Isotopes in Environmental and Health Studies
Vol. 39, No. 4, December 2003, pp. 301–310

THE USE OF STABLE ISOTOPES TO EVALUATE WATER MIXING AND WATER USE BY FLOOD PLAIN TREES ALONG THE GARONNE VALLEY

L. LAMBS[a,*], M. LOUBIAT[a] and W. RICHARDSON[b]

[a]*Federation of Research in Ecology, Laboratory of Biodiversity and Dynamics – CNRS, 29 Rue Jeanne Marvig, Toulouse, 31055, France;* [b]*U.S. Geological Survey, La Crosse, Wisconsin, USA*

(Received 27 November 2002; In final form 31 March 2003)

Before the confluence of the Tarn, the Garonne valley was the driest area in the entire south-west of France, due to the relatively low rainfall and low summer discharge of the Garonne River and its tributaries. The natural abundance of the stable isotope of oxygen (^{18}O) and ionic charge of surface and ground water were used to estimate the water source for the Garonne River and phreatic subsurface water. We also measured these constituents in the sap of trees at several flood plain sites to better understand the source of water used by these trees. ^{18}O signatures and conductivity in the Garonne River indicated that the predominance of water was from high altitude surface runoff from the Pyrenees Mountains. Tributary inputs had little effect on isotopic identity, but had a small effect on the conductivity. The isotopic signature and ionic conductivity of river water ($\delta^{18}O$: −9.1‰ to −9.0‰, conductivity: 217–410 μS/cm) was distinctly different from groundwater ($\delta^{18}O$: −7.1‰ to −6.6‰, conductivity: 600–900 μS/cm). Isotopic signatures from the sap of trees on the flood plain showed that the water source was shallow subsurface water (<30 cm), whereas trees further from the river relied on deeper ground water (>1 m). Trees at both locations maintained sap with ionic charges much greater (2.3–3.7×) than that of source water. The combined use of ^{18}O signatures and ionic conductivity appears to be a potent tool to determine water sources on geographic scales, and source and use patterns by trees at the local forest scale. These analyses also show promise for better understanding of the effects of anthropogenic land-use and water-use changes on flood plain forest dynamics.

Keywords: Oxygen 18; Riparian forest; Trees; Water origin

INTRODUCTION

The Garonne valley around the city of Toulouse displays an asymmetric shape with high terraces on the left bank and numerous low terraces on the right bank [1]. Bands of naturally regenerated riparian forest and poplar plantations occur close to the Garonne River, where annual floods prohibit other forms of cultivation. This alluvial vegetation depends on hydrological resources and has to adapt to the changes in water levels and soil moisture conditions [2]. The relationship between the variation in river discharge, soil moisture, and dynamics of alluvial vegetation lead us to study in more detail the origin and mixing of water in the streamside corridor using stable isotopes, such as ^{18}O [3]. The upper Garonne valley around

* Corresponding author. Tel.: 00 33 (0)5 62 26 99 94; Fax: 00 33 (0)5 62 26 99 99; E-mail: lambs@ecolog.cnrs.fr

ISSN 1025-6016 print; ISSN 1477-2639 online
DOI: 10.1080/10256010310001621100

the city of Toulouse receives between 600 and 700 mm of rainfall per year, whereas the potential evapotranspiration is between 850 and 900 mm/year, increasing from west to east due to the influence of the Mediterranean Ocean. The small tributaries (Save, Gimone, Hers, Tauris Rivers) discharge only a small amount of water (*e.g.*, mean discharge for the Save river is 7 m^3/s), relative to the Garonne River (mean discharge 200 m^3/s in Toulouse). For this reason, the water from the Pyrenees foot hills through the Garonne River (up to 1500–2000 mm/year) is responsible for 90% of the discharge in Toulouse and is vital for the survival of vegetation of the floodplain. However, due to the lack of an extensive glacier system as in the Alps, summers with extended low water periods can present significant water stress for the riparian woodland. To better understand the pattern of water distribution the $^{18}O/^{16}O$ ratio and the electrical conductivity characteristics of the ground water and the river water were studied for over 5 years and are reported here. We also determined the source and use of water by riparian trees by evaluation of isotopic signatures and conductivity of sap to better understand how changes in the water resources affect riparian forest dynamics.

