

Infiltration in sewer systems: comparison of measurement methods

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Abstract

Since 20 years, several methods for the estimation of infiltration were developed in various countries. These conventional methods are subject to considerable uncertainties due to their underlying assumptions and general principles which are not estimated. Two extended comparative studies of the conventional methods have been made in order to assess the variability in infiltration estimations and associated uncertainties according to the method used. The choice of the methods is not critical when the objective of a sewer diagnostic study is to define the spatial distribution of infiltration contributions at sub-catchment scale. Nevertheless, the methods based on the analysis of the minimum night flow that are generally applied during one dry weather day should be applied during 8 to 10 dry weather days in order to provide estimations with acceptable uncertainties.

Keywords

Sewer system, infiltration, measurement, uncertainty.

INTRODUCTION

The progressive degradation of the structural state of urban sewer systems leads to the presence of tightness defects which, depending on the level of groundwater table or on the water content in the sewer trenches, can generate two phenomena: infiltration of groundwater and exfiltration of raw sewage. Infiltration and exfiltration have both an impact on the economical, technical and environmental performance of sewers systems, respectively i) with the decreasing efficiency of treatment plants due to the dilution of raw sewage and to the decrease of hydraulic capacity, and ii) with the pollution of soil and groundwater potentially used for drinking water supply. Furthermore, the water exchange between sewers and the surrounding soil accelerate the ageing process of sewer systems. The measurement of infiltration and exfiltration allows to assess the impact and the potential risks generated by these two phenomena which can be included in the sewer rehabilitation strategy.

Infiltration and exfiltration are phenomena studied respectively since 20 years and 10 years. Consequently the measurement method of infiltration are more diversified and used. Infiltration is usually assessed as an annual volume at the inlet of a treatment plant or as a daily volume at the scale of sub-catchments during a sewer diagnostic study. Several measurement methods of infiltration were developed and applied in different countries, with definitions of infiltration specific to the developer and/or to the operator. As an example, in France, infiltration water is usually qualified as clear parasitic water because its quantity and its quality are not adapted to the function of the wastewater treatment plant. In the United Kingdom, the term infiltration/inflow is used in order to distinguish the various space and time characteristics of these contributions. No method can be considered as ideal because the developed methods consider partially, altogether or without distinction the various components of "infiltration": groundwater infiltration but also all other sources of clear waters as the discharges of groundwater pumping for industrial purposes as cooling or for the drainage of underground works like parkings, the fast drainage of rainwater through the sewer trenches, the leakage from drinking water networks, etc. Thus, traditional methods provide uncertainty as well in the origin of infiltration as in the reliability of infiltration rate estimations. Moreover, whatever the method used, the uncertainty associated to infiltration estimations is not calculated. Uncertainty is necessary to evaluate the reliability of any method, especially if the methods are used to detect low infiltration rates or to measure infiltration at a small spatial scale which allows locating individual leaking sewers.

In complement to the European research program APUSS (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems) which is developing new measurement methods for infiltration and exfiltration, a study has been carried out to compare the existing traditional methods used to evaluate infiltration, which are summarised in Table 1 (De Bénédictis, 2004). Very few comparative studies have been published about these methods. The analysis of the existing comparative studies reveals that all the methods have never been compared simultaneously on the same experimental site for various reasons: the ignorance of their existence, the ignorance of the practice in other countries, the insufficient availability of long term data series of flow rates and pollutants concentrations. Generally, only comparative studies concerning some of these methods have been carried out in the countries where the methods have been developed: e.g. in Germany (Weiss *et al.*, 2002), in Austria (Ertl *et al.*, 2002), in Switzerland (Hager *et al.*, 1985) and in France (Joannis, 1994).

