Stable isotopes ($\delta^{18}O$ and δD) analyses to identify the main sources of aquifer recharge in the Brussels Capital Region (Belgium)

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Abstract

Urban aquifers are particularly difficult to manage mostly because urban activities and infrastructures severely impact their recharge. Impervious surfaces reduce the natural infiltration of rainwater, concurrently waste and drinking waters represent an important contribution to the aquifer recharge. These modifications vary geographically due to the local particularities of the urban infrastructures but also in function of the type of aquifers (perched, confined) present. We analyzed the stable isotope ($\delta^{18}O$ and δD) composition of more than 500 samples of ground water, drinking water and rainwater within the Brussels Capital Region (BCR), collected between 2010 and 2013, to distinguish the main sources of aquifer recharge. The results show distinct isotopic values for the aquifers in the BCR. These values are used to assess the connectivity between aquifers. The "Brussels Sands" aquifer shows stable isotope values varying in concordance with the spreading of the urban settings above this unconfined aquifer. The possible causes of the urban effect on the isotopic signature are discussed by comparison with the values obtained for rainwater, as well as waste and drinking waters. The stable isotopes analyzes ($\delta^{18}O$ and δD) may also be coupled with other isotopes or chemical signals and constitute a useful tool for urban aquifers management.
Keywords: urban aquifer recharge, ground water resource management, stable isotopes, cavity ring-down spectroscopy.

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1 Introduction

Urban water cycle is impacted by the human activities and infrastructures. Sewers in poor conditions leak waste water through cracks and collapses that recharges and pollutes the urban aquifers. Drinking water also drains from the pressurized drinking water distribution network and recharges urban aquifers (Lerner [1]). Beside the pollution risk, these recharge sources impact the ground water fluxes and consequently should be clearly identified for ground water resource management.

Urbanization also disturbs the way shallow aquifers are connected to surface waters. Urban aquifers are often not disconnected from their natural watercourses. The urban watercourses are culverted and numerous urban infrastructures drain the aquifer. Sewers and other undergrounds infrastructures (parking, house basements), protected from the water-table elevation by the installation of drains, lower the water table and conduct ground water into the sewers (Broadhead *et al*. [2]).

In Europe, the application of the Water Framework Directive implies that aquifers must obtain a good ecological status (both qualitatively and quantitatively) for 2015. To correctly manage urban aquifers, more knowledge is required on the localization of the potential or preferential recharge sources and the connections between the aquifers or with the urban infrastructures.

Stable isotopes are regularly used in hydrogeology to detect connections between aquifers or human-induced aquifer recharge (Seiler *et al.* [3]). This article presents stable isotopes concentration ($\delta^{18}O$, δD) results obtained on more than 500 water samples geographically spread over in the Brussels Capital Region (BCR).

2 Methodology – instrument

Ground water samples were collected between 2010 and 2013, while the others types of water (rainwater, reservoir water, tap water) were sampled twice a month during one year (in the 2011–2012 period). The samples are collected in plastic or glass bottles hermetically sealed.

The analyses of stable isotopes ($\delta^{18}O$ and δD) were made at the Vrije Universiteit Brussel (VUB), mainly with the Picarro L2130-i instrument. This instrument is based on the recently developed Cavity Ring-Down Spectroscopy principle. The development of good experiment protocols at the VUB laboratory required time and efforts. The first analyzes presented uncertainty similar or higher than comparable analyses made with the classic mass spectrometry technique (0.1‰ and 1‰ for $\delta^{18}O$ and δD), while the most recent analyses present a typical uncertainty (2 sigma) of 0.06‰ and 0.4‰ for respectively $\delta^{18}O$ and δD (intern laboratory comparisons).

3 Results

3.1 Rainwater

Rainwater has been collected in jars in which a few millilitres of paraffin oil was placed. The paraffin oil floating on the collected water hampers the exchange of oxygen isotopes with ambient air. The stable isotopes concentrations of the rainwater form a regression line called Local Meteoritic Water Line (LMWL). The LMWL serves as reference to discuss the possible natural or human-induced recharge sources (cf. Figures 1–3 and 5) (Seiler *et al.* [3]).