MATERIAL AND METHODS

Site Description

The characteristics of the Garonne River and ground water were studied from 22/07/97 to 22/7/99 40 km downstream of Toulouse near the village of Verdun, on the right bank towards Monbéqui (position 43°53′ N and 1°12′ E: ‘1’ in Fig. 1). A reference well for the ground water was more inland with an average depth of 380 cm. A second study well was located a few kilometers upstream on the left bank near the poplar plantation of St. Pierre (‘2’ in Fig. 1), and sampled from 25/01/00 to 27/09/01. The reference well for this site was on the higher terrace with an average depth of 950 cm. The well in the Monbéqui site was sampled again from 17/01/02 to 15/10/02. In all, more than 5 years of field data are reported, including the ground water level, temperature, electrical conductivity and the isotope (^{18}O) data for both the ground water and surface water of the Garonne River. The adjacent tributaries (Save, Tauris) were also regularly sampled. On two dates, 10/02/00 and 13/09/01, water samples were taken on the Garonne River above the confluence with the Ariège river (43°30′ N and 1°24′ E) about 10 km upstream of Toulouse (‘3’ on Fig. 1).

Electrical Conductivity and Isotopic Analysis

Surface water, as well as ground water 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. 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 (SMOW), in parts per thousand, given as a ratio of $^{18}O/^{16}O$ equal to 2.005×10^{-3}.

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

The measurements were made on an Optima spectrometer from Micromass, equipped with an Isoprep off-line gas production, using the CO_2 equilibration method. This technique has an analytical performance with a precision of 0.04‰.

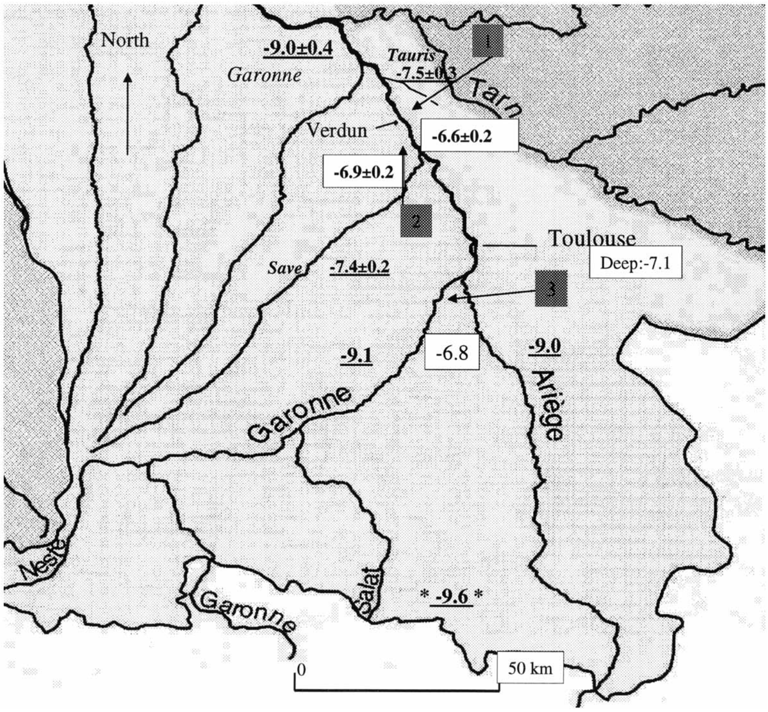

FIGURE 1 Typical $\delta^{18}O$ values of water in the Garonne valley, in the south-west of France, near Toulouse. The values of the surface water are underlined; the '*' indicates a snow sample; white rectangles indicate ground water values; the one at Toulouse corresponds to deep ground water (53 m deep below surface). The numbers in grey rectangles indicate the place of the reference wells for the ground water: 1 is Monbéqui, 2 is St Pierre and 3 is Pinsaguel (confluence).

