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

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Abstract
The paper presents the principle of a method for the measurement of infiltration rates in sewer system based on the use of oxygen isotopes and the study of its applicability in Lyon (France). Investigations in the urban area of Lyon benefit from the isotopic differences between underground waters originating from the two rivers Rhone and Saone and their associated alluvial aquifers. The oxygen isotopic composition of the Rhone water is roughly 3 ‰ lighter than that of the river Saone, due to the large differences in the mean altitude and topographic situation of their catchment. Large amounts of water are pumped in the Rhone aquifer for drinking water supply. In consequence, a usable difference in the oxygen isotope composition between wastewater and local groundwater is available for application studies in some parts of the city. The results obtained in a case study allow to evaluate the reliability and the uncertainties of this new method.

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 EU. 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 (see Table 1) are still subject to considerable uncertainties due to their underlying assumptions and general principles.

Methods	Origin	Reference	Principle	Type
Dry weather flow	-	-	(1)	F
Dry weather flow bis	Switzerland	(Hager et al, 1985)	(1)	F
Density average	Austria	(Ertl et al, 2002)	(1)	F
Annen & Muller	Austria	(Annen, 1980)	(1)	F
Triangle	Germany	(Weiss et al. 2002)	(1)	F
Moving minimum	Germany	(Weiss et al. 2002)	(1)	F
Difference of daily flow	France	(Joannis, 1994)	(1)	F
Difference of night flow	France	(Joannis, 1994)	(2)	F
Minimum night flow	France	(Renault, 1983)	(2)	F
Corrected night flow	France	(Renault, 1983)	(2)	F
Corrected night flow bis	Switzerland	(Hager et al, 1985)	(2)	F
Shape parameter	France	(Joannis, 1994)	(2)	F
IMHOFF	France	(Renault, 1983)	(1)	C
Swiss	Switzerland	(Hager et al, 1985)	(1) and (2)	C
Hybrid or Horizon	France	(Horizon, 1992)	(1) and (2)	C

Table 1: Synthesis of traditional methods to estimate infiltration in sewers

Two types of methods can be distinguished : i) flow rate methods (F) based on the analysis of daily hydrographs and ii) chemical methods (D) based on the analysis of pollutants dilution. 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 closed 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 the permanent contributions like groundwater pumping for cooling, drinking water leaks, etc. Thus, traditional methods provide uncertainty as well in the origin of infiltration as 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 thought sewer defects, but also discharges of groundwater pumping which are not declared. So it is necessary to develop a new method to estimate infiltration, which allows the identification of the origin of both wastewater flow components during dry weather : drinking water and groundwater. The principle of this method consists to use natural tracers in water as 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: drinking water (strict wastewater) and groundwater infiltration, 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. Indeed, it is necessary to find tracers which are conservative. Their contents shall not be altered by phenomena of adsorption linked to the presence of 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 a valuable approach. The main objectives 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 δ^{18}O METHOD

Definition of δ^{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 isotopes ^{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 ‰ :

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

Application of δ^{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 a groundwater sample (or other possible sources of infiltration as rivers, creeks, etc) constitutes the reference value

δ_{INF} for infiltration components. The $\delta^{18}O$ of a drinking water sample 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}. Indeed, drinking water and potentially infiltrated groundwater can result from the same aquifer. Then 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 determine the respective proportions of these two components in the total wastewater flow, according to a set of mixing equations :

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

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

$$a = \frac{Q_{WW}}{Q_T} \qquad \text{Eq. 5}$$

$$b = \frac{Q_{INF}}{Q_T} \qquad \text{Eq. 6}$$

$$a + b = 1 \qquad \text{Eq. 7}$$

The variables a and b are respectively defined as the fraction of drinking water (or strict wastewater) and the fraction of groundwater (or infiltration fraction). They are expressed in percentage of the total wastewater flow Q_T measured when wastewater have been sampled. It could be instantaneous, mean daily or night and diurnal mean samples. The interesting variables are the infiltration fraction b and the infiltration flow rate Q_{INF} , which are defined by :

$$b = \frac{\delta_T - \delta_{WW}}{\delta_{INF} - \delta_{WW}} \qquad \text{Eq. 8}$$

$$Q_{INF} = bQ_T \qquad \text{Eq. 9}$$

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 amount of water. Raw samples are introduced in PVC bottles (500 mL or 1L). Then samples are filtered in conical filter and sent to the laboratory in glass flasks of 60 mL which are completely filled with water to avoid any contact with atmosphere or 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 :

$$\Delta b = \frac{\Delta\delta\sqrt{2}}{\delta_{INF} - \delta_{WW}}\sqrt{b^2 - b + 1} \qquad \text{Eq.10}$$

