results

3.1. Monbéqui site

The study of the mixing of groundwater with river water could not begin without a previous analysis of both end parts River water was relatively easy to approach and measure, but the availability of groundwater was more limited.

3.1.1. Groundwater homogeneity of the upper terrace and choice of a reference well

The groundwater was quite homogeneous in the higher terrace (altitude between 90 and 93 m) as can be seen from the results of sampling in 20 agriculture wells on 22 April 1998 (when the Garonne water level was 1.1 m). Over an area of $2 \times 3\ km^2$, the conductivity was 682 ± 29 μS/cm, a variation of less than 5%. The water level in these wells was between 2.60 and 4.60 m deep relative to ground level. After a relatively high flood on 28 April 1998 (a level of 2.69 m), a repetition of this survey gave results that were only a little higher (703 ± 52 μS/cm), and only a few wells within a few hundred metres of the Garonne river were affected. A reference well was chosen that was located in the middle of the area and 1 km from the Garonne river. The conductivity of the water sampled in this well was in accordance with the mean value (682 μS/cm on 22 April 1998) and so this well was selected for the weekly measurement of the groundwater. Over a 2-year period (9 July 1997–22

July 1999), the average conductivity value was 815 ± 116 μS/cm over 47 samplings, and the mean isotopic content of ^{18}O was −6.63 ± 0.26‰ over 26 samplings. This isotopic value is in accordance with the mean ^{18}O isotopic value of local rainfall (−6.9 ± 0.7‰).

Over the same 2-year period, the mean conductivity value of the Garonne was 246 ± 48 μS/cm over 48 samplings, about one-third of the groundwater. The mean isotopic content of ^{18}O was −9.05 ± 0.42‰ over 23 samplings. This water is more depleted of heavy isotopes since this river is mainly dependant on the precipitation falling on the Pyrénées mountains (snow melt about −9.6‰). Also noteworthy is the higher standard variation, which is a result of the variability of water sources, including snow melt and rain at widely different altitudes.

3.1.2. Heterogeneity of the water in the lower part of the meander

Groundwater flows from the fields, where it has been shown to be homogeneous, under the poplar plantation to the old ripisylve and finally to the gravel banks, where it mixes with the river water. A 300 m-long transect has been designed along this path, oriented roughly south to north, to measure this progressive dilution of the groundwater by the river water. This transect extends from piezometers p54 and p57 in the poplar plantation, p01 in the old ripisylve, and p1, p2, p4, p5 and p6 in the gravel bar forming the bank of the Garonne. Results of measurements along this transect are given in Table 1, under the series named 'transect', with the addition of the two reference waters (groundwater taken from the selected agricultural well and the Garonne river water taken

Table 1
General characteristics of the water sampled on Monbequi filed site (40 km dowstream of Toulouse, SW France) along the Garonne river banks

Series	Name	Location	Temperature (°C)	pH	Conductivity (μS)	$\delta^{18}O_{\text{V-SMOW}}$ (‰)
Transect	puits ref	Upper terrace	13.5	7.39	900	−6.6
	P54	Poplar plantation	14.0	6.91	1020	−6.9
	P57	Poplar plantation	13.0	7.85	930	−7.1
	P 01	Old riparian wooland	13.5	7.57	950	−7.5
	P1	Gravel bar	14.0	7.59	665	−7.9
	P2	Gravel bar	14.0	7.92	496	−8.6
	P4	Gravel bar	13.5	7.60	366	−9.6
	P5	Gravel bar	14.0	8.12	361	−9.4
	P6	Gravel bar	14.0	7.60	276	−9.5
	Garonne		10.5	7.63	280	−9.3
Other points	P51	Poplar plantation	13.5	7.26	910	−6.7
	P53	Poplar plantation	13.5	7.25	910	−6.7
	P55	Poplar plantation	13.5	7.60	1050	−7.2
	P59	Poplar plantation	13.5	7.47	930	−7.1
	Pool		13.0	7.77	500	−8.8
	P7	Gravel bar	11.5	7.81	268	−9.5
	P8	Back channel	14.5	7.82	594	−8.3
	P10	Back channel	14.5	8.00	469	−9.0
	P14 b	Back channel	13.5	7.99	421	−8.8
	P14 t	Back channel	13.0	7.38	580	−8.7
	P15	Back channel	13.5	7.58	752	−8.0
	P16	New riparian woodland	13.0	7.98	476	−9.1
	P18	New riparian woodland	14.0	8.03	680	−8.2
GW output	G Res 1	Garonne river	15.5	7.75	330	−9.1
	G Res 1b	Garonne river	15.5	–	346	–
	G Res 1t	Garonne river	13.0	7.47	392	−8.8
	G Res 2	Garonne river	16.0	7.39	709	−7.7
	G Res 2b	Garonne river	14.0	–	460	–
	G Res 3	Garonne river	12.5	7.84	821	−7.4