Sampling of Tree Sap

Four trees (three black poplars and one white willow) have been studied, located on the back side of the young riparian woodland (about 250 m long and 75 m wide, trees aged 10–15 years) of the Monbéqui site. The trees were along an old channel which is flooded at least once a year. The xylem sap from four trees was squeezed from wood core with a 'sap-press' [4]. Cores were obtained with an increment borer. The electrical conductivity of these small volumes (about 0.5 ml) was measured in the laboratory with the use of a micro-conductivity cell. The soil water was sampled, between the first poplar and the willow, from six porous ceramic suction cups called 'tensionics' [5] installed in Spring 2002. The tensionics were installed at depths of 15, 30, 45, 60, 90 and 120 cm. Sample extraction was performed with a hand pump, and soil water was sampled nearly every week. The isotopic measurement was made on May 23, 2002.

RESULTS AND DISCUSSION

Characteristics of Ground Water and River Water

Figure 1 summarises typical $\delta^{18}O$ values of ground and surface water in the Garonne valley. The lower line on this map represents the border with Spain and the Pyrenees Mountains. Pyrenees snow displayed a $\delta^{18}O$ value of about -9.6‰ and a conductivity of 60 $\mu S/cm$.

The upper part of the Garonne as well as the Ariège River arise from the Pyrenees Mountains and display $\delta^{18}O$ values of −9.1‰ and −9.0‰, respectively, showing a large percentage of high altitude (mountain) water. The Garonne River then maintains a $\delta^{18}O$ value around −9.0‰ until the confluence with the Tarn. The conductivity for both rivers before Toulouse is around 217 μS/cm for the Garonne River and 148 μS/cm for the Ariège River, showing the progressive mineralisation of the snow and rain water from the river bedrock. After Toulouse, the conductivity of the Garonne water increases to an average of 245 μS/cm. The lower altitude tributaries, like the Save River (left bank) or the Tauris River (right bank), display $\delta^{18}O$ values ranging from −7.4‰ to −7.5‰, their conductivity averaging 410 μS/cm. The ground water sampled in three riparian sites has $\delta^{18}O$ values of −6.6‰ (Monbéqui), −6.8‰ (St. Pierre) and −6.8‰ (the confluence). This relative isotopic homogeneity reveals the same sources of rainfall for these parts of the Garonne valley, situated 100–150 m above sea level, and is similar to the average isotopic value of local rainfall (−6.9‰ ± 1.7‰) [1]. The conductivity of the ground water is 600–900 μS/cm for a temperature close to 13 °C year round. A deep underground aquifer (below 50 m) exists under Toulouse and in the rest of the Garonne valley with a $\delta^{18}O$ of −7.2‰, conductivity of 640 μS/cm and temperature of 16.5 °C. This deep water with these specific parameters is certainly old and could be captive, as the alluvial plain has many horizontal layers of impermeable clay [6].

Figure 2 shows the variation of the $\delta^{18}O$ values of the water sampled between 09/07/97 and 23/05/02. The Garonne River mean value was −9.05‰ ± 0.44‰ during this period. This value is a little higher in $\delta^{18}O$ than other streams coming out of the Alps mountain *i.e.*, Rhine River (at Lobith): −10.0‰ ± 0.5‰ or the Danube River (at Ulm): −9.95‰ ± 0.25‰ [7]. However, the Pyrenees range is also lower and the glacier system is less well developed. In fact, the only possible buffer is the snow, which melts beginning in April until May–June, and does not compensate river discharge for the lack of precipitation

