Measurement of infiltration rates in urban sewer systems by use of oxygen isotopes

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Abstract

The paper presents the principle of a method to measure infiltration rates in sewer systems based on the use of oxygen isotopes and its application in Lyon (France). In the urban area of Lyon, significant differences in $\delta\ ^{18}O$ that can reach 3 ‰ are observed between the oxygen isotopic compositions of groundwater originating from Rhone, Saone and from their associated alluvial aquifers. Drinking water supplying Lyon results mainly from pumping in the Rhone alluvial aquifer. Therefore, in some areas, the difference of isotopic composition between wastewater resulting from the consumption of drinking water and local groundwater can be used to measure infiltration in sewer system. The application in the catchment of Ecully shows that the infiltration flow rate presents strong fluctuations at hourly scale: it varies between 15 and 40 m^3/h. This variability could be explained by non constant discharges of pumping and by variations of the water level in the sewer.

Keywords

Infiltration, oxygen isotopes, uncertainty, reliability, sewer systems

INTRODUCTION

Urban sewer systems constitute a very significant asset in European cities. As sewer systems are deteriorating, their functional and structural performance is impaired, leading to groundwater infiltration into sewer systems, which is particularly detrimental to the efficiency of wastewater treatment plants due to hydraulic overloading and dilution of pollutant loads. Infiltration is critical on a long-term basis for sustainable urban water management and has significant economic consequences for cities through the European Union. Infiltration measurements can also be used by sewer operators as a performance indicator relating to structural state and environmental efficiency of sewer systems. However, traditional measurement methods are still subject to considerable uncertainties due to their underlying assumptions and general principles.

Two types of methods can be distinguished : i) flow rate methods (F) based on the analysis of daily hydrographs and ii) chemical methods (C) based on the analysis of the dilution of pollutants. For any method applied during dry weather periods, two principles are used either separately or jointly : (1) infiltration is calculated by substraction of a theoretic strict wastewater flow which is usually estimated from the annual drinking water consumption or by a reference value of discharge per inhabitant; (2) infiltration is supposed close to night flow. These two basic principles should be carefully discussed because i) the strict wastewater flow presents daily and seasonal variations linked to human activities, ii) the use of a reference value can induced large uncertainties and iii) the night flow is not only due to infiltration but also to all permanent contributions like groundwater pumping for cooling, drinking water leakages, etc. Thus, traditional methods are affected by uncertainties in both the origin of infiltrated water and in the reliability of infiltration rate estimations.

The study of the origin of wastewater is important because sewer operators are focused on groundwater infiltration, i.e. not only real infiltration through sewer defects, but also discharges of undeclared groundwater pumping. So it is necessary to develop a new method to estimate infiltration, which allows the identification of the origin of wastewater flow components during dry weather : drinking water and groundwater. The principle of this new method consists to use natural tracers in water, like in hydrogeology, and especially the isotopic composition of the elements in the dissolved phase or even in the water molecule itself. The use of such tracers offers two advantages: i) the identification and the quantification of wastewater flow components and ii) the determination of the uncertainty in infiltration estimations. It is assumed that each wastewater component has a specific content in tracer, which is i) significantly different from that of the other component and ii) constant whatever the conditions. It is necessary to use tracers which are conservative and not altered by phenomena like adsorption on sewer sediments, oxydo-reduction, pH, temperature variations, etc. In the specific context of sewer systems, the analysis of oxygen isotopic composition, usually expressed as $\delta^{18}O$, seems to be an interesting approach. This idea to use water isotopes to measure infiltration in sewer systems has been first proposed by W. Gujer (EAWAG, Switzerland) as one of the key ideas on which the European research project APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems) is based. Some brief information about the method and its application has already been given in Kracht *et al.* (2003). The main objective of this paper is to present i) the measurement method by use of oxygen isotopes, i.e. the $\delta^{18}O$ method, ii) the investigations carried out in Lyon, France in order to check its applicability and iii) the results of a case study in order to check its reliability.