The objective of this work consists to carry out a more exhaustive comparative study of the methods in order to clarify the conditions of use and of validity of the methods and to recommend, for specific contexts, the use of the method which, from experience, is considered as the most appropriate one. Two comparative studies have been carried out in Lyon in different contexts and for different purposes: (i) the study on the Yzeron catchment carried out in the frame of a diagnostic study. The objective was to evaluate the impact of the estimations variability on the spatial location of infiltration defined at sub-catchment scale; (ii) the study on the Ecully catchment carried out at a permanent monitoring station where appropriate sensors and procedures allow to estimate the uncertainty in the wastewater flow rate. The objective was to evaluate the uncertainties in infiltration estimations, the reliability of the methods and their detection limits. The paper will describe briefly the methods, the data necessary for their application and the principle of uncertainty calculation. The protocol used for the design of the comparative studies is detailed. Some of the most important results obtained will be given and discussed. As a conclusion, some advices are suggested in order to obtain accurate estimations of infiltration, especially during a sewer diagnostic study.

CONVENTIONAL METHODS FOR INFILTRATION MEASUREMENTS

Principle of infiltration calculation

Two generic 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 pollutant dilution. For any method generally applied during dry weather periods, the measurement of the total wastewater flow rate Q_T is necessary. According to Equation 1, the estimation of infiltration consists to split Q_T into two components: (i) the strict waste water flow rate Q_{WW} that includes domestic and industrial sewage and ii) the infiltration flow rate Q_{INF} . The infiltration rate is also frequently expressed as the percentage of the dry weather flow, named the infiltration fraction F_{INF} .

$$Q_{INF} = Q_T - Q_{WW} \quad \text{Eq. 1} \quad F_{INF} = 100 \frac{Q_{INF}}{Q_T} \quad \text{Eq.2}$$

According to the method used, Equation 1 can be applied at annual scale (or at the scale of available times series), at daily scale, at mean hourly scale or at the scale of instantaneous values (night minimum) of the wastewater flow rate. The calculation of infiltration results in the estimation of a theoretic strict wastewater flow that is appreciated more or less approximately according to several data and calculation techniques: (i) a mean daily strict wastewater flow based on the annual drinking water consumption on the studied catchment, (ii) the number of inhabitants on the studied catchment and references values of sewage discharge per capita, (iii) the characteristics of the catchment or wastewater flow measurements in low water period for the estimation of a residual night flow and (iv) the continuous or daily measurements of pollutants concentration (COD, BOD, ammonia, etc) at the outlet of the studied catchment and reference values of pollutant discharges per capita. The principle used, the time scale of estimation with or without distinction of dry weather days (DWD) and the data necessary for the application of each method are defined in Table 1. In order to simplify the presentation of the results obtained during the comparative studies, each method is designated by an abbreviation.

Abbreviation	Methods	Reference	Principle	Time scale	Data used
F.1	Dry weather flow	-	(1)	Daily, DWD	(i)
F.1 bis	Dry weather flow bis	(Hager <i>et al.</i> , 1985)	(1)	Daily, DWD	(ii)
F.2	Density average	(Ertl <i>et al.</i> , 2002)	(1)	Annual	(i)
F.3	Annen & Muller	(Annen, 1980)	(1)	Annual	(i)
F.4	Triangle	(Weiss <i>et al.</i> , 2002)	(1)	Annual	(i)
F.5	Moving minimum	(Weiss <i>et al.</i> , 2002)	(1)	Annual or Daily	(i)
F.6	Difference of daily flow	(Joannis, 1994)	(1)	Daily, DWD	only Q_T
F.7	Difference of night flow	(Joannis, 1994)	(2)	Daily, DWD	
F.8	Minimum night flow	(Renault, 1983)	(2)	Daily, DWD	
F.9	Corrected night flow	(Renault, 1983)	(2)	Daily, DWD	(iii)
F.10	Corrected night flow bis	(Hager <i>et al.</i> , 1985)	(2)	Daily, DWD	(ii)
F.11	Shape parameter	(Joannis, 1994)	(2)	Daily, DWD	(iii)
C.1	Imhoff	(Renault, 1983)	(1)	Daily, DWD	(iv)
C.2	Swiss	(Hager <i>et al.</i> , 1985)	(1) and (2)	Daily, DWD	(iv)
C.3	Hybrid or Horizon	(Horizon, 1992)	(1) and (2)	Daily, DWD	(iv)