3.2 Drinking water

Before distribution, the drinking water is stored in large reservoirs by the water distribution Company (Vivaqua). Drinking water comes from ground- and river-waters pumped outside of the BCR. The proportion of the different types of drinking water varies through the seasons in the same reservoir but also from one reservoir to another. The isotopic composition of drinking water differs from that of the local ground waters due to the continentality effect impacting the shallow ground waters, the different climatic conditions during the recharge of old ground waters, and/or the seasonality effect present in the river waters. Therefore, drinking water distributed across the BCR does not show the same isotopic composition everywhere. Tap water has been sampled and sorted in function of the different reservoir zones.

The leakage of drinking water towards the aquifers occurs when pressurized drinking water network segments are broken. This mainly happens during or just after cold periods. The average isotopic composition of tap waters collected between December and February is considered to be representative of the isotopic composition of leaking drinking waters (cf. Figure 5B).

3.3 Waste water

The sewers are in poor state in the BCR. One third of the segments has to be replaced and another third repaired (Brussels Environment [4]). Consequently some waste waters ex-filtrate towards the aquifers underneath. The stable isotope composition of waste water is considered similar to that of drinking water. However the leakage of waste water occurs during the whole year while the drinking water leakages mainly occur during the winter (see before). The mean isotopic composition (on year basis) of waste water differs from the winter mean isotopic composition of drinking water.

3.4 Deep ground waters

In the BCR, 6 distinct aquifer systems have been determined. The unconfined Basement aquifer, the confined Basement and Cretaceous aquifer and the semi-confined Landenian sands aquifer) are deep aquifers, and are considered less vulnerable to pollution risk than shallow aquifers unless they are locally connected to shallow ones. This is why, the potential mixing zones have to be identified, in order to develop appropriate ground water resource management.

The Landenian sands aquifer is present over the whole region. The deeper aquifers have been separated in two distinct systems based on their position (confined or un-confined) and the presence (or absence) of Cretaceous chalks. The limit between the two deepest aquifer systems is shown in the Figure 4 (dotted line). The border has been drawn based on a study made at the larger scale of the Schelde basin (Brussels Environment [4]) and adapted to the BCR. The isotope analyses validate the limit at the regional scale but also provide hints on the local connectivity of the two deepest aquifer systems with the above Landenian sands.

The $\delta^{18}O$ (‰) results of the deep ground waters (cf. Table 1) are constant and do not show any variations at the typical uncertainty of 0.1‰ (except P5). Moreover, the oxygen isotope concentration (^{18}O) seems to be well differentiated between the three aquifers, except for the piezometers L6, P24, P33 and P15, which show abnormal values in comparison with the bulk isotopic composition of the aquifer. This state is supported by the Figure 1 where $\delta^{18}O$ and δD (‰) results are plotted.

In Figure 1, almost all ground waters are localized along the LMWL. However, the sampling station P45 shows variable isotope concentrations, sometimes away from the LWML. This indicates that the sampling station P45 should be verified as it may also collect rainwater or drinking water.

The basement aquifer presents values close to the ones of the Landenian sands aquifer and is then supposed to be directly connected to it. On the contrary the ground water from the “Basement and Cretaceous chalks” presents more depleted values but also plotted on the LMWL (between -8.3 and -9.1‰ for $\delta^{18}O$, between -56 and -61‰ for δD). These values indicate a recharge during the last glacial age (Rozanski [6]). Sadly, ground water age is not documented for this aquifer system. In conclusion, the two ground water systems show different connectivity with the above Landenian sands and the limit drawn at the scale of the Schelde basin seems also correct at the BCR scale.

However, some stations (P33 and P15) show intermediate values. Possibly, these stations pump water from both the Landenian sands and the Cretaceous chalks (large well) or are situated in a local mixing zone between these aquifers.

The station L6, associated to the Landenian sands displays depleted values, closer to the ones of the Cretaceous chalks. All these sampling stations have to be verified and the local geology studied to understand these special features.

3.5 The “Ypresian hills” aquifer system

The “Ypresian hills” aquifer system is one of the three shallow aquifer systems in the BCR. It is constituted of many sandy-perched aquifer above the main siltstone aquifer of Ypresian age (cf. Figure 4). Figure 2 presents the isotopic values of water ($\delta^{18}O$ and δD) collected from this aquifer system. The values show a large geographical and seasonal variability, mainly for the resurgences

Table 1: $\delta^{18}O$ (‰) of deep ground waters for 4 sampling campaigns.