PRINCIPLE OF THE $\delta^{18}O$ METHOD

Definition of $\delta^{18}O$

The water molecule is constituted by two elements, O and H, each one possessing three stable or radioactive isotopes. The relative abundance of an isotope in natural water depends on several factors : the location of rain events (altitude, latitude, distance from the ocean), the cycle of evaporation/condensation, exchanges with minerals, etc. The relative abundance of the stable isotope ^{18}O is expressed according to its abundance in the standard mean oceanic water (SMOW). The isotopic ratio $^{18}O/^{16}O$ in water samples, also named $\delta^{18}O$, is described by its relative variations compared to SMOW, expressed in ‰ :

$$(\delta^{18}O)_{sample} = 1000 \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}}{(^{18}O/^{16}O)_{SMOW}} \qquad \text{Eq. 1}$$

Application of $\delta^{18}O$ measurements to estimate infiltration

The estimation of infiltration by the use of oxygen isotopic composition is analogous to the method of decomposition of flood hydrographs developed in hydrogeology (Blavoux, 1978). In dry weather periods, the mixing of strict wastewater flow Q_{WW} which origin is drinking water with infiltration flow Q_{INF} which origin is groundwater constitutes the total wastewater flow Q_T:

$$Q_T = Q_{WW} + Q_{INF} \qquad \text{Eq. 2}$$

At catchment scale, infiltration is assumed to result only from groundwater infiltration and strict wastewater is assumed to result only from drinking water consumption. The $\delta^{18}O$ of groundwater samples (or other possible sources of infiltration as rivers, creeks, etc) constitutes the reference value δ_{INF} for infiltration components. The $\delta^{18}O$ of drinking water samples constitutes the reference value δ_{WW} for strict wastewater components. The $\delta^{18}O$ method can only be applied if δ_{WW} is significantly different from δ_{INF}, which is problematic if drinking water and potentially infiltrated groundwater originate from the same aquifer. The applicability of the $\delta^{18}O$ method depends on the hydrogeological context and on the location of drinking water pumping stations. Moreover, reference values must be constant at the space and time scales of the study. If these conditions are satisfied, the measurement of $\delta^{18}O$ in total wastewater δ_T, in drinking water δ_{WW} and in potential infiltration water δ_{INF} sampled simultaneously in the catchment allows to evaluate the respective proportions of these two components in the total wastewater flow, according to a set of mixing equations :

$$Q_T\delta_T = Q_{WW}\delta_{WW} + Q_{INF}\delta_{INF} \quad \text{Eq. 3} \qquad \delta_T = a\delta_{WW} + b\delta_{INF} \quad \text{Eq. 4}$$

$$a = 100\frac{Q_{WW}}{Q_T} \quad \text{Eq. 5} \qquad b = 100\frac{Q_{INF}}{Q_T} \quad \text{Eq. 6} \qquad a + b = 100 \quad \text{Eq. 7}$$

The variables *a* and *b* expressed in % are respectively defined as the fraction of drinking water (or strict wastewater) and the fraction of groundwater (or infiltration fraction) in the total wastewater flow Q_T. Instantaneous, mean daily or night and diurnal mean samples can be used, depending on the objectives of the study. The two most interesting variables are the infiltration fraction *b* and the infiltration flow rate Q_{INF} , which are defined by :

$$b = 100\frac{\delta_T - \delta_{WW}}{\delta_{INF} - \delta_{WW}} \quad \text{Eq. 8} \qquad Q_{INF} = \frac{bQ_T}{100} \quad \text{Eq. 9}$$

This simple protocol can be used for a first measurement campaign carried out at catchment scale. For an accurate study, the space variability of the reference values should be assessed by the constitution of several samples of drinking water and possible sources of infiltration. The estimation of infiltration is then realised using the mean reference values $\bar{\delta}_{INF}$ and $\bar{\delta}_{WW}$.

Preparation of water samples

The measurement of $\delta^{18}O$ requires only 2 or 3 mL of water : so it is not necessary to sample large volumes of water. Raw samples are taken in 500 mL or 1 L PVC bottles. They are then filtered in conical filters and sent to the laboratory in 60 mL glass flasks which are completely filled with water to avoid any contact with atmosphere and any evaporation.