The uncertainty in b depends on the uncertainty in the $\delta^{18}O$ analyses, on the difference of $\delta^{18}O$ between drinking water and infiltration water and on the value of b itself. Considering that the mean value of the uncertainty in $\delta^{18}O$ analyses is 0.1 ‰, one can draw various curves of uncertainty in b according to the theoretic difference observed between the reference values δ_{INF} and δ_{WW}. The uncertainty in b is lower when b is closed to 0,5 and when the difference between δ_{INF} and δ_{WW} increases. This last factor is the most influencing one. 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 if the relative uncertainty $\Delta b/b$ is lower than 1. If $\Delta b/b$ is higher than 1 (hatched area in Figure 1), the $\delta^{18}O$ method does not provide valid results. The intersections between the dotted curve and the uncertainty curves are used to define the threshold corresponding to measurable infiltration fractions. The application of the law of propagation of uncertainties to Eq.9 allows to calculate the uncertainty ΔQ_{INF} in the calculated value of an infiltration flow rate $Q_{INF:}$:

$$\Delta Q_{INF} = \sqrt{\Delta b^2 Q_T{}^2 + \Delta Q_T{}^2 b^2} \qquad \text{Eq.11}$$

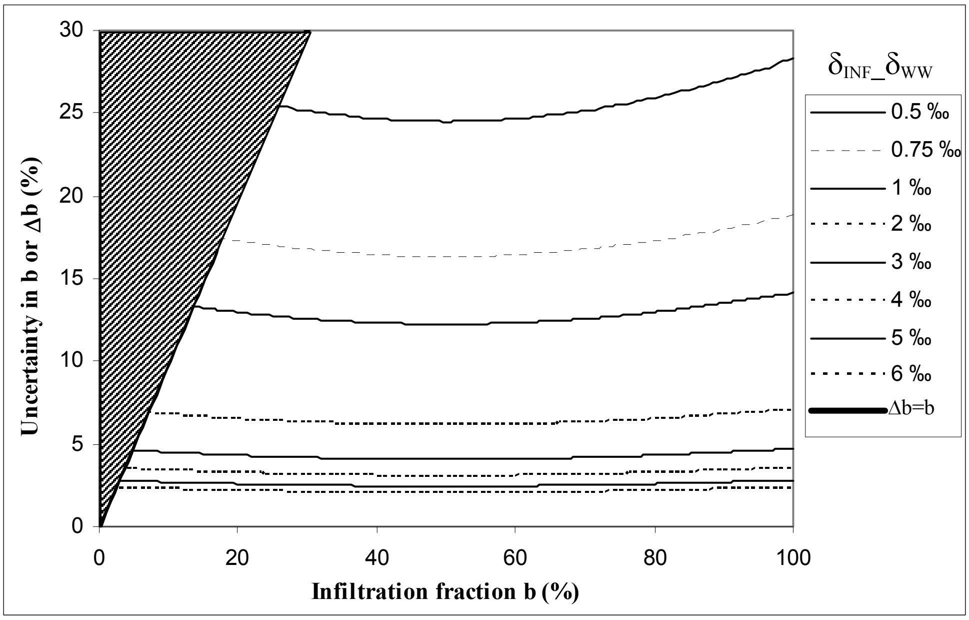

Figure 1: Curves of uncertainty in *b*.

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 the two principal origins of wastewater flow components during dry weather : drinking water and groundwater. Drinking water in Lyon is pumped from the aquifer in the Rhone 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 Rhone river, the Saone 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 2.