Table 1: Conventional methods used to estimate infiltration in sewers

Uncertainty in infiltration estimation

The application of the uncertainty propagation law (NF ENV 13005, 1999) to Equation 1 allows to calculate the uncertainty ΔQ_{INF} associated to the estimated values Q_{INF} of infiltration flow rate :

$$\Delta Q_{INF} = \sqrt{\Delta Q_T^2 + \Delta Q_{WW}^2} \quad \text{Eq.3}$$

The uncertainty in the total infiltration flow rate ΔQ_T is estimated according to the protocol defined by Bertrand-Krajewski *et al.* (2000). ΔQ_T depends on (i) the uncertainties linked to the polynomial relation $S(h)$ between the wastewater height h and the wet section S defined for the permanent monitoring point at the outlet of the Ecully catchment and (ii) the measurement uncertainties in h ($\Delta h = 0.005$ m) and in the measurements of the flow velocity U ($\Delta U = 0.1$ m/s) links to the sensor used. The uncertainty in the theoretic strict wastewater flow rate ΔQ_{WW} is calculated according to the method used with the consideration of a relative uncertainty of 10 % in the mean daily consumption of drinking water, a relative uncertainty of 10 % in reference values of sewage discharge per capita or a relative uncertainty of 15 % in pollutant concentrations measured in the laboratory.

DESIGN OF THE COMPARATIVE STUDIES

The comparative studies are carried out after three first steps: (i) the determination of the time scale for the comparison, (ii) the selection of the methods that can be applicable according to the data available in the two Yzeron and Ecully catchments and (iii) the validation of flow rate data and the determination of the studies duration.

Time scale of comparison

As shown in Table 1, the various conventional methods do not estimate the infiltration volume at the same time scale. Thus, extended comparative studies should be made at different time scales:

- annual scale or time series scale : it allows to compare the methods F.3, F.4 and F.5 with the methods F.1, F.1 bis, F.8, F.9, F.10 and F.11 for which the sum of the daily infiltration flow rate estimated for each dry weather day is calculated. This sum is extrapolated to the total duration of the time series or to the annual scale in order to be compared to the total volume of infiltration estimated with F.3, F.4 and F.5.

- scale of each dry weather day : it allows to compare the methods F.1, F.1 bis, F.5, F.6, F.7, F.8, F.9, F.10, F.11 and to characterize the capacity of a method to reproduce the event variability of infiltration contributions like the fast drainage through sewer trenches and its progressive decrease after a rain event.

- scale of the dry weather day of sampling for pollutant measurements : it allows to compare the methods F.1, F.1 bis, F.5, F.6, F.7, F.8, F.9, F.10 and F.11 with the chemical methods C.1, C.2 and C.3.

Data availability and methods used

An extended comparative study of all the conventional methods can only be made if long term data series of flow rate (one year of two measurements campaigns respectively in high and low water period) and pollutants are available. In the frame of the study carried out in the Yzeron and Ecully catchments, continuous measurements were not available: consequently the chemical method C.2 could not be applied. Due to the lack of flow rate data, F6 and F.7 were not applied. The method F.2 was also not used because the calculation protocol is not clear and seems to be closed to F.1.