Uncertainty in infiltration estimation

The application of the law of propagation of uncertainties (NF ENV 13005, 1999) to Eq. 8 allows to calculate the uncertainty *Δb* (95 % confidence interval) in the fraction *b* :

$$\Delta b = 200\sqrt{u(\delta_T)^2\left(\frac{1}{\delta_{INF} - \delta_{EU}}\right)^2 + u(\delta_{EU})^2\left(\frac{\delta_T - \delta_{INF}}{(\delta_{INF} - \delta_{EU})^2}\right)^2 + u(\delta_{INF})^2\left(\frac{\delta_T - \delta_{EU}}{(\delta_{INF} - \delta_{EU})^2}\right)^2} \quad \text{Eq. 10}$$

The analysis uncertainty $\Delta\delta$ in one measurement of $\delta^{18}O$ in the laboratory is closed to 0,1 ‰, so in the case of an estimation of infiltration with three instantaneous sample of drinking water, potential infiltration water and total wastewater flow :

$$u(\delta) = u(\delta_T) = u(\delta_{EU}) = u(\delta_{INF}) = 0{,}05 \quad \text{Eq. 11}$$

The Equation 10 can be simplified using the Equations 5, 6, 7 and 11. The uncertainty in *b* depends on the uncertainty in the $\delta^{18}O$ analyses, on the difference observed between reference values δ_{INF} and δ_{WW}.and on the value of *b* itself. This last factor is the most influencing one.

$$\Delta b = 100\frac{\Delta\delta\sqrt{2}}{\delta_{INF} - \delta_{WW}}\sqrt{b^2 - b + 1} \quad \text{Eq. 12}$$

A proper estimation of the uncertainty is important because it is necessary to draw valuable conclusions regarding infiltration. An estimation of the infiltration is considered as pertinent only if the relative uncertainty *Δb/b* is lower than 1. If *Δb/b* is higher than 1, the $\delta^{18}O$ method is considered as not adequate.

During an accurate study, the spatial variability of the reference values δ_{WW} and δ_{INF} must be considered in the uncertainty calculation. Then, the Equation 10 is applied with their mean values $\bar{\delta}_{WW}$ and $\bar{\delta}_{INF}$. Their respective associated uncertainty are defined according to the standard deviation σ characterizing the distribution of the reference values around the average and the analysis uncertainty in the laboratory $u(\delta)$.

$$\Delta b = 200\sqrt{u(\delta_T)^2\left(\frac{1}{\overline{\delta_{INF}}-\overline{\delta_{EU}}}\right)^2 + u\left(\overline{\delta_{EU}}\right)^2\left(\frac{\delta_T-\overline{\delta_{INF}}}{\left(\overline{\delta_{INF}}-\overline{\delta_{EU}}\right)^2}\right)^2 + u\left(\overline{\delta_{INF}}\right)^2\left(\frac{\delta_T-\overline{\delta_{EU}}}{\left(\overline{\delta_{INF}}-\overline{\delta_{EU}}\right)^2}\right)^2} \quad \text{Eq. 13}$$

$$u\left(\overline{\delta_{EU}}\right)^2 = \sigma(\overline{\delta_{EU}})^2 + u(\delta)^2 \quad \text{Eq. 14} \qquad u\left(\overline{\delta_{INF}}\right)^2 = \sigma(\overline{\delta_{INF}})^2 + u(\delta)^2 \quad \text{Eq. 15}$$

The application of the law of propagation of uncertainties to Eq. 9 allows to calculate the uncertainty ΔQ_{INF} in the calculated value of Q_{INF} (sampling uncertainties are neglected in this calculation):

$$\Delta Q_{INF} = \frac{\sqrt{\Delta b^2 Q_T{}^2 + \Delta Q_T{}^2 b^2}}{100} \quad \text{Eq. 16}$$

APPLICABILITY OF THE $\delta^{18}O$ METHOD IN LYON

Preliminary measurement campaigns are necessary to test the applicability of the $\delta^{18}O$ method. The objective is to highlight significant $\delta^{18}O$ differences between drinking water and groundwater during dry weather periods. Drinking water in Lyon is pumped from the aquifer in the Rhône modern alluvia. A sample taken at the production plant which supplies all the city of Lyon was analysed. Its $\delta^{18}O$ constitutes the reference value δ_{WW}. Infiltration water in the sewer system of Lyon during dry weather periods can have two major origins : the Rhône river, the Saône river and their respective alluvial aquifers. Samples were taken in both rivers. Their $\delta^{18}O$ constitute the reference values δ_{INF}. Two sampling campaigns have been carried out in March and September 2002 in order to evaluate seasonal effects on the reference values. The results are given in Table 1.