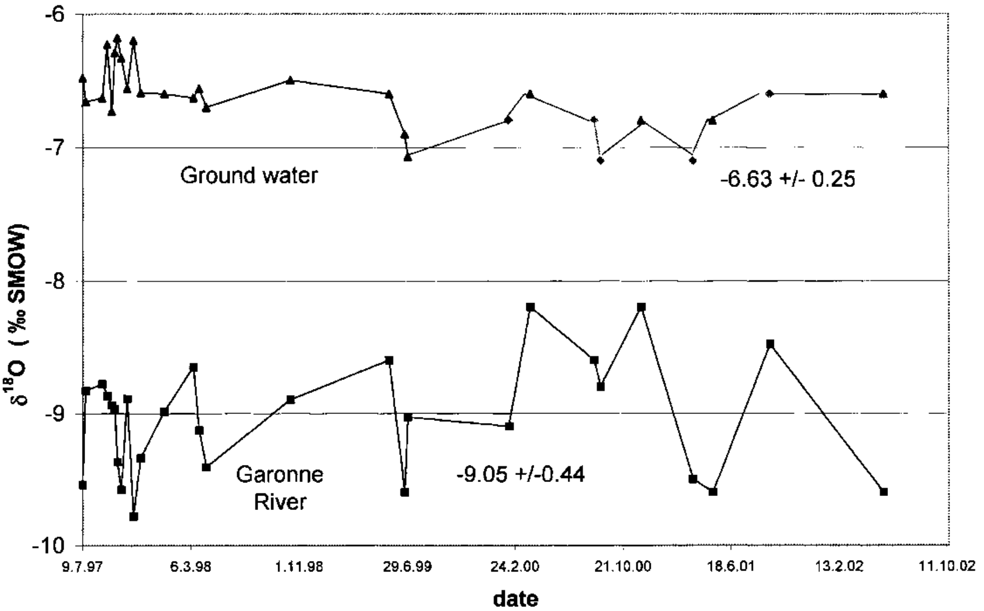

FIGURE 2 $\delta^{18}O$ variation of the Garonne River (28 points) and the ground water from July, 1997 through June, 2002. The river water was sampled in Verdun whereas the ground water was taken in the reference well in Monbéqui (triangle) on the right bank and in the reference well in St Pierre (square) on the left bank.

between August and September. The strong seasonal effect observed for river water originating in the Alps resulted in more negative values in summer due to the glacier melt, a pattern not seen in the Garonne River. For the Garonne, the variations in discharge and isotopic value are more variable depending on the speed of the snow melt and the location and amount of the rain on the foothills: more negative values (about −9‰ to −8‰) due to the increasing continental and altitude effect should be linked with rain or snow fallen at higher altitude, that is more depleted in heavy isotope, whereas less negative values (around −7‰) indicate lower altitude rainfalls.

The pattern of the ^{18}O content of ground water is more dampened, with less variation (−6.63‰ ± 0.25‰), and very close to the signature of average local rainfall (−6.7‰) in the low altitude Garonne plain. The variation of the rainfall is buffered by the large valley and the slow water motion. If we separate the origin between the three samples of ground water, there is no real difference between the phreatic water in Monbéqui (right bank −6.58‰ ± 0.22‰) or Verdun St. Pierre (left bank −6.88‰ ± 0.21‰) or in Pinsaguel (near the confluence with Ariège river: −6.8‰, not reported in Fig. 2) showing the relative homogeneity of the rainfall over this valley.

Figure 3 reports variations in the electrical conductivity of the water sampled between 09/07/97 and 15/10/02. Here again the shape is similar to that found between the two curves, as in the previous figure, but the variability is now higher for the ground water and lower for the river water. It is interesting to note that the ionic charge of the Garonne River is about 240 μS/cm, half that of the small tributaries like the Save or the Tauris Rivers (about 480 μS/cm for both, not reported in this figure) and one third that of the ground water (720 μS/cm). The lowering of the conductivity of the Garonne River was observed during flood from the heavy local rain (conductivity 40–70 μS/cm) and had no time to gain ionic charge. Flood durations of the Garonne River do not exceed a few days, and can occur nearly at any moment of the season. In fact around Toulouse the type of flood is more