Sample description	$\delta^{18}O$ (‰)	$\lvert\delta_{INF} - \delta_{WW}\rvert$	$\delta^{18}O$ (‰)	$\lvert\delta_{INF} - \delta_{WW}\rvert$
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
Saone river	-8,11	1,33	-7,45	3,3
Alluvial aquifer of Saone	-8,03	1,41	-7,32	3,43

Table 2: $\delta^{18}O$ of the main components of total wastewater flow in Lyon

In March, 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 Fig.1, the infiltration fraction is meaningful for *b* values higher than 9 %. In September, there is no clear distinction between drinking water and parasitic water which origin is the Rhone river or the groundwater from its alluvial aquifer. This fact can be explained by the seasonal variations of the Rhone river and groundwater levels. The drinking water is pumped in the Rhone alluvial aquifer and the level of the Rhone river is higher during summer because of snow melting in the Alps where the Rhone is coming from. In summer, δ_{WW} is closed to $\delta^{18}O$ of the Rhone river. In winter and spring, δ_{WW} is influenced by local groundwater. There is no seasonal effect on the $\delta^{18}O$ of the Rhone river due to the mixing process in the Leman Lake. Consequently, the $\delta^{18}O$ method can not be applied all the year to sewers located closed to the Rhone river and to its alluvial aquifer. On the contrary, an average variation of 3 ‰ between δ_{WW} and infiltration from the Saone river or its groundwater is observed. The $\delta^{18}O$ method can thus be applied anytime and, according to Fig.1, 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 urbanisation. Continuous measurements of wastewater flow rate and pollutants are available since April 2001. The application of the traditional methods listed in Table 1 shows that infiltration is significant. The $\delta^{18}O$ method has been applied during one day, with 24 mean hourly samples of wastewater flow taken from 12/03/03 at 10:00 am till 13/03/03 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.

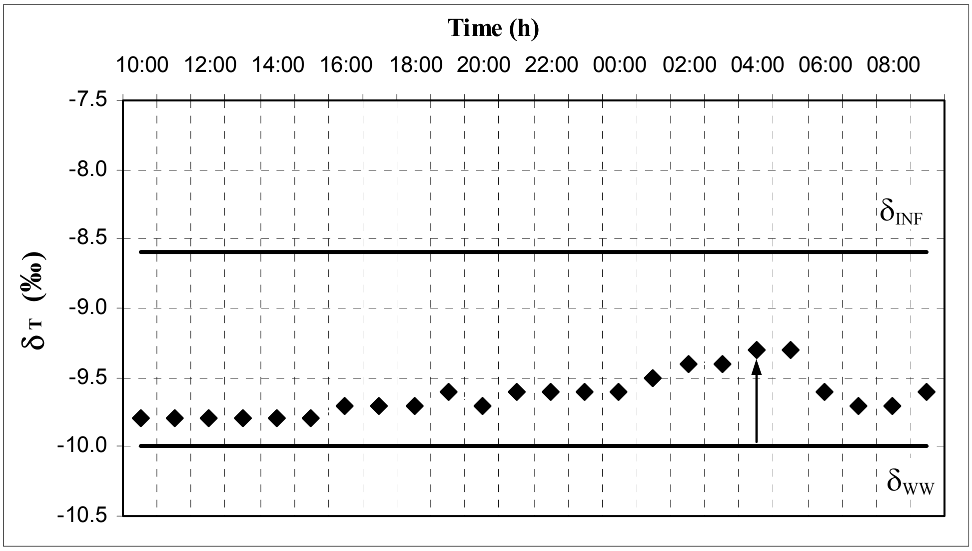

Figure 2: Values of $\delta^{18}O$ measured in the Ecully catchment

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. This leads also 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).