Campaigns:		**Nov. 2010**	**June 2011**	**June 2012**	**Nov. 2012**
Semi-confined Landenian sands aquifer	L6	-8.5	-8.6	-8.4	-8.5
	P18b	-	-	-7.6	-7.7
	P24	-	-8.1	-	-
	P25	-	-	-7.4	-7.5
	P26	-7.4	-	-7.5	-7.6
	P27	-7.4	-7.4	-7.4	-7.5
	P33	-	-	-8	-8
	P5	-7.1	-7.2	-7.5	-7.6
Confined aquifer complex of basement and Cretaceous chalk	325	-8.8	-	-8.8	-8.8
	P15	-7.7	-	-7.7	-7.8
	P18a	-	-	-8.8	-8.9
	P21	-8.9	-8.9	-9	-9
	P3	-8.8	-	-8.8	-8.8
	S1	-	-	-8.7	-8.6
Unconfined basement aquifer	384	-	-7.5	-7.5	-
	P23	-7.3	-	-	-
	P4	-7.3	-	-7.2	-7.1
	P45	-	-7.9	-7.9	-7.8

collected in green areas. The isotopic values during the winter (surrounded by a circle in Figure 2) are more depleted for the resurgences: Molenbeek 4, Thaborberg, RB2 and RB3. This effect is especially important for the Thaborberg where ground water evaporate in a wetland zone before to be sampled downstream. This seasonality effect is probably the result of a second evaporation process after the resurgence (Geyh *et al.* [5]). The repartition of these values develop a regression line of $\delta D = 6.0\ \delta^{18}O - 4.1$ and can be characterized as the evaporation trend in natural environment.

The connection between the different perched aquifer cannot be characterized. More deep sampling stations are needed to do so. The latter have the advantage to not be affected by second evaporation processes that strongly alter the isotopic values and hide the primary ground water isotopic composition.

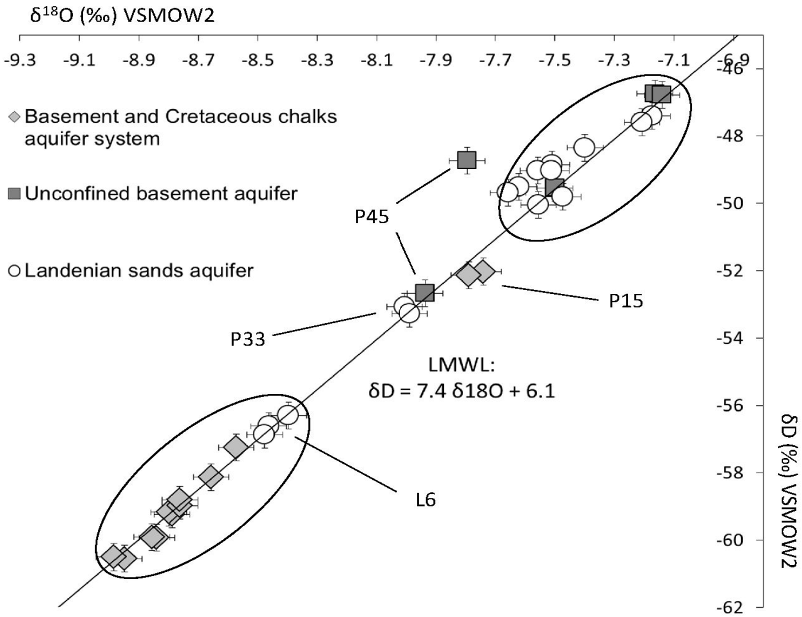

Figure 1: Distribution of δ18O (‰) and δD values of deep ground waters along the LWML.