Validation of the data and duration of the comparatives studies

The comparative study on the Yzeron catchment has been made by using the data series collected by a private company during a diagnostic study between 13/11/2002 and 10/12/2002 on 13 measuring points that constitute the outlet of 13 sub-catchments illustrated in Figure 1. An extended comparative study should allow to apply simultaneously the estimation methods using the flow rate data validated at each measuring point for a maximum number of dry weather days. The validation of wastewater flow measurements available at a 6 minutes time step consists to verify that no sensor used to measure the water depth or the flow velocity was not technically deficient during the diagnostic study. Moreover, the sensors were not installed in the sewer and removed during the same day because of the high number of measuring points. A first analysis of the data was made in order to select the days with pertinent flow rate data for all the measuring points. The corresponding rainfall data series was used to distinguish the dry weather days among all selected days. The use of F.5 constitutes an other indicator for the selection of valid dry weather days and for the duration of the comparative study. Indeed, the values of flow rate data should be available during the $k-1$ days before the day for which an estimation of infiltration is calculated. During this study a k value equal to 6 days was used. Thus, for each measuring point, 6 days with pertinent data should be available before the first day of the comparative study. After this protocol, the comparative study designed for the Yzeron catchment take place between 20/11/2002 and 09/12/2002 for a total duration of 20 days with 10 dry weather days.

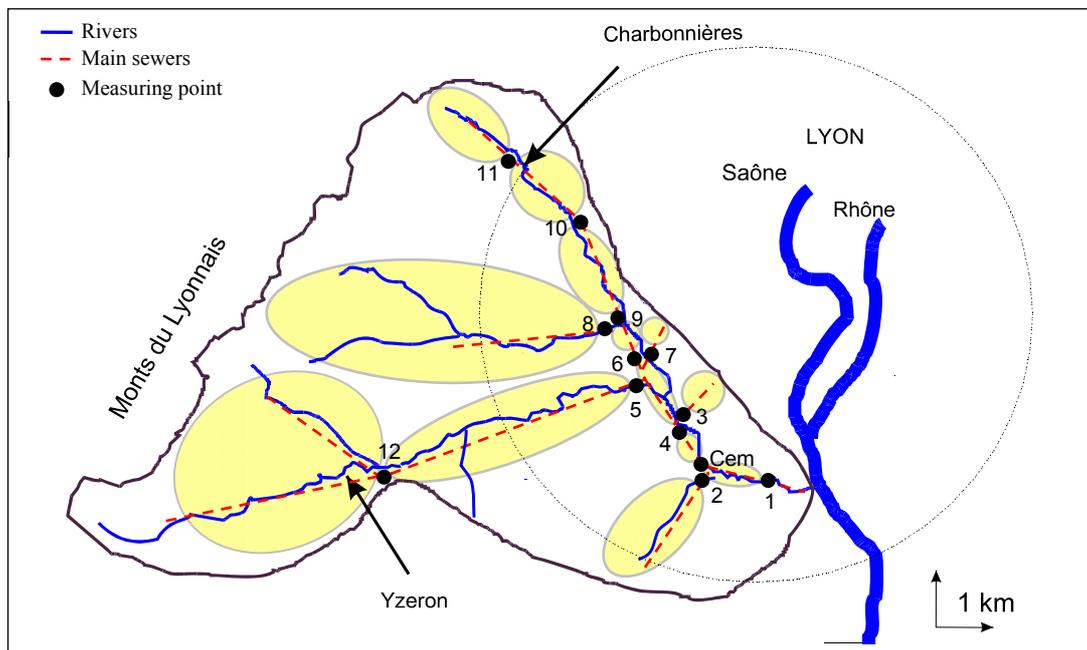


Figure 1: Location of the measurement points in the sewer system of the Yzeron catchment

The comparative study on the Ecully catchment has been made at a permanent monitoring station where the flow measurement is measured with a 2 minutes time step. These data are validated since February 2003. Considering the quality of the data, the protocol of data selection presented before for the Yzeron catchment has not been used for the Ecully catchment. The comparative study has been made with the data recorded during March 2003 with 28 dry weather days. The chemical methods were applied using pollutant concentrations measured in 24 mean hour wastewater samples collected between 12/03/2003 at 10h00 and 13/03/2003 at 10h00.