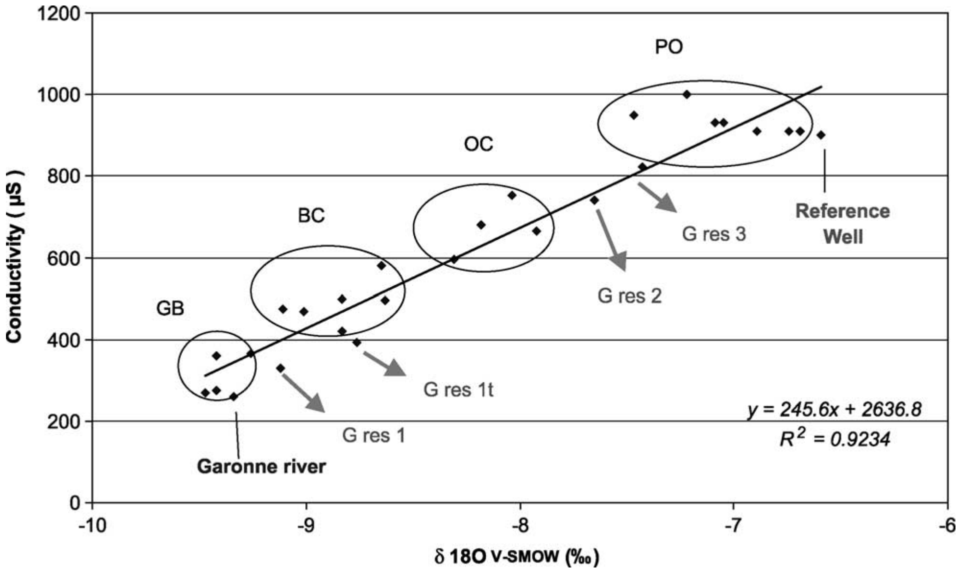

Fig. 4. Correlation curve between conductivity and ^{18}O for the 27 groundwater and surface water samples taken at the Monbéqui field side along the Garonne river on 14 November 1997. This curve represents the mixing of the two reference waters: Garonne river water (260 µS/cm, $\delta^{18}O = -9.34‰$) and phreatic water (900 µS/cm, $\delta^{18}O = 6.59‰$). The four ellipses represent the main locations with similar water mixing characteristics—i.e. GB (Gravel Bar: p4, p5, p6, p7), quite pure river water, BC (Back Channel: p2, p10, p 14b, p14t, p16, pool), mainly river water plus a little groundwater, OC (Outside Channel: p1, p8, p15, p18), about half groundwater and half river water, and PO (Poplar: old riparian woodland: p01, and poplar plantation: p51, p53, p54, p55, p57 and p59). The four water outputs sampled (G res1, 1t, 2 and 3) for their isotopic contents are also reported.

just before the riffle and a few metres away from the bank). We can clearly see how the high-conductivity groundwater is diluted by the less concentrated river water. The conductivity initially is about 960 ± 60 µS below the field, and it maintains this value until the old riparian woodland. It then decreases progressively in the gravel bar, reaching a value around 274 ± 6 µS/cm. The ^{18}O isotopic content shows this progressive dilution even more regularly, beginning at piezometer p01 in the old riparian wood, as can be seen on the regression line in Fig. 4.

3.1.3. Determination of the water flow

The micro topographic survey and the piezometric study have revealed the lower water-table level (10–30 cm) of the back channel in the upper part (upstream) of the gravel bank relative to the river water. Before and after the riffle area, the river level alters by about 40 cm. This particular topography leads to loss of water from the river in favour of groundwater in the upstream part of the gravel bar—i.e. before the riffle (see arrows on Fig. 1). After mixing of this river water with the groundwater coming through the old riparian woodland, this water is returned to the river through the downstream part of the gravel bar. Of course, the mixing area and the water percentages are not stable and depend mainly on the river level. During flood, this system is under water.