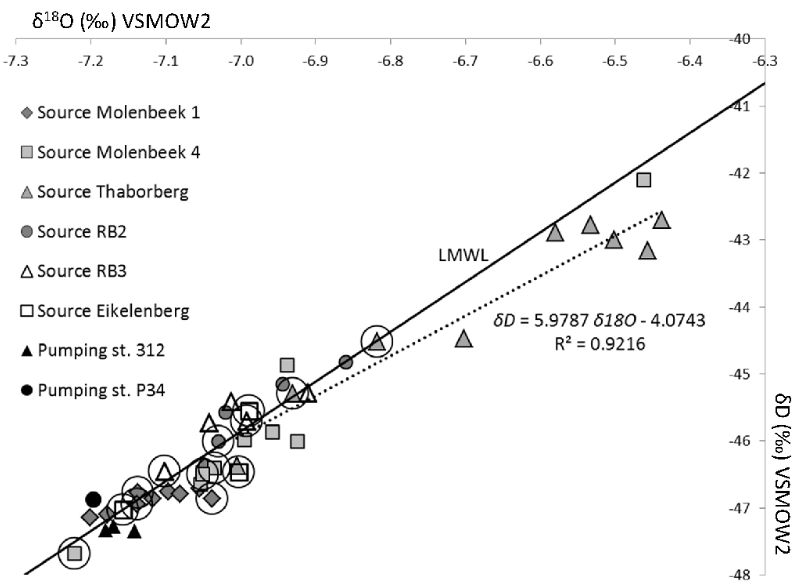

Figure 2: Ground water form "Ypresian hills" aquifer system.

3.6 The Senne's alluvial aquifer

Eleven observation wells in the South of the BCR (plus one pumping station in the North) were sampled to characterize ground water near the surface within the alluvial aquifer or next to it (cf. Figure 4). The alluvial aquifer is highly heterogeneous, from gravel to clays, and presents many underground urban infrastructures (drains, sewers, pumping stations, parking, basements) limiting the extension of the lenses of alluvial deposits. The alluvial aquifer system is in fact composed of a multitude of local aquifer layers with complex ground water flows, driven by the connections with the urban infrastructures.

The isotopic values of the water samples taken in the observation wells are distributed away from the LWML (cf. Figure 3). Apparently, rainwater does not constitute the only source of recharge.

In wells Pz6, Pz8, Pz10 and Pz11 isotopes concentrations remain constant during the two years of sampling. A constant isotopic composition is characteristic of either a large and well mixed aquifer and/or an aquifer disconnected its recharge (confined aquifer).

Three other sampling stations (Pz1, Pz7 and Pz12) show an enrichment or a depletion in heavy isotopes concentration constant over the period of sampling. However the shift of values occur in opposite directions. $\delta^{18}O$ and δD decrease in Pz1. $\delta^{18}O$ increases and δD stays constant in Pz7. $\delta^{18}O$ and δD increase in Pz12. These different trends probably represent a gradual mixing of the local ground water with a different recharge source (that has a constant isotopic composition).

The ground waters sampled in the observation wells Pz2, Pz4 and Pz9 show variable isotopic compositions. The ground water sampled is influenced by different recharge sources or by a source with varying isotopic composition. These sources are difficult to determine because they may be different for each of the sampling station.

Therefore, we observe three different recharge/mixing dynamics in this aquifer system. This supports the vision (based on the geological description) of an aquifer system extremely heterogeneous and potentially strongly influenced by (past) interactions with the urban infrastructures.

3.7 The Brussels sands aquifer

The Brussels sands aquifer is the largest shallow aquifer in the BCR (cf. Figure 4). The ground water is pumped under the Sonian forest and the "*La Cambre*" wood to produce drinking water (cf. Figure 4). The aquifer is recharged by rainwater infiltrating in the Sonian forest and in the urban settings, from a slow transfer of ground water coming from outside of the BCR (South) due to the North-dipping of the Brussels sands aquifer base, but also from the ex-filtration of the sewers and the drink-water network (Brussels Environment [4]).

The ground water under the Sonian forest is much less exposed to the urban recharge sources than in the rest of the BCR. There are no buildings, no sewers and few drinking water distribution pipes. The recharge there may be considered as natural. The ground waters from the Sonian forest area, or at the border of