Sample description	March 2002		September 2002	
	$\delta^{18}O$ (‰)	$\lvert\delta_{INF} - \delta_{WW}\rvert$	$\delta^{18}O$ (‰)	$\lvert\delta_{INF} - \delta_{WW}\rvert$
Drinking water	-9,44	-	-10,75	-
Rhone river	-11,05	1,61	-10,53	0,22
Alluvial aquifer of Rhone	-10,81	1,37	-10,47	0,28
Saône river	-8,11	1,33	-7,45	3,3
Alluvial aquifer of Saône	-8,03	1,41	-7,32	3,43

Table 1: $\delta^{18}O$ of the main components of total wastewater flow in Lyon

In March 2002, an average variation of 1,5 ‰ between drinking water and all possible sources of infiltration is observed. The $\delta^{18}O$ method can be applied and, according to the Equation 10, the infiltration fraction is meaningful for *b* values higher than 9 %. In September 2002, there is no clear distinction between drinking water and parasitic water which origin is the Rhône river or the groundwater from its alluvial aquifer. This fact can be explained by the seasonal variations of the Rhône river and of groundwater levels. The drinking water is pumped from the Rhône alluvial aquifer after artificial re-injection. As the level of the Rhône river is higher during the summer because of snow melting in the Alps where the Rhône has its source, the groundwater drains the Rhône and δ_{WW} is close to the $\delta^{18}O$ of the Rhône river. In winter and spring, the Rhône level is lower, it drains the groundwater and δ_{WW} is more influenced by local groundwater than by the Rhône. As a consequence, the $\delta^{18}O$ method can not be applied during all the year to sewers located close to the Rhône river and to its alluvial aquifer. On the contrary, an average variation of 3 ‰ between δ_{WW} and infiltration from the Saône river or its alluvial aquifer is observed. The $\delta^{18}O$ method can be applied through the year and, according to the Equation 10, the infiltration fraction is meaningful for *b values* higher than 4,5 %.

RELIABILITY OF THE $\delta^{18}O$ METHOD : A CASE STUDY IN LYON

The catchment of Ecully in Lyon has an area of 245 ha and a residential land use. Continuous measurements of wastewater flow rate and pollutants concentrations are available since April 2001. The application of the traditional methods listed in Table 1 reveals that infiltration is significant. The $\delta^{18}O$ method has been applied during one day, with 24 mean hourly samples of wastewater taken between 12/03/2003 at 10:00 and 13/03/2003 at 10:00. The reference values δ_{INF} and δ_{WW} are provided by two instantaneous samples taken respectively in the drinking water network and in a creek located closed to the sewer system. All measurement results are given in Figure 2.

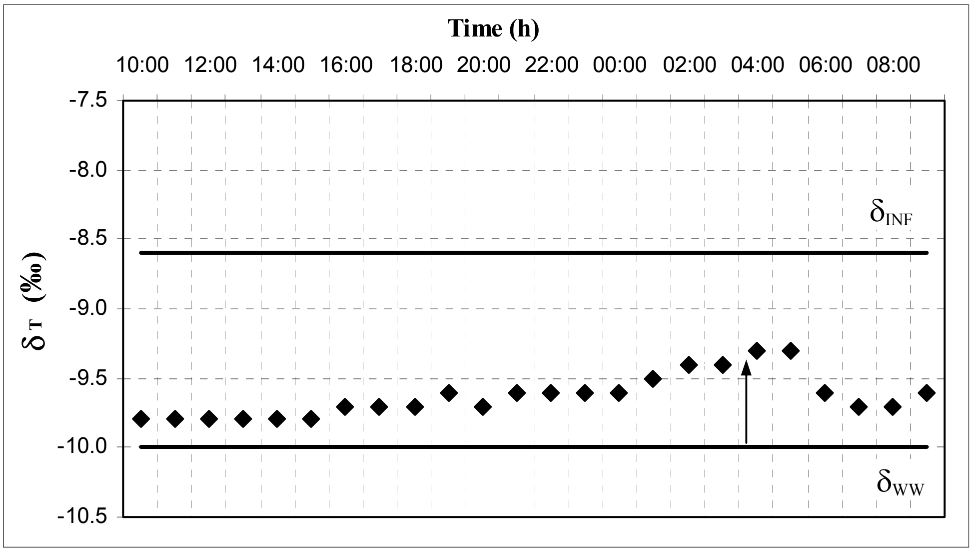

Figure 2: Values of $\delta^{18}O$ measured in the Ecully catchment on 12 and 13/03/2003