RESULTS AND DISCUSSION

Comparative study on the Yzeron catchment

During a diagnostic study, the estimation of infiltration rates at several measurement points defining several sub-catchments allows to establish the spatial distribution of infiltration contributions. This distribution results in the expression of the volume of infiltration produced by each sub-catchment as the percentage of infiltration produced by the whole catchment. According to the method used, the total volume of infiltration produced by the Yzeron catchment during the 20 days of the comparative study varies from 630925 m³ with F.3 to 1017755 m³ with F.11. The total infiltration volumes estimated during the comparative study with each method for each sub-catchment are illustrated in Figure 2.

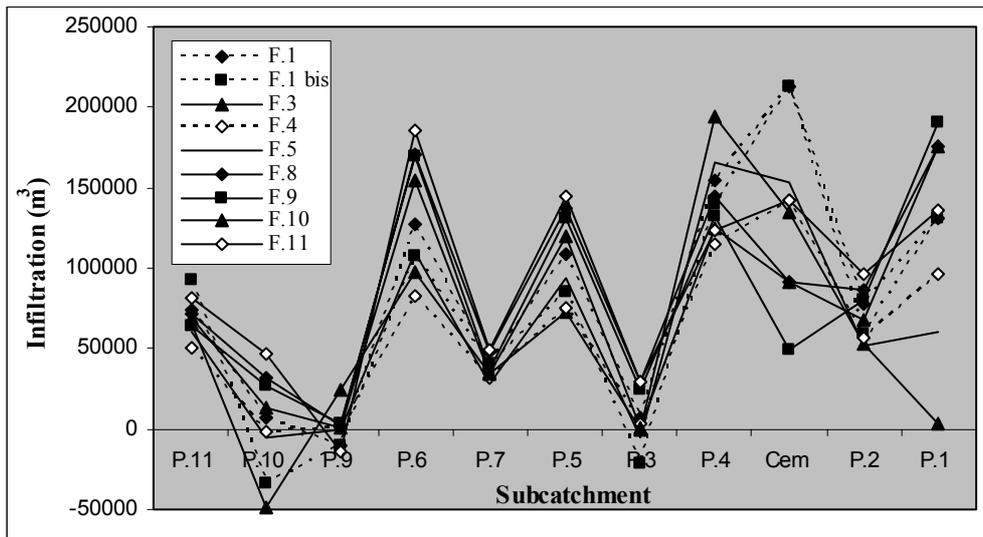


Figure 2: Total volumes of infiltration estimated between 20/11/2002 and 09/12/2002 for each sub catchment

The estimated values of infiltration show great variations whatever the considered sub-catchment. This variability may have an impact on the spatial distribution procedure. Thus, a distribution is established using each estimation methods (Figure 3).