The study of the phreatic water output was done at low river water (40 m^3/s) during the 1997–1998 winter. Downstream of the riffle, many small discharges could be seen between the gravel stones on the river bank, a few tens of centimetres above the river level (i.e. only a few cm in elevation). These points are noted as G res 1, 1b, 1t on Figs. 1 and 4. Further, downstream, no more water discharges could be seen. The locations of other possible outflows along the river bank were investigated using the temperature probe of the conductivity meter, as described. Increases of up to 5 °C above the average river temperature, 105 °C, could be measured (see the end part of Table 1). The interesting points were then confirmed by conductivity measurements. These locations are noted G res 2 and G res 2b in Fig. 1. The last location, where the gravel joined the foot of the poplar plantation, was named G res 3. The G res 2 and G res 3 points were localized in small, quiet coves with relatively deep water (about 40 cm), where we observed the presence of willows, a good indicator of groundwater proximity. In contrast, at the G res 2b point, the river flow was strong, but the relatively high conductivity value (460 μS/cm) in comparison to the river (280 μS/cm) could only be explained by a strong groundwater outflow. In most cases, the temperature of the outflow was above the groundwater temperature, 135 °C. The lower temperature in the G res 3 area, 125 °C, could be explained not only by the heavy shading from the adjacent trees, but also by the fact that in this area the groundwater is not heated by contact with the gravel bar. Still, this groundwater was coming directly from the poplar plantation, as confirmed by its isotopic value.

In Fig. 4, we can see how these different outflows (from G res 1 to G res 3) are more charged in groundwater the further they are from the riffle location. This means that the river water present in the gravel, coming from the upstream part of the gravel bar, is progressively diluted by the groundwater coming out of the old riparian woodland. It is interesting to note that the groundwater flows into the river through only a few areas (a few tens of centimetre wide), and not over a large area.

3.2. Study of the confluence of the Garonne and the Ariège rivers in France

The study was carried out on 13 September, 2001, during low water (the river flow was 46 m^3/s). As no riffle was seen close to the confluence on the Ariège river side (see Fig. 2), and as there was mostly no gravel (the field ended with some trees overhanging the river) outside the confluence area, the main investigation was along the Garonne river. The conductivity of the water in the Garonne River was around 238 μS/cm, while that for the Ariège River was about 149 μS/cm. This difference had also been observed during the preliminary measurement on 10 February, 2000 (respectively 197 and 147 μS/cm; refer to Table 2) during a period of relatively low water for this time (110 m^3/s).

Table 2
Characteristics of the water sampled at the confluence of the Ariege and the Garonne rivers, about 10 km upstream of Toulouse, SW France

Date	Name	Location	Temperture (°C)	pH	Conductivity (μS)	$\delta^{18}O_{\text{V-SMOW}}$ (‰)	$\delta^{2}H_{\text{V-SMOW}}$ (‰)
10/02/00	*Ariège*	Lacroix F	8.5		147	−9.0	
	Garonne	Pinsaguel	9.0		197	−9.1	
	Save	Verdun	8.5		*424*	−7.4	
	Garonne	Verdun	9.0		334	−8.5	
	Ground water	Verdun	13.5		778	−6.8	
01/09/00	Save	Verdun	21.5		300	−7.6	
	Garonne	Verdun	21.5		270	−8.8	
	Ground water	Verdun	14.0		694	−7.1	
26/03/01	Save	Verdun	13.5		*494*	−7.2	
	Garonne	Verdun	13.0		232	−9.5	
	Ground water	Verdun	13.5		648	−7.1	
13/09/01	Ariège	Lacroix F	18.5	8.02	149	−9.0	−64.1
	Garonne	Pinsaguel	19.5	8.16	237	−8.7	−59.5
	Water/GW	Res 3	14.0	7.83	672	−6.8	−46.7
	Garonne	Res 3/Res 4	16.5	8.08	244	−8.5	−58.5
	Confluence	Res 4 surf.	20.5	8.27	233	−8.6	−60.5
	Confluence	Res 4 deep	19.5	8.19	259	−8.8	−60.2
	Confluence	*Ariège side*	17.5	8.09	146	−9.1	−63.4
	Garonne	Toulouse	18.5	8.29	183	−9.0	−62.0
	Save	Verdun	17.0	8.16	332	−7.2	−49.5
	Garonne	Verdun	19.5	7.49	265	−8.5	−61.6
	Ground water	Verdun	14.0	6.94	615	−6.6	−48.4
	Gravel Bar	Verdun	15.0	7.34	767	−6.5	−46.2

The ^{18}O isotopic values of both rivers are both quite highly depleted of heavy isotopes due to their mountain origins (respectively, -8.66 and $-9.05‰$). During the February 2000 sampling, they had nearly the same value, about $-9‰$. Notice also the value of the small river reference, the Save river, which had a mean value of $-7.35‰$, a little more depleted than the groundwater (mean value $-6.9‰$) and indicative of its origin in hill rainfalls.