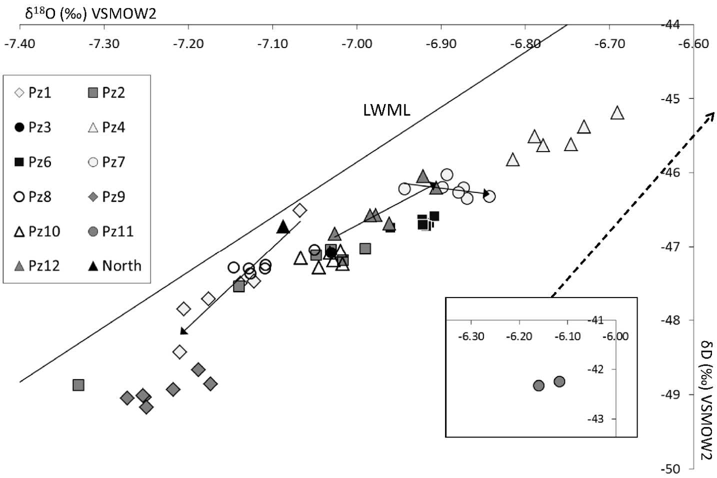

Figure 3: $\delta^{18}O$ (‰) and δD (‰) values ground water within or at the border of the alluvial plain.

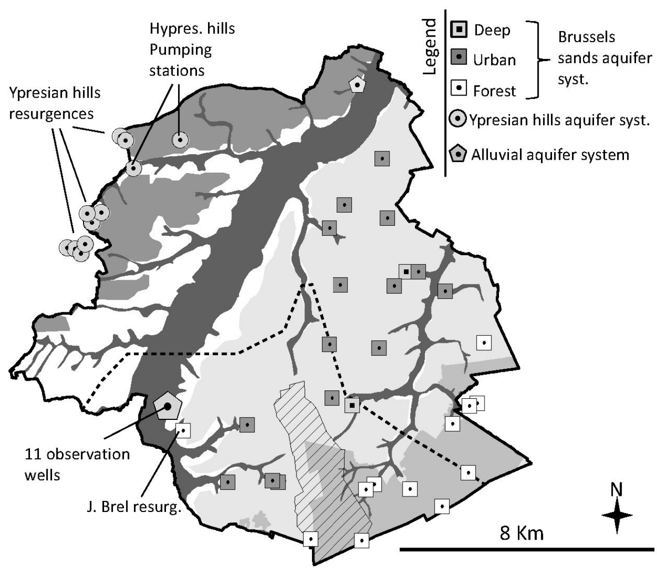

Figure 4: Shallow aquifer systems. The darkest grey represents the alluvial plains of the Senne River or its tributaries. The two lightest greys represent the Brussels sands aquifer (under urban settings or under the forest). The middle grey (west of the BCR) represents the "Ypresian hills" aquifer system. The hatched area represents the protection zone of drinking water pumpings. The white represents areas where there is no shallow aquifers.

this last, show δD and $\delta^{18}O$ results close to the LMWL, especially for the depleted results. However some sampling points appear affected by a second evaporation process as shown by the regression line (δD = 6.0 $\delta^{18}O$ – 4.0) similar to the one detected for the "Ypresian hills" aquifer system. A source located in a forested park (J. Brel. resurgence) is also classified as "natural", together with the Sonian forest waters, as it is located on this evaporative trend (cf. Figure 5A).

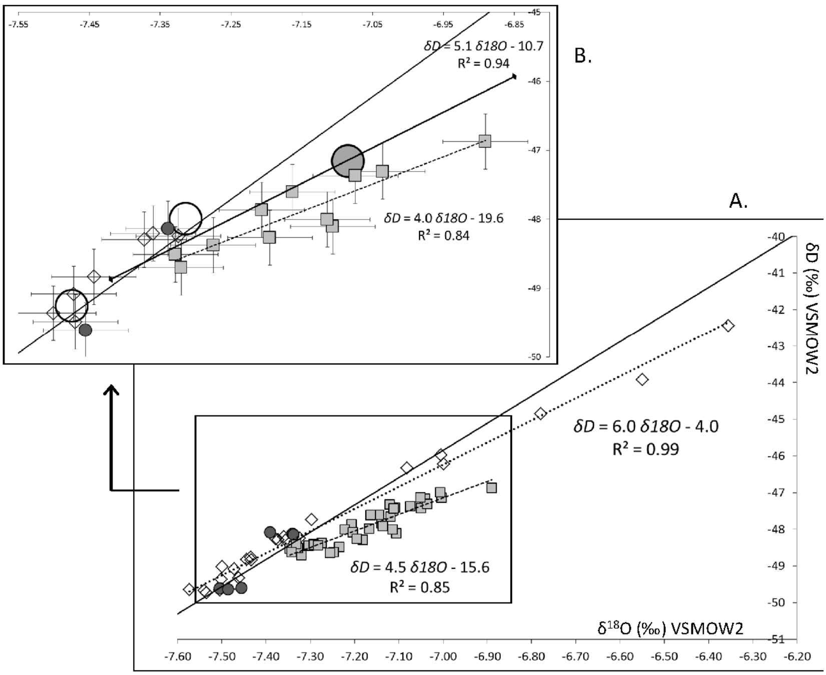

Figure 5: $\delta^{18}O$ (‰) and δD (‰) values of the Brussels sands aquifer showing the impact of the urbanization on the aquifer.