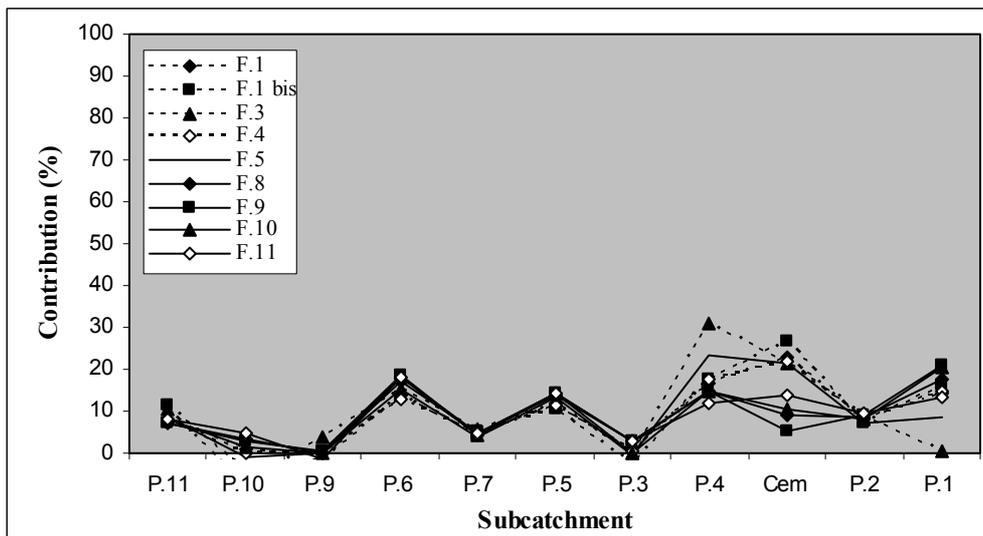


Figure 3: Spatial distribution of infiltration contributions defined by each estimation method

For most of the sub-catchments, the variability in the spatial distribution seems to be limited compared to the variability in the estimation of the total volume of infiltration (Figure 2). The choice of the method is not critical if the objective consists to define the sub-catchments that contribute mostly to the global infiltration. Nevertheless, it is useful to apply the more accurate method in order to assess infiltration contributions at a space and time scale that allows a better definition of next measurement campaign or of CCTV inspections.

Comparative study on the Ecully catchment

The daily volumes of infiltration estimated from various flow rate methods for each of the 28 dry weather days are illustrated in Figure 4. For each dry weather day, the estimated values present great variations. However, the evolution of the daily volumes of infiltration during March 2003 is quite similar whatever the method used, excepted for F.5. All the methods characterize the increase and the decrease of infiltration after a rain event due to the fast drainage of rainwater by sewer trenches. But between 17/03/2003 and 30/03/2003, the daily volume present significant variations which are not linked to fast drainage because no rain event was observed during this period. These phenomena are very likely due to abnormal variations of the total waste water flow linked to human activities.

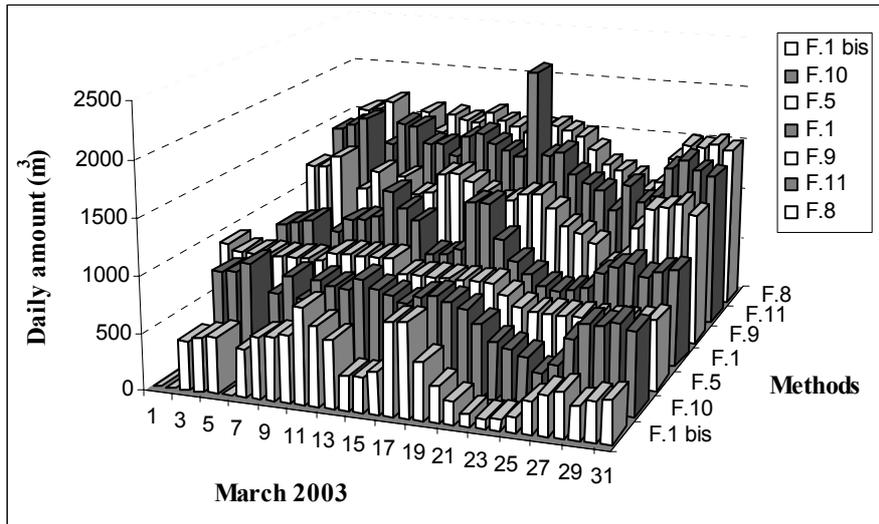


Figure 4 : Variation of the daily infiltration rate according to various estimation methods

The total volume of infiltration and the associated uncertainties estimated with various methods in March 2003 are illustrated in Figure 5. There is a strong variability between the various estimations (from 1 to 3.5). The methods based on the night flow tend to overestimate infiltration compared to the other methods. The width of the 95 % interval confidence allows to define the most accurate methods. F.8 and F.11 present the lowest uncertainty respectively 6 % and 11 %. F.1, F.3, F.4, F.5, F.9 and F.10 show a similar level of uncertainty between 15 and 20 %. F.1 bis presents the largest uncertainty : up to 50 %.