In contrast to the first study, during October the temperature of the river water (195 °C for the Garonne river) was higher than the temperature of the groundwater (about 14 °C). Fine water flows were sampled on apparent (on air) molasses table, the fluvial sandstone, in Res 1 and Res 2, but their conductivity values (respectively, 259 and 248 μS/cm) were not much different from that of the Garonne River. In the middle of the cove after the riffle, a small pool (Res 3) was present in the lower gravel bar, surrounded by a few willows. The low temperature (140 °C), the high conductivity (672 μS/cm) and the ^{18}O content ($-6.80‰$) reveal quite pure groundwater. The Garonne water sampled a little downstream (denoted Res 3/ Res 4 in Table 2) was 3° colder (165 °C) than the average river temperature (195 °C) and the isotopic value ($\delta^{18}O = -8.5$) could indicate a groundwater outflow.

For this area, the mean pH value was 8.09 ± 0.14. At the Verdun site, the mean pH value was 7.26 ± 0.28 and in winter 1997 in Monbéqui this average value was 7.65 ± 0.28. However, in all cases, the lower value was given by the groundwater sample.

At the point of the confluence (Res 4 surface), the water characteristics are closer to those of the Garonne. At a depth of about 1 m (Res 4 deep), the isotopic value ($\delta^{18}O = -8.79‰$) reveals also the presence of colder Ariège water. The influence of groundwater, as seen from the temperature and the conductivity, is negligible. In the present case, the output of the groundwater seems to be localized in the cove. The low influence of the Ariège River on the sampled river water is certainly due to the previous length of the low-water period. Also interesting is the isotopic value ($\delta^{18}O = -8.98‰$) of the Garonne right bank a few kilometres downstream of this confluence, which illustrates the low mixing percentage of the two rivers.

The relation between $\delta^{18}O$ and $\delta^{2}H$ values is given in Fig. 5. The characteristic values of the two tributaries, i.e. the Garonne and the Ariège rivers,

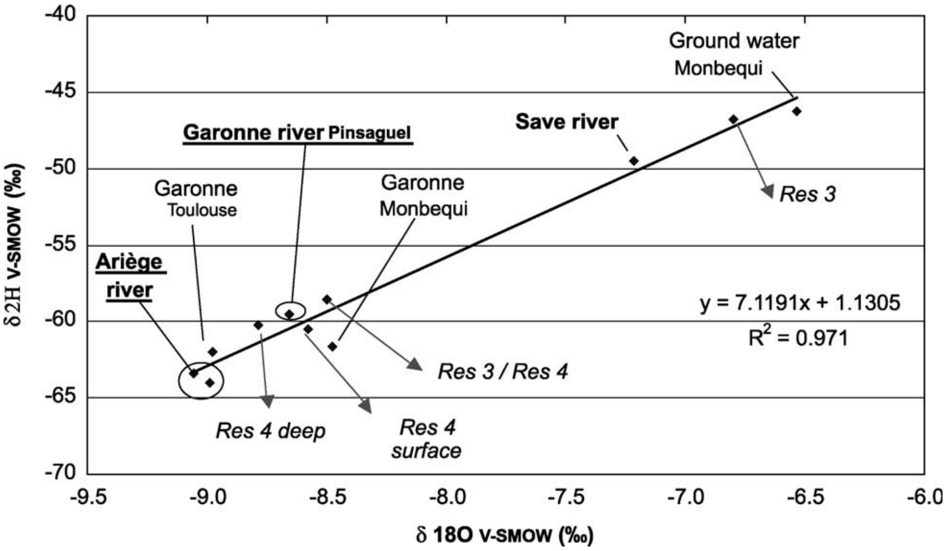

Fig. 5. Relation between $\delta^{18}O$ and $\delta^{2}H$ values for the water samples taken at the confluence of the Garonne and Ariège Rivers and downstream on 13 September 2001. The two ellipses represent the characteristics of the water upstream of the confluence, and the black arrows the different water outputs (Res 3 to Res 4). The groundwater (GW), the Garonne sampled downstream of Toulouse in Monbequi and the Save river are also reported.

