Assessing the impact of infiltration and exfiltration in sewer systems using performance indicators: case studies of the APUSS project

A. Cardoso[1]*, V. Prigiobbe[2], M. Giulianelli [2], E. Baer [3], J. De Bénédittis [3], S.T. Coelho [1]

[1] *LNEC, National Civil Engineering Laboratory of Portugal, Av. do Brasil 101, 1700-066 Lisbon, Portugal*
[2] *Water Research Institute of the Italian National Research Council (IRSA-CNR), Via Reno, 1, 00198 Rome, Italy*
[3] *URGC Hydrologie Urbaine, INSA de Lyon, 34 avenue des Arts, 69621 Villeurbanne cedex, France*
**Corresponding author, e-mail macardoso@lnec.pt*

ABSTRACT
The structural quality and functional efficiency of sewer systems are key parameters to guarantee the transfer of domestic, commercial and industrial wastewater to treatment plants without infiltration nor exfiltration. Infiltration of groundwater is particularly detrimental to treatment plant efficiency, while exfiltration of wastewater can lead to groundwater contamination. The APUSS project associating universities, SMEs and municipalities in 7 European countries, developed new methods and techniques to assess and quantify infiltration and exfiltration (I/E) in sewer systems. This paper describes the establishment of a set of performance indicators (PI) developed to assess the impact of I/E on sewer systems and their application to three project case studies, in Italy and France, focusing on sewer systems characteristics, I/E measurements campaigns and PI application results. The methodology for PI definition consists in the selection and development of a sewer network property or state variable, which is expressive of aspects being scrutinized (I/E); the PI values are then calculated; finally, a classification of the PI values is made in relation to good or bad performance. The use of PI allows a standardized and objective comparison of the performance of sewer systems and constitutes a means to technically support the establishment of priorities for rehabilitation and/or construction investments taking into account I/E impacts.

KEYWORDS
Exfiltration; infiltration; performance indicators; rehabilitation; sewer systems

INTRODUCTION
Sewer systems constitute a very significant patrimony in European cities. Their structural quality and functional efficiency are key parameters to guarantee the transfer of domestic, commercial and industrial wastewater to treatment plants (WWTP) without infiltration nor exfiltration. Infiltration of groundwater is particularly detrimental to treatment plant efficiency, while exfiltration of wastewater can lead to groundwater contamination. The APUSS (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems) project, associating universities, small and medium enterprises (SMEs) and municipalities in 7 European countries, developed new methods and techniques to assess and quantify infiltration and exfiltration (I/E) in sewer systems. The methods were developed by EAWAG (Kracht *et al.*, 2003 and Rieckermann and Gujer, 2002), tested and validated in different catchments by several APUSS partners. Associated models and tools were established for application and end-user decision.

One of the objectives of the APUSS project was to provide end-users with integrated elements for decision support that account for I/E rates, impacts on the sewer functioning, wastewater treatment plant and on the economic value, and facilitate the comparison of different investment strategies to reduce infiltration and exfiltration. In order to facilitate the decision process, a set of performance indicators (PI) has been developed to assess the impacts of I/E on sewer systems, both combined and separate domestic systems, and has been applied to project case studies. The specific application considered herein is the sewer systems performance evaluation with regard to infiltration of clean water into foul sewers and exfiltration of sewage into the soil and groundwater.

METHODOLOGY FOR PERFORMANCE ASSESSMENT

Description

The principal requirements considered for the performance assessment methodology are: i) flexibility, in order to accommodate with ease the different sensitivities, interpretations or objectives of the analysis; ii) a certain degree of standardisation in order to facilitate a multi-disciplinary approach, where the various aspects to be considered may be brought down to the same quantified basis; and iii) a quantitative, numerical base - the envisaged tool should be translatable computationally in order to afford intensive use, either from within or as post-processor to the current modelling techniques or monitoring data (Cardoso *et al.*, 1999).

The methodology consists in the selection and development of three components for each aspect of performance analysed (Cardoso and Coelho, 2004): i) the numerical value of a sewer network property or state variable, which is expressive of the particular aspect being scrutinized (I/E), i.e. the Performance Indicator (PI) definition; ii) a classification of the PI values scoring them in relation to good or bad performance; iii) an operator, which allows the performance values at element level to be aggregated across the system or parts of it to obtain an overall system performance figure. The performance assessment scale depends on the scale of available data. In cases where data are available at element level, there are i) a global value that is achieved through a particular operator in order to represent the performance assessment of the network, e.g. a simple or weighted average, and conversely ii) a population of elementary values, which leads itself to a basic statistical treatment, giving information on the PI values dispersion on the system through, e.g., percentile bands. In cases where data are only available at catchment level, only a global PI value for that catchment is achieved.

Performance Indicators for infiltration and exfiltration

Infiltration. In the APUSS project seven PI for infiltration were established for the assessment of impacts of infiltration in sewer systems (Cardoso and Coelho, 2004). The following set of four PI is presented for the analysis of the case studies. They can be calculated at either pipe or catchment scales.

- $\frac{Q_{inf}}{Q_{full}}$ (%) – **PI_{I1}** proportion of the sewer full section flow capacity used by the infiltration flow. This indicator supplies information on the hydraulic performance of the analysed sewer(s), but gives no indication about the net infiltration flow. White *et al.* (1997) refer that, for design purposes, in UK 10% of sewer capacity should be allocated to infiltration in separate domestic systems according to the Water Authorities Association (WAA, 1989).
- $\frac{Q_{inf}}{Q_{avdwf}}$ (%) - **PI_{I2}** infiltration flow expressed as a percentage of the daily mean dry weather flow. A drawback of this indicator is its dependency on the values of the dry weather flow. This indicator gives an estimate of the weight of infiltration flow on treatment costs. It may be expressed either as percentage of volume or cost. Stevens (1998) presents a study in New York where about 50% of the

total flow reaching WWTP was infiltration flow; Belhadj *et al.* (1995) report values of 42% of dry weather flow.

- $\frac{Q_{inf}}{Q_{avdwf} - Q_{inf}}$ (%) - **PI_{I3}** infiltration flow expressed as a percentage of the daily mean domestic wastewater. A drawback of this indicator is its dependency on the values of the dry weather flow. The German guidelines ATV-A118E (ATV, 1999) considers an infiltration/inflow flow equal to 100% of domestic flow, for design purposes of separate domestic systems.