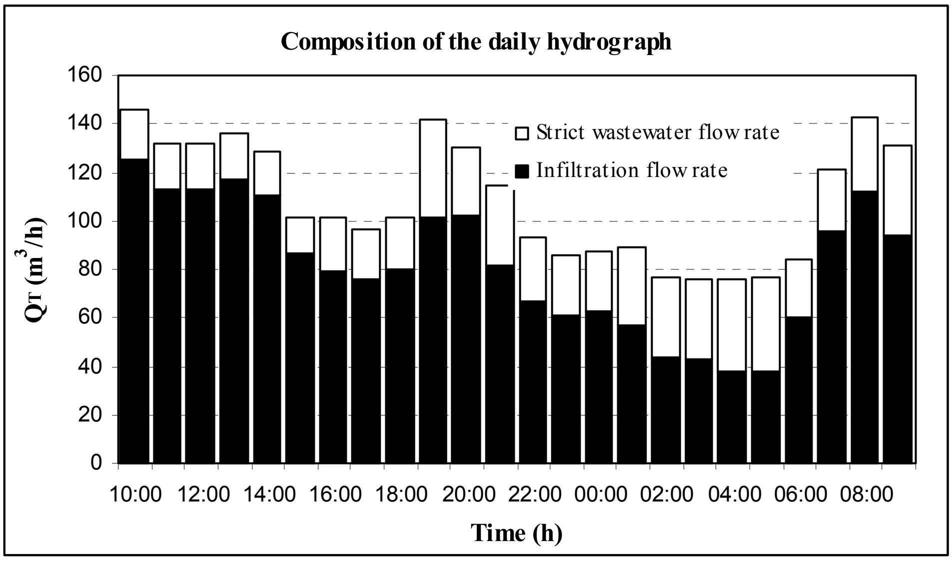

Figure 3: Composition of a daily total hydrograph using the $\delta^{18}O$ method

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. These properties can be partially observed in Figure 3, and appear more clearly with the hourly variations of the infiltration fraction *b* and of the total wastewater flow Q_T as shown in Figure 4.

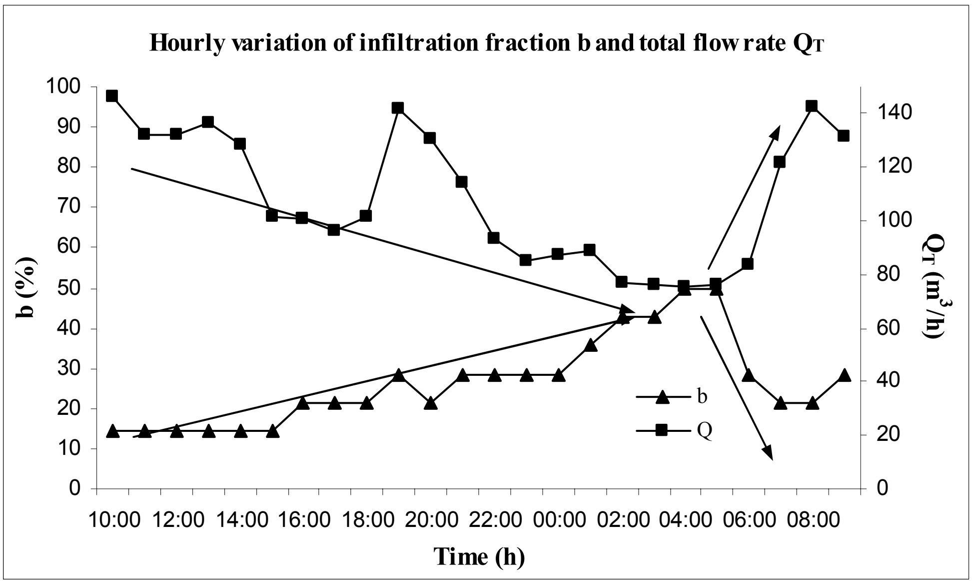

Figure 4: Hourly variations of the infiltration fraction *b* correlated with total wastewater flow Q_T

The hourly variations of the infiltration fraction *b* are conversely proportional to the hourly variations of the total wastewater flow Q_T. The $\delta^{18}O$ method reproduces the daily cycle of strict wastewater with a strong decrease of the contributions during the night period represented by a strong increase of the infiltration fraction *b*. The peak flows of the strict wastewater contribution are also characterized by a strong decrease of the infiltration fraction *b* 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 5.