A variation of 1,4 ‰ is observed between the reference values for strict wastewater and groundwater : the $\delta^{18}O$ method is applicable. As all values of δ_T are between the reference values δ_{INF} and δ_{WW} , one can conclude that the total wastewater is a mixture of groundwater and drinking water (if no other sources are considered). This leads to positive infiltration rates, which confirms the reliability of the method. Moreover, during the night period, the values of δ_T tend to δ_{INF} which corresponds to a logical reduction of domestic discharges. The proportion of the two components can be calculated for every mean hourly sample of wastewater in order to obtain the composition of the total daily hydrograph (Figure 3).

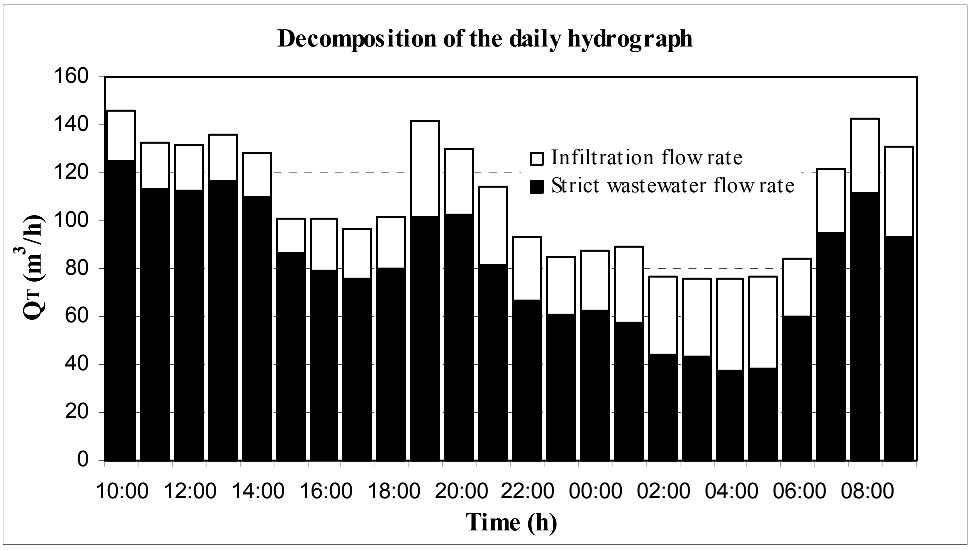

Figure 3: Composition of a daily total hydrograph using the $\delta^{18}O$ method

The reliability of the method means its capacity to reproduce the characteristics of a daily hydrograph with the presence of infiltration. Usually, infiltration flow is assumed to be constant at daily scale while strict wastewater flow is characterised by strong variations due to human activities with two peak flows in the morning and in the evening. The daily cycle of strict wastewater can be observed in the Figure 3 with a strong decrease of the contributions during the night period and flow peaks during the evening (20:00) and the morning (07:00-09:00). From the total hydrograph given in Figure 3, one can easily derive the hydrograph of infiltration given in Figure 4.