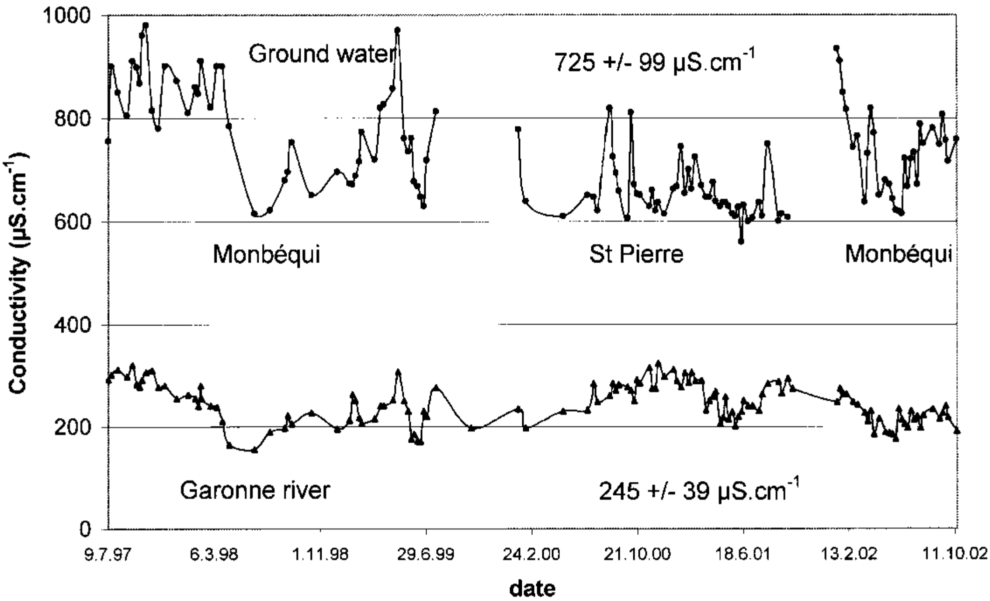

FIGURE 3 Variation in conductivity of the Garonne River (126 points) and the ground water from July, 1997 through June, 2002. The river water was sampled in Verdun whereas the ground water was taken in the reference well in Monbéqui (first and third set of points) and in the reference well in St. Pierre (second set of points).

'Mediterranean' with rapid rise and fall of the hydrograph compared to an 'oceanic' type that comes mainly from the further west tributaries as the Tarn or the Lot Rivers, and exhibits a more 'damped' hydrograph.

Variation in the conductivity of ground water was 725 ± 99 μS/cm for the range of the monitoring. If we consider the river banks separately, the mean value for the ground water in the Monbéqui well is 756 ± 97 μS/cm, whereas the deeper well in St. Pierre is a little less charged (644 ± 40 μS/cm). We had previously determined that the outflow of the ground water from the lower terrace at the right bank was in part retained by the level and pressure of the Garonne River [3]. As the terrace is higher on the left bank, as in St. Pierre, the ground water would be less restrained to flow out to the Garonne River, and so could be less charged.

The variation of the Garonne River level and the ground water level for this 5 year period is reported in Figure 4. In some years (*e.g.*, 1997) the level of the Garonne remained low until the beginning of November (1997 being the driest on average over the last 10 years) or through the entire winter (2001). In contrast, in 1998, the low period was very short and intense, and with a very dry summer because the rainfall of about 465 mm was abnormally low in comparison to the 600–700 mm of rainfall recorded for the other years. However, the average annual level was normal due to the high spring and fall floods. The level of ground water at Monbéqui was similar to the Garonne River level, likely influenced by the river water pressure. This effect of the Garonne is not seen in the ground water at the St. Pierre site situated on a more elevated terrace.