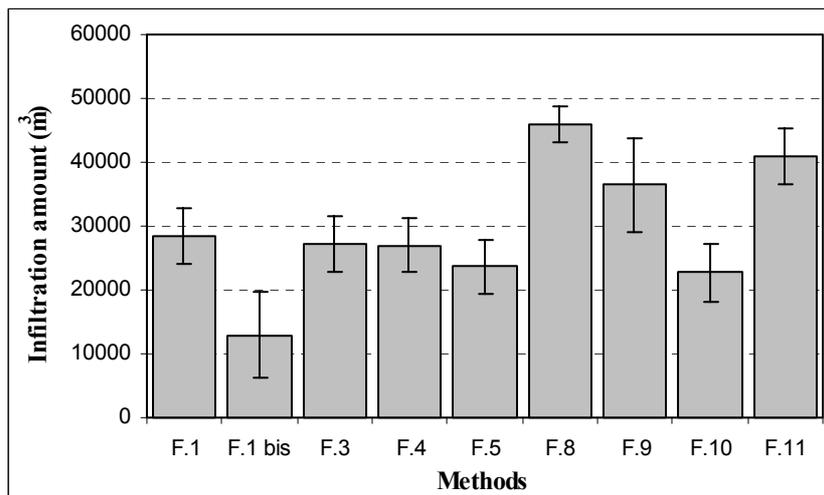


Figure 5 : Infiltration estimated according to several flow rate methods

The total volume of infiltration and the associated uncertainties estimated with various methods during the single day of pollutant measurements are illustrated in Figure 6. There is a strong variability between the various estimations (from 1 to 2.5). The methods based on the night flow or pollutants concentration tend again to overestimate infiltration compared to the other methods. The width of the 95 % confidence interval allows to define the most accurate methods at

daily scale. In a general way, the methods based on the minimum night flow (F.8, F.9 and F.10) are less accurate because the uncertainty in an instantaneous value is quite high : in the case of Ecully, it is reaching 30 %.

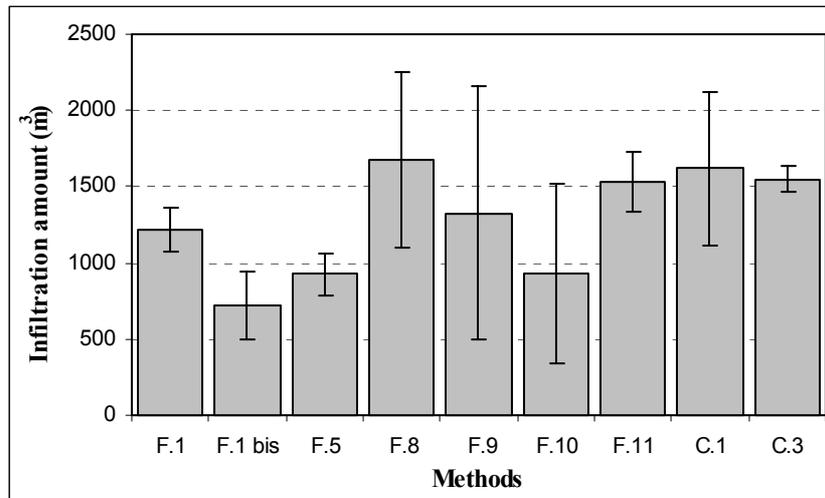


Figure 6 : Infiltration estimated according to several flow rate and chemical methods.