are encompassed by an ellipse. It is interesting to note that the pool water (Res 3) from the confluence gravel bar is very similar to the groundwater in Monbequi (GW), closed to the first field site, which shows the relative homogeneity of the rainfalls between the two sites. The isotopic characteristics of the Garonne River remain nearly constant while it passes through Toulouse, (compare Garonne Pinsaguel and Garonne Monbequi in Fig. 5). The Save river is a small tributary that merges into the Garonne upstream of Verdun, and displays less heavy isotopes owing to its lower altitude origin.

The Meteoric Water Line (MLW) calculated by Rozanski et al. (1993) gives the relation: $\delta^2H = 8.17\delta^{18}O + 10.35$, based on data from the world precipitation network. However, this global MWL is derived from water samples that arose in diverse local conditions, and the MWLs of local rain or river sites usually have much lower slopes. A relation of $\delta^2H = 7.12^{18}O + 1.13$ were found for our river and groundwater samplings, which is not far from the one obtained for precipitation in temperate countries (in Groningen (Netherlands) $\delta^2H = 7.36\delta^{18}O + 6.11$ and Vienna (Austria) $\delta^2H = 7.21\delta^{18}O - 0.34$ (Gat et al., 1998–2001). This value reveals the insignificance of the evaporation process in our area. In general, the river MWL slopes in the range of about 7–8.5 are within the normal range for precipitation, whereas slopes in the range 6–7 may indeed reflect substantial amounts of post-rainfall evaporation (Kendall and Coplen, 2001).

3.3. Study of the confluence of the Ganges and Yamuna rivers in India

The area of the confluence is illustrated in Fig. 3. The terraces on which the city and the villages are located are at least 10 m above the river banks, because the flow in these rivers during the summer monsoons can be very high. The isotopic characteristics of the two rivers are very similar, the $\delta^{18}O$ for the Yamuna river being equal to $-4.1‰$ and that for the Ganges river $-4.2‰$. For the Ganges at the Bangladesh border, oxygen values between -4.8 and $-7.7‰$ have been reported (Rozanski et al., 2001). Just a few days before, the Ganges isotopic content was $-7.0‰$ in Haridwar. As spring is a dry and hot season on the Ganges plain, both rivers receive their water mainly from the snow melt in the Himalayas ($\delta^{18}O$ from -13 to $-10‰$). The progressive depletion of ^{18}O water from the mountains (from -13 to $-9‰$) to Haridwar ($-7‰$) and to Allahabad ($-4‰$) could be explained by evaporation or mixing with less depleted water in ^{18}O.

The local groundwater, as seen from the two sampled wells, has ^{18}O values of about $-6.4‰$. This is in accordance with the values found, -6.5 to $-5‰$, in Rajasthan by Yadav (1997) and the $-6‰$ value given in the world-wide distribution of the annual mean of $\delta^{18}O$ in precipitation (Yurtsever and Gat, 1981). Notice the high ion level content of this groundwater, with a conductivity value around 1200 μS/cm.

At the lower part of the confluence area, there was a little water puddle. The water analysis showed that this was highly evaporated, with a $\delta^{18}O$ value of $+0.6‰$. More interesting were the two samples taken in about 20 cm deep river water, about 15 m away. Both, with an identical isotopic value of $-5.3‰$, reveal a high content of groundwater. This value is about midway between the river and groundwater values, which should emphasize that, in these places, the river water content is about 50% groundwater. Moreover, the sample taken on the other bank downstream shows nearly the same value ($-5.4‰$), which shows that this groundwater flow is strong enough to be detected many hundreds of metres away. In fact, when we looked more closely at the water movement (noting that the Yamuna and Ganges were not exactly the same colour, and pilgrims make offerings of flowers in the confluence), it seems that this warmer groundwater was pushed downstream by and between the flow of the two rivers.

It is interesting to note that in the south-east of the city, in the Red Fort, there is a water resurgence that is said to be linked with the confluence, where there stands a very old banyan tree (*Ficus religiosa*) called Akshya Bata. Unfortunately, this place is a restricted area and it was not possible to sample this water. This tree was already described by the travelling Chinese monk Xuanzang in 643 (Frederic, 1984).