Interaction Between Ground Water and Riparian Trees

The aim of the second part of this work was to look at how the river water and the ground water mixed in the alluvium and how this mixture was then absorbed by riparian trees. Stream banks are not only the beginning and end points of ground water flow and water supply,

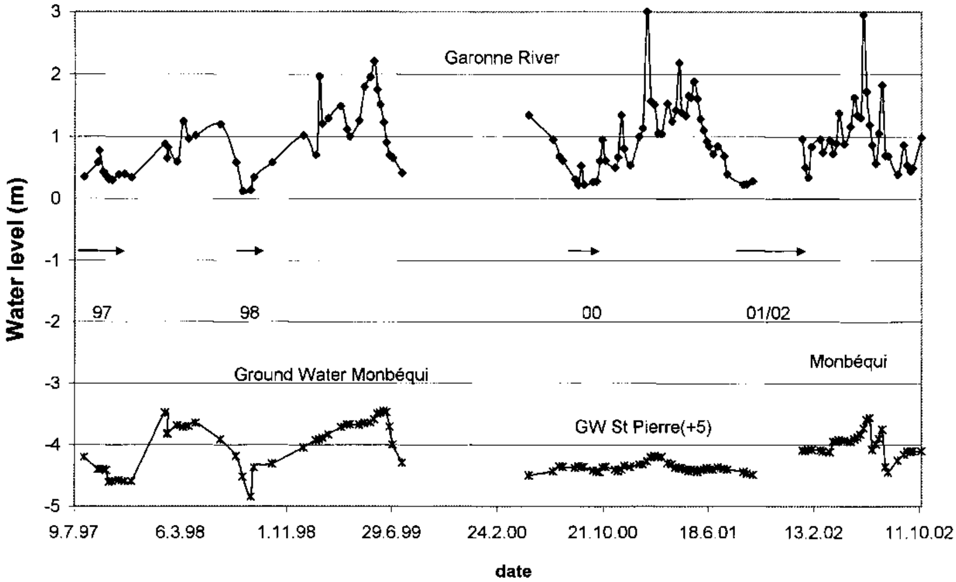

FIGURE 4 Level of the Garonne River at Verdun for the sampling dates during the study time and comparison with the ground water level in Monbéqui and St. Pierre. The St. Pierre values have been upgraded by 5 m for a better comparison of the variations. The arrows indicate the low water period for the year with the corresponding date.

but also critical components of the riparian and riverine ecosystem. From a physical and geochemical point of view, this area is called the *hyporheic zone* and is a portion of the saturated zone in which the surface water and ground water mix [8]. Good correlations (r^2 up to 0.95) have been found between ^{18}O content and conductivity for the water sampled on a gravel bar in the Garonne River [3]. The discharge of the river is high enough to ensure that evaporation does not influence the isotopic value of water. Also, there is no isotopic shift due to the average local rainfall. However, when the phreatic water, which is a mixture of the ground water and the river water, diffuses through the bank soil to the surface, there is an isotope fractionation of this water. This gradient can be used to determine from which soil depth the trees are taking their water, as there is no isotope fractionation when the water is absorbed by the tree root [9–11]. Table I reports the δ^{18}O values and the conductivity for the soil water from various depths taken between the poplar and the willow. As in 1999 [4], the fractionation of the soil in those wet areas seems to occur close to the surface. This was confirmed over the season by the installation of additional 'tensionics' at 15 and 45 cm during 2002. Due to more contrasted conditions at the surface (higher evaporation and evapotranspiration, influence of rainfall or flood), higher variability was observed in the first two tensiometers at a depth of 15 and 30 cm. Table I also summarises the sap characteristic of four trees relative to the ground water. As in 1999, there was no difference between the willow and the poplar for the water absorption [4] although they are considered to be obligatory and facultative phreatophytes, respectively. Also, the difference in δ^{18}O signatures between tree sap and ground water is always about one unit (1.05 ± 0.13‰) and shows that these trees mainly take their water close to the surface.

The poplars located more inland, exposed to less flooding, and with deeper ground water levels (*e.g.*, at St. Pierre) absorbed water from the deeper layer [1]. In the case of the wetter period of May 2001 the soil water fractionation was first reversed (likely due to the presence of older water with different composition) and then fractionated strongly in the last 60 cm.