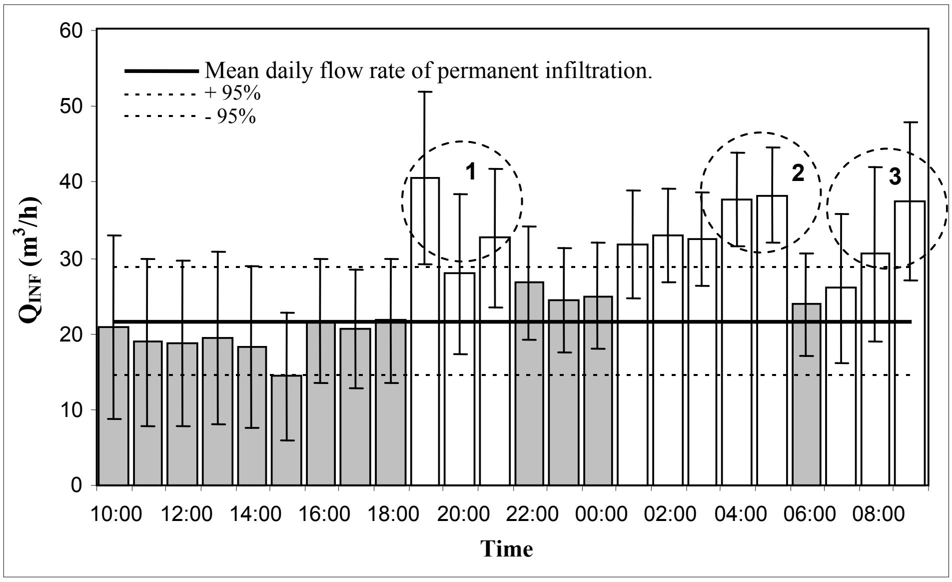

Figure 4: Daily hydrograph of groundwater infiltration

The hydrograph of infiltration shows strong variations during the day: infiltration can vary with a factor 1 to 2 during three peak periods marked with circles in Figure 4. Without these peaks, the infiltration rate would be relatively constant (grey blocks). Before trying to explain this first observation, the reliability of those variations should be guaranty by the uncertainties associated to each estimated values of hourly infiltration rate (Figure 4). All estimated values are considered as valid. The peak values observed between 18:00 and 19:00 and between 04:00 and 06:00 are significantly higher than the mean value that characterises permanent contributions: there is no crossing between their respective 95 % confidence intervals. Thus, the $\delta^{18}O$ method highlights here transitory groundwater contributions. The assumption of a permanent and constant infiltration rate during the day can be questioned.

The observed variations could be explained by two phenomena. The first phenomenon relates to the $\delta^{18}O$ method which provides a value of groundwater infiltration rate without knowing its way to enter the sewer system : either true infiltration trough tightness defects or discharges of groundwater pumped for various purposes (cooling, etc.). Infiltration variations could be explained by the variability of groundwater pumping contributions. Indeed, two peaks (1 and 3) are observed during the period of strict wastewater peaks. These two peaks could be explained by the contribution of groundwater pumping used specifically for domestic activities. The word specifically is used because some groundwater pumping (cooling) constitute permanent contributions. The breakdown of such permanent groundwater pumping could explain the infiltration decrease observed from 15:00 till 16:00. The second phenomenon relates to the mechanisms regarding true infiltration. Indeed, true infiltration occurs mainly around the tightness defects which are located along the pipe wall between the wastewater surface level and the groundwater level around the sewer. When the wet perimeter in the pipe decreases during the night period (i.e. decreasing water level in the pipe), two mechanisms may simultaneously occur: i) more defects can potentially contribute to infiltration, and ii) the infiltration flow through defects which also contribute during the day period can increase. These mechanisms could explain the peak nr 2 observed from 04:00 till 06H00, period during which the total wastewater flow is minimum.

According to the size of the studied catchment and to the transit time of groundwater, the isotopic composition of drinking water and especially of the possible sources of infiltration may present some variations. Thus, it is recommenced to collect several samples in order to study the variability of the reference values for strict wastewater and infiltration and to estimate the impact of uncertainty connected to the spatial variability in the reliability of infiltration estimations. For this purpose, a new measurement campaign has been carried out in December 2003. During one day (17/12/2003), several instantaneous samples were taken from the drinking water network and from the superficial waters in the Ecully catchment. At the same time, day and night samples were collectted at the outlet of the catchment proportionally to the total wastewater flow rate. The values of $\delta^{18}O$ measured in each sample are illustrated in Figure 5.