4. Discussion

4.1. Mixing of river water and groundwater

In fluvial systems, the mixing of river water and groundwater is localized along the river banks and also beneath the river flow. Groundwater flow is generally parallel to the higher hydraulic conductivity fluvial plain. Exchange of groundwater with the stream occurs by discharge, recharge, and flow-through. Exchange of surface water and groundwater also occurs at the channel-bed scale. Local, shallow surface water circulation into the underlying sediments creates areas of groundwater recharge and discharge within zones generally characterized as gaining or losing stream sections (Woessner, 2000).

The definition of hyporheic zone given by White (1993) could specified the porous area where this mixing is possible: 'The hyporheic zone may be defined conceptually as the saturated interstitial areas beneath the stream bed and into the stream banks that contain some proportion of channel water (i.e. river water) or that have been altered by channel water infiltration.'

It is important to understand that the boundary between the groundwater and the surface water is not fixed but varies over the seasons (Fraser and Williams, 1998). These hyporheic zones are also influenced by heterogeneities in the distribution of sediment hydraulic conductivities and the topography of the streambed. Geomorphology studies help us to understand this zone, which is beyond our direct observation and not easy to sample. Steiger et al. (2000) have delimited different reaches for the Garonne river. The mean slope downstream of Toulouse decreases from 1 to 0.8 m/km at Monbéqui meander. Also the channel incision has been measured over a 66-year period. Owing to the lateral immobilization of the river channel and a decrease in bed load, the mean channel incision was 2.5 cm/year. In some areas, the river water level is now 2.60 m lower, which is not without consequences on the alluvial water table and thus on its riparian woodland. Also at many places, the lowering of the below-river hyporheic zone is large enough that, in the low-water period, large parts of the bedrock (called Molasse) appear, which certainly causes a diminution of the water quality.

As seen from our measurements and also the reports of Woessner (2000), the riffle/pool sequence seems to be the main factor controlling the groundwater/river exchange. The most surprising point was the relative narrowness of the groundwater output zones, perhaps a way to overcome the hydraulic pressure imposed by the river flow. A phenomenon observed several times can be reported to show the action of the hydraulic pressure of the river into the gravel bar. At the beginning of the flood, many piezometers situated in the back channel, distant from the river channel by many tens of metres, temporarily become small geysers. The water expelled is phreatic, as evidenced by its high conductivity value as well as the presence of small invertebrates. Also, on some previously cored trees, xylem sap begins to leak during this period of river water level increase.

In the case of lakes, the interaction between surface water and groundwater is different. The role of groundwater input and output from less dynamic surface waters such as lakes has intrigued hydrologists for many years, in part because it is a difficult flux to determine. Yet, the quantification of groundwater/lake interactions has been done for some systems, particularly in relatively small lakes where both long-term chemical and hydrological data exist. The estimation of these water balances is important with respect to the long-term recharge potential (Ojiambo et al., 2001).

4.2. Confluence

Papers on water mixing at river confluences are relatively scarce. Most works are theoretical and discuss the mixing of the two waters, but do not take in account the possible role of groundwater. Lane et al. (1999a,b) have described the complexity of water mixing in a river confluence. For river channel confluences with irregular boundaries, the identification of the primary flow is difficult, and hence the separation of primary and secondary flows is not easy. This secondary circulation involves net cross-stream and downstream transfer and momentum in the form of a helix. When do the two primary flows of each tributary become a single primary flow in the main channel? There is a shear layer between the two confluent flows, and hence two primary flow directions, each of which is progressively aligned to become parallel to the other with increasing distance downstream through the confluence. This shear layer may exist for a significant distance downstream—indeed, more than several channel widths before the two flows become fully mixed. It is also what we have observed for the confluence of the Garonne and the Ganges tributaries.

Rhoads and Kenworthy (1995) report water mixing at a confluence. Stream confluences are characterized by complex hydrodynamic conditions associated with the convergence of separate flows. Conceptual models indicate that hydrodynamic features at confluences include a zone of flow stagnation at the upstream junction corner (which could explain the capacity for groundwater to flow out at this point), a shear layer between the merging flows, twin surface-convergence helical cells on either side of the shear layer, and separation of flow from one or both channel banks immediately downstream of the confluence. Only a few field investigations have examined flow patterns at stream confluences, and the results of these investigations have not been entirely consistent with the conceptual models.