These examples show the complex water distribution in the riparian area and the variation of water content in vertical soil profiles. Trees have the ability to maintain a high ionic concentration in xylem sap regardless of the water origin. Such homeostasis is maintained despite frequent and rapid changes in water levels, mixtures of variable ionic strength, and the appearance of distinctly different layers of water in the soils.

The alluvial forests have to adapt to this variation, some of which is being intensified by human activity (including the lowering of the river and water table, diminished water quality, and increased sediment load) in order to survive. Certain species seem to be able to adapt to or take advantage of such changes to the detriment of other tree species. For example, poplar (*Populus nigra*) populations in the flood plain appear to be expanding, while willow (*Salix alba*) populations decline. It is likely that declining ground water has a strong negative impact on the survival of willow because of its heavy reliance on ground water. Such community changes may be related to changes in phreatic water quality and quantity.

Successful conservation of alluvial forests will require knowledge of the dependence of riparian species on ground water and conversely, and on the feedback between riparian vegetation and stream and ground water dynamics. Not all species in these forests use only ground water (*i.e.*, from the saturated zone) for transpiration as the term 'phreatophyte' implies. Phreatophytes encompass a wide spectrum of functional types that respond uniquely to spatial and temporal variation in the distribution of available water in the rhizosphere [10]. The ability to trace water source and uptake by trees using ^{18}O could also be applied as a surrogate for the movement of materials out of the landscape. For example, there is strong interest in the knowledge of the movement of agriculturally applied nutrients into streams and rivers, particularly nitrogen and phosphorus, because of their effect on aquatic productivity [12, 13]. Keen interest also exists in determining the role of riparian forests as sites for

TABLE I Comparison of ^{18}O Concentrations and Electrical Conductivity of the Sap of Poplar Trees Relative to the Water Collected from the Piezometer (Water Table) and the Soil Water Collected from Different Depths from Within the Vacuum Ceramic Tensiometers (Soil Water).

	Soil water		*Poplar 1*		*Willow*		*Poplar 2*		*Poplar 3*	
	$\delta^{18}O$ (‰)	*Conductivity* ($\mu S/cm$)	$\delta^{18}O$ (‰)	*Conductivity* ($\mu S/cm$)	$\delta^{18}O$ (‰)	*Conductivity* ($\mu S/cm$)	$\delta^{18}O$ (‰)	*Conductivity* ($\mu S/cm$)	$\delta^{18}O$ (‰)	*Conductivity* ($\mu S/cm$)
Trunk sap			**−7.1**	2044	**−7.0**	1580	**−7.6**	1978	**−7.9**	1686
Soil water at 15 cm	−7.0	637								
Soil water at 30 cm	−8.3	820								
Soil water at 45 cm	−8.5	634								
Soil water at 60 cm	−8.2	797								
Soil water at 90 cm	−7.9	939								
Soil water at 120 cm	−8.0	701								
Water table			**−8.1**	690	**−8.1**	690	**−8.8**	529	**−8.8**	529

Ground water levels were 1.55 m for poplar 1 and willow, 1.37 m for poplar 2 and about 2 m for poplar 3. The values for the water references were −9.05‰ and 185 µS/cm for the Garonne River and −6.6‰ and 644 µS/cm for the ground water [1, and present data]. All data were obtained on May 23, 2002.

removal of agricultural runoff [14–16]. If the identity of the flow paths of ground water from various aquifers and the use by riparian trees could be determined with ^{18}O signatures, and the water nutrient constituents then quantified, future evaluations of material fluxes from agricultural systems could be estimated from ^{18}O signatures alone. Clearly, this approach would depend on a tight fit between ^{18}O and nutrient concentrations, but studies exist to suggest this to be the case [12]. However, the simultaneous determination of water source and tree water consumption is uncommon and would further help elucidate the linkages between agricultural landscapes and riparian forests.