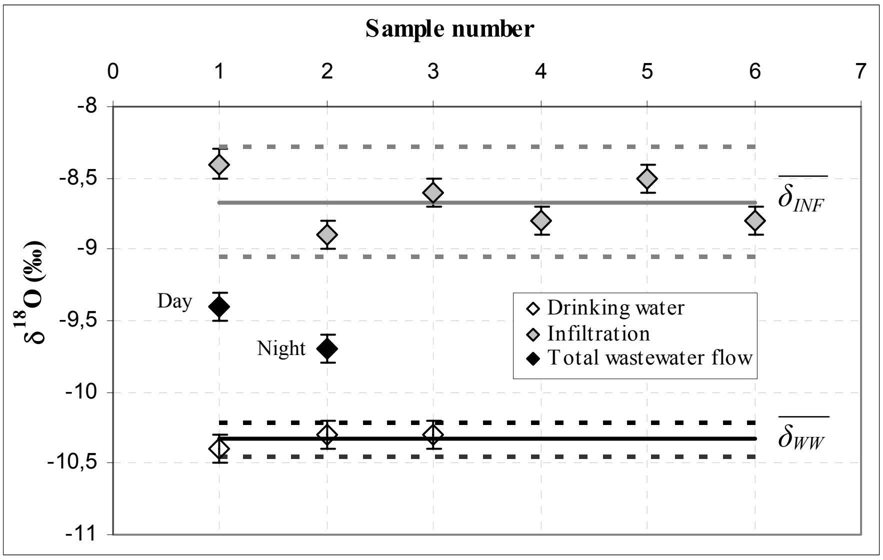

Figure 5: Values of $\delta^{18}O$ measured in the Ecully catchment on 17/12/2003

There is still a significant difference between drinking water and infiltration waters. In average the observed variation is closed to 1,6 ‰. In one hand, the dispersion of the three δ_{WW} values around the mean value $\overline{\delta_{WW}}$ = - 10,3 ‰ is low and presents the same range as the analysis uncertainty in the laboratory. On the other hand, the dispersion the six δ_{INF} values around the mean value $\overline{\delta_{INF}}$ = - 8,7 ‰ is more important. Therefore, if single values of δ_{WW} and δ_{INF} would have been taken as reference, according to the location of the sampling point the difference between the references values for strict wastewater and for infiltration could vary between 1,4 and 2 ‰. This variability may have an impact on the magnitude of the uncertainty associated to infiltration estimations. The two samples of total wastewater flow allow to calculate two estimated values of b and Q_{INF} specific to the day and night periods. The results are given in Table 2.

	b (%)	**Q_T (m^3/h)**	**Q_{INF} (m^3/h)**
Day period	38,0 ± 12,4	167,2 ± 2,4	63,5 ± 20,8
Night period (02h00-06h00)	56,0 ± 15,4	74,6 ± 4,1	41,7 ± 11,7

Table 2: Estimated values of infiltration and their associated uncertainties on 17/12/2003

The infiltration is more important in day period than in night period. According to the Equation 10, for a 1,6 ‰ variation between δ_{WW} and δ_{INF}, the uncertainty in infiltration fraction Δb is closed to 8 %. Accounting for the spatial variability of infiltration sources represents an added uncertainty of 4 % or 7 % according to considered period of the day. The uncertainty ΔQ_{INF} associated to the estimated values Q_{INF} of infiltration flow rate is then relatively important and there is a light crossing between the 95 % confidence intervals of the daily infiltration flow and 95 % confidence intervals of the night infiltration flow. However, it is necessary to keep in mind that this uncertainty calculation considers the fact that 100 % of infiltration produced can have only single origin one among the 6 samples taken as reference. Thus, uncertainties are certainly overestimated because they depend mostly on the standard deviation σ characterizing the distribution of the reference values. To reduce this uncertainty, it would then be necessary to increase the number of samples.

CONCLUSIONS AND PERSPECTIVES

This study shows that the use of oxygen isotopes for the measurement of groundwater infiltration is possible if the conditions for its applicability are satisfied. The results obtained in the case study of Ecully show that the groundwater infiltration rate is variable during the day and that the $\delta^{18}O$ method can be used to study transitory contributions. Nevertheless, the possible space variability of the reference values at catchment scale can generate uncertainty in infiltration estimations and in the conclusion of a study. A further step in the use of the $\delta^{18}O$ method will be the decrease of uncertainty in infiltration rate estimation. As uncertainty depends mainly on the difference between δ_{INF} and δ_{WW}, one solution could be the use of hydrogen isotopes which are more subject to fractionation processes than oxygen isotopes because of their lighter mass. Another way to reduce the uncertainty would consist to develop an improved sampling strategy by accounting the fact that uncertainty decreases during night periods because i) infiltration fraction is higher and ii) if several samples are taken, the uncertainty in the mean infiltration rate is lower, as shown in Figure 4. Another perspective of application would be the analysis of the location of infiltration in diagnostic studies of sewer systems. Compared to the traditional methods, the $\delta^{18}O$ method can provides information on the infiltration fraction without flow or pollutants measurements, only with instantaneous samples of wastewater, drinking water and groundwater. This method is less expensive and provides results faster.

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