The first conclusion is that an estimation of infiltration carried out during one single day in the frame of a diagnostic study can be rather wrong due to wastewater flow variations. Moreover, the uncertainties associated to an estimated value of infiltration may be important according to the method used. This remark concerns especially the methods F.8, F.9 and F.10 based on the minimum night flow that are generally used in France by sewer operators. Thus, one single daily value of infiltration is insufficient to provide pertinent conclusions, especially when the spatial distribution of infiltration contribution is analysed at the scale of several sub-catchments. In order to provide a pertinent estimation, the calculation of a total volume of infiltration during several successive dry weather days is recommended. Indeed, the comparison of uncertainty range between Figure 5 and Figure 6 shows that, with the methods F.8, F.9 and F.10, the relative uncertainty in infiltration over 28 days decreases by a factor 3 to 5 compared to the relative uncertainty in infiltration during one single day. In the frame of a traditional diagnostic study, data concerning 28 dry weather days are not available because of the limited duration of measurement campaigns and of the occurrence of a rain events. Thus, it can be interesting to find a compromise between an observable number of dry weather days and an acceptable uncertainty in infiltration. Using the estimated values carried out with F.8, F.9 and F.10 for each of the 28 dry weather days (Figure 4), n values of the total volume of infiltration over i dry weather days can be calculated with i ranging from $i = 1$ to $n = 28$. The study of the relative uncertainty associated to these n values allows to determine the number of dry weather days necessary to obtain an acceptable level of uncertainty. The results are given in Figure 7.

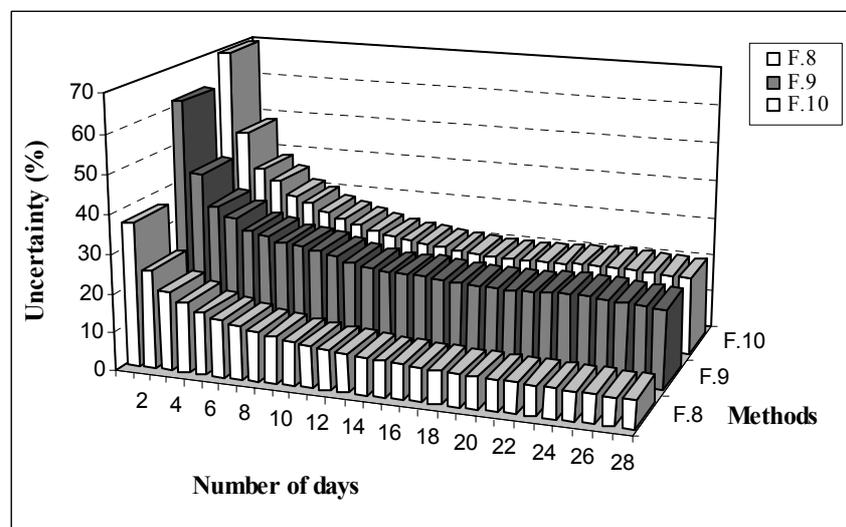


Figure 7: Uncertainty in the total volume of infiltration according to the number of dry weather days

The shapes of these curves are similar for the methods F.8, F.9 and F.10. Compared to an estimation based on one single day, the relative uncertainty decreases with a factor 2 when the total volume of infiltration is estimated over 4 dry weather days and with a factor 3 when it is estimated over 8 dry weather days. From 10 dry weather days, the decrease of uncertainty is less marked and tends to be stable. Consequently, a number of dry weathers days included between 4 and 10 days seems to be a good compromise.

CONCLUSIONS AND PERSPECTIVES

According to the method used, the estimated value of infiltration fraction varies in a large range close to 20 % of dry weather flow. However, this strong variability seems to have a limited impact on the spatial definition of infiltration contributions at sub catchment scale realised during a diagnostic study. The study of uncertainty variability according to the number of dry weather days used for the calculation of a total volume of infiltration shows that a diagnostic study based on the night flow analysis must have a sufficient duration in order to observe 8 to 10 days of dry weather. There are no ideal measurement methods but a set of methods that can be applied according to the experimental conditions specific to the studied site. Additional experiments are necessary to better define the conditions of use and validity of existing methods. The data assessed within the framework of the self monitoring of sewer systems can be used for this purpose with as final objective the continuous measurement and its use for the development of rehabilitation strategies.

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