Other deeper waters present a distribution of their isotopic results on the LWML even if they are located under urban settings. These stations sample water from the sandy silts under the Brussels sands. This water has apparently not yet mixed with the above ground water present in the Brussels sands (Figure 5B).

The isotopic results of ground water under urbanized areas show a specific distribution, away from the LWML and at the same time different from the evaporative trend observed in natural areas (cf. Figures 5A and 5B). The cause of this trend is clearly linked to the urbanization as revealed by the geographical repartition of the impacted stations (cf. Figure 4). In the Figure 5B, the isotopic composition of the pumping stations (no resurgences) sampled in December 2012 is represented together with the averaged isotopic composition of tap water in the winter (December, January and February) for three reservoir zones. The grey circle is the average isotopic composition of drinking water distributed during the winter above the observation wells (Rhode reservoir). The bold line represents the repartition of the Rhode reservoir waters during the whole year. Two remarks are important. First, two points localized in the south west of the BCR develop the same trend even if they are out of the distribution area of the Rhode reservoir. Second, the regression line of the urban waters do not coincide with the bold line but is localized under this last. A regression line of isotopic results with a low slope (~4) is the result of an intense evaporation under dry climatic conditions, like in urban settings. We can then conclude that sewage and drinking water may (or not) constitute a source of recharge but these waters (together with rainwater) are affected by evaporation before they infiltrate deeper and recharge the ground water. This evaporation can affect rainwater stored in the soil or in culverts created by the urban infrastructures. The dashed line could then be the impact of rainwater evaporation only or a mixing line between a drinking water evaporated in urban soils and more natural waters (Seiler *et al.* [3]).

4 Conclusions

Stable isotopes results show great variability of values and distribution in the BCR resulting from the different condition of recharge and connections between the aquifers. The values are sufficiently different to identify the distinct aquifer systems in the BCR and asses the connections between them.

The border between the Basement aquifer and the “Basement and Cretaceous chalks aquifer complex”, drawn at the scale of the Schelde basin is adequate for the BCR. The two aquifer complexes are differently connected to the Landenian sands. This connection requires adapted ground water resource management at the aquifer system scale.

This work reveals observation wells that need to be verified and compared to the local geology (P45, P5, P24, P33, P15 and L6). The isotopic results of these observation wells are different from the bulk isotopic composition of the corresponding aquifers. This highlights the presence of another source of ground water recharge or the presence of a mixing zone between aquifers.

Evaporation processes greatly impact the isotopic composition of shallow aquifers. A second evaporation process occurring in forested areas above the Ypresian hills aquifer system and above the Brussels sands aquifer, is identified with a distribution trend of $\delta D = 6.0\ \delta^{18}O - 4.0$.

Evaporation in urban soils also strongly alters the isotopic composition. Under urban settings, the isotopic values of the Brussels Sands show a distribution identified as the result of the evaporation in urban soils combined with a possible recharge from sewer water and drinking water.

The main result of this study is that the extended Brussels sands aquifer shows extreme vulnerability to the urban water cycle management. The ground water flows from the South, appear to be negligible in comparison with local urban recharge.

The stable isotopes ($\delta^{18}O$ and δD) have demonstrated great usefulness to validate or invalidate hypotheses on the connectivity between aquifers or with the urban infrastructures. However, to continue the study of aquifers connections by stable isotopes, more observation wells need to be placed in the base gravels in the alluvial aquifer, in the Ypresian hills aquifer system and in the Brussels sands under urban settings (in the city centre and in the east).

Analyzes of stable isotopes of nitrates ($\delta^{18}O$, $\delta^{15}N$), may also help to distinguish the main sources (drinking water, waste water or rainwater) of the urban recharge. This work will be carried out in the summer of 2015.

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