As separate streams enter a confluence, either one or both of the flows must curve to become aligned with the downstream channel. This curvature should produce super-elevation of the water surface and resulting helical flow. The degree of curvature of each stream is controlled by the planform of the confluence, the junction angle and the momentum ratio.

Temperature and velocity can indicate that curvature-induced secondary circulation plays an important role in transverse mixing of the two flows at the confluence. Because confluences are locations where streams with different water quality characteristics join, the occurrence of secondary currents at these sites may have important implications for the dispersion of solutes and suspended solids throughout river networks.

4.3. Isotopes

The δ^{18}O and δ^{2}H of rivers reflect how the relative amounts of precipitation and groundwater vary with time, and how the isotopic compositions of the sources themselves change over time. Seasonal variations will be larger in streams where recent precipitation is the main source of flow, and smaller in streams where groundwater is the dominant source. As the basin size increases, the isotopic compositions of rivers are increasingly affected by subsequent alterations of the precipitation compositions by selective recharge and runoff, mixing with older groundwater and newer rain water, and by evaporation (Kendall and Coplen, 2001). These scale and climate effects were seen at the Garonne site, where the isotopic composition was stable from the foothills until the confluence with the Tarn river, about 70 km downstream of Toulouse, whereas for the Ganges site the ^{18}O content varied along the plain.

From an isotopic point of view, it is often difficult to distinguish the water of two tributaries if they have the same kind of origin. This was the case in our both study cases in France and India. Only in specific cases, as with a large main stream and a smaller tributary, is this water mixing quantifiable (Hardegree et al., 1995). Our aim was to explore the possible influence of groundwater in these confluence areas. At the confluence of the Garonne and the Ariège rivers, the measured output was low, perhaps also minimized by the relatively long period needed (in 2001) to reach low-water level. In contrast, in India the sampling was done just after a rapid decrease of the flows in the Yamuna and Ganges, which helped in the detection of the groundwater. This measured water flow could explain the old legend which report the presence of a third invisible river flowing at this confluence point. It is interesting to note that the old vedic name of Allahabad city (given by the Moghols) was *Prayag*, which means confluence, and to note also the existence of a specific name in India linked with this notion: *doab* (two rivers) or *Antarvedi* (between rivers).

4.4. Riparian woodland

River banks are the places where groundwater and river water mix and merge. This active interface leads to a high degree of vegetative diversity. Riparian forest are characterized by a mixed assemblage of obligate phreatophyte plants (those that send their roots into or below the capillary fringe to use the alluvial groundwater) and facultative phreatophytes, plants that can also survive in upland environments where groundwater is not directly available (Snyder and Williams, 2000). Phreatophyte riparian trees are species adapted to fluctuating water tables and sensitive to changes in the hydrogeological regime. This may be in the form of a water table declining at a rate faster than root growth, or an alteration in the annual fluctuations of the water table (Le Maitre et al., 1999). These conditions influence the whole rhizosphere, where water purification processes such as denitrification occur. In a way, riparian woodlands are natural phytoremediation areas. Successful conservation of these forests will require more knowledge on the dependence of riparian species on groundwater and conversely on the feedback between riparian vegetation and stream and groundwater dynamics. These alluvial wet areas, which should also include the river, are also important for preservation of the rest of the biodiversity: fishes, birds, etc.

5. Conclusion

Along the two sites studied in the south-west of France, conductivity and isotopic measurements showed/confirmed that the groundwater of the upper terrace was quite homogeneous. This clearly demonstrates the rainfall and soil similarities of this 50 km long transect of the Garonne river. On the contrary, the river banks display high water heterogeneity in the lower part of the meanders. These areas are the places where the groundwater and the river water merge, and the proportion of the mixing is highly variable due to river level dynamics. But the more surprising result, is that the groundwater flowing out into the river can be precisely located, and is not diffuse.

All these considerations can help to better understand the complex water fluxes at the river's confluences. Groundwater trapped between the two river beds has to flow outside upstream of or at the point of confluence. At both confluences studied, groundwater outputs were effectively detected, even considering the high flux for the Indian case. The river confluence is, in fact, the mixing of three waters: two distinct river waters and one groundwater, even if this latter is generally obscured by the higher discharge of the rivers.

Riparian vegetation growing on these river banks also bear witness to this mixing of waters and their dynamics. Firstly, the presence of trees, such as the willow, can show the presence of groundwater. Second, the history of the river dynamic can be recorded in the age and shape distribution of the riparian woodland along the river banks.

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