CONCLUSION

As seen for its ^{18}O values, the Garonne River keeps its high altitude water characteristics until the confluence with the Tarn river. The lower altitude tributaries, as well as the ground water, do not have enough discharge to influence the isotopic and ionic characteristics of the Garonne River. The difference of two units for the ^{18}O values between the river and the ground water is enough to make the distinction between these two main sources of water throughout the year. Hence it is possible to determine the mixing of these two waters in the alluvial banks. The percentage of each water type depends mainly on the type of the river discharge. Riparian forests have to adapt to these water sources and water level fluctuations. Even in these conditions, the upper roots seem to be active, in order to capture the surface moisture with its higher ionic content from the humus horizon. More field measurements are needed to see if during drought the tap roots also become active.

Acknowledgements

We are grateful to the CEMES laboratory, Toulouse, for the access to the deep well in Toulouse, the European Commission (ENV4-CY96-0317 and EVK1-1999-000154) for supporting this research project and to the anonymous referees for their valuable comments and suggestions.

References

[1] Lambs, L., Loudes, J.-P. and Berthelot, M. (2002). The use of the stable oxygen isotope (O^{18}) to follow the water distribution and absorption in riparian woodlands. *Nukleotika* **47**, 71–74.
[2] Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A. M., Muller, E. and Decamps, H. (2000). Impact of riparian vegetation on hydrological processes. *Hydrol. Process.* **14**, 2959–2976.
[3] Lambs, L. (2000). Correlation of conductivity and stable isotope ^{18}O for the assessment of water origin in river system. *Chem. Geol.* **164**, 161–170.
[4] Lambs, L. and Berthelot, M. (2002). Monitoring water from the underground to the tree: first results with a new sap extractor on a riparian woodland. *Plant Soil* **242**, 197–207.
[5] Vigouroux, A. (1997). A first approach to assessing soil oxygenation in the field using Tensionic ceramic tensiometer. *Agronomie* **17**, 389–394.
[6] Steiger, J., Corenblit, D. and Vervier, P. (2000). Les ajustements morphologiques contemporains du lit mineur de la Garonne, France, et leur effet sur l'hydrosystème fluvial. *Z. Geomorph. N.F.* **122**, 227–246.
[7] Rozanski, K., Froehlich, K., Mook, W. G. and Stichler, W. Environmental Isotopes in the Hydrological Cycle, Principles and Applications. UNESCO/IAEA Series Vienne, volume 3: Surface Water, 2001; pp. 19–31.
[8] Woessner, W. W. (2000). Stream and fluvial plain ground water interactions: rescaling hydrogeologic thought. *Ground Water* **38**, 423–429.
[9] Ehleringer, J. R. and Dawson, T. E. (1992). Water uptake by plants: perspectives from stable isotope composition. *Plant Cell Env.* **15**, 1073–1082.
[10] Snyder, K. A. and Williams, D. G. (2000). Water sources used by riparian trees varies among stream types on the San Pedro river, Arizona. *Agri. For. Metorol.* **105**, 227–240

[11] Thornburn, P. J., Hatton, T. J. and Walker, G. R. J. (1993). Combining measurements of transpiration and stable isotopes to determine ground water discharge from forest. *Hydrology* **150**, 563–587.
[12] Bohlke, J. K. and Denver, J. M. (1995). Combined use of ground water dating, chemical, and isotopic analysis to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic Coastal Plain, Maryland. *Water Resourc. Res.* **31**, 2319–2339.
[13] Rabalais, N. N. (2002). Nitrogen in aquatic ecosystems. *Ambio* **31**, 102–112.
[14] Lowrance, R., Todd, R., Jail, J., Hendrickson, O., Leonard, R. and Asmussen, A. (1984). Riparian filters as nutrient filters in agricultural watersheds. *Bioscience* **34**, 374–377.
[15] Haycock, N. E., Pinay, G. and Walker, C. (1993). Nitrogen in river corridors: European perspective. *Ambio* **22**, 340–346.
[16] Sanchez-Perez, J. M., Tremolieres, M., Takatert, N., Ackerer, P., Eichorn, A. and Maire, G. (1999). Quantification of nitrate removal by a flooded alluvial zone in the Ill floodplain (Eastern France). *Hydrobiol.* **410**, 185–193.