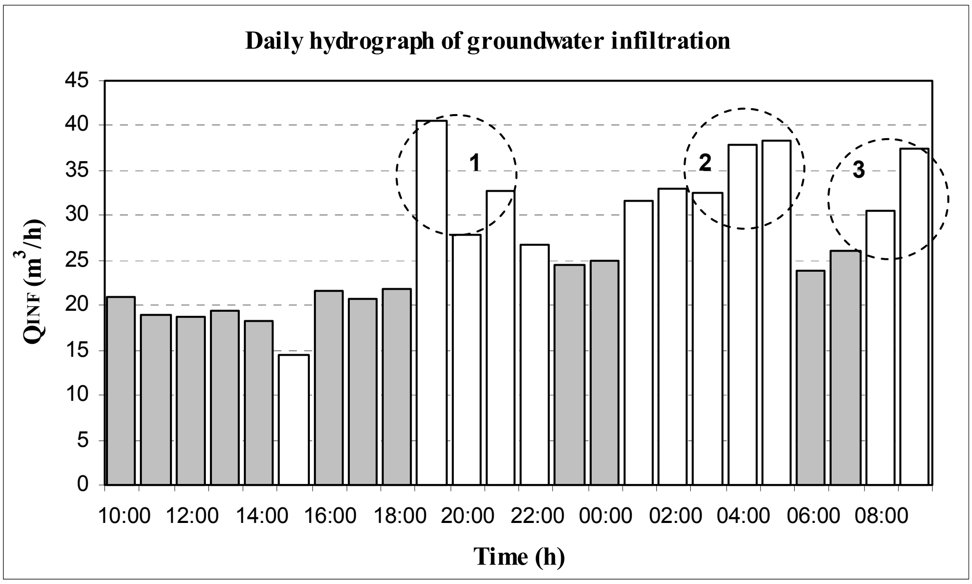

Figure 5: Daily hydrograph of groundwater infiltration

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 the circles in Figure 5. A lower value is observed from 15:00 till 16:00. Without these peaks, the infiltration rate would be relatively stable (grey blocks). 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 reach 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 flow. 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 01:00 till 6:00, mainly from 04:00 till 06H00, period during which the total wastewater flow is minimum. However, before confirming such assumptions, it is necessary to take into account the uncertainty in hourly rates (Figure 6).

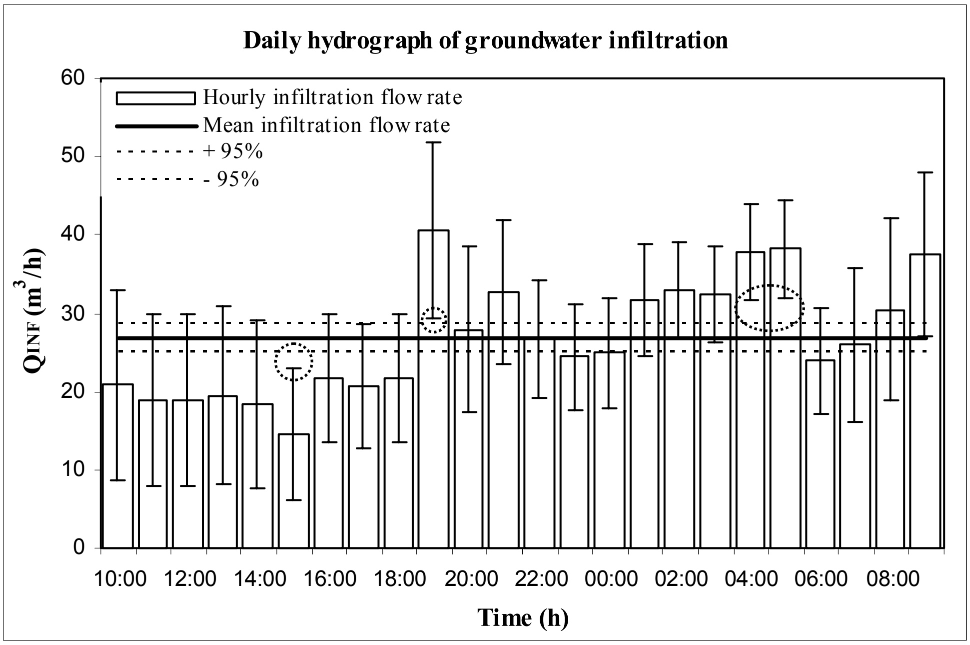

Figure 6: Uncertainties in the infiltration hydrograph

Accounting for uncertainties, all estimated values of hourly infiltration rate are considered as valid. The low value from 15:00 to 16:00 is significantly lower than the mean value, while the peak values between 18:00 and 19:00 and between 04:00 and 06:00 are significantly higher than the mean value: the limits of the 95 % confidence intervals of the hourly infiltration rates do not cross the limits of the 95 % confidence interval of the mean daily infiltration rate. This observation may confirm the previous assumptions and also shows that the $\delta^{18}O$ method can detect transitory groundwater contributions.

CONCLUSIONS AND PERSPECTIVES

This study shows that the use of oxygen isotopes for the measurement of groundwater infiltration is reliable if the conditions for its applicability are satisfied. The results obtained in the case study of Ecully show that groundwater infiltration rate is variable during the day and that the $\delta^{18}O$ method can be used to study transitory contributions. 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 the fractionation process 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 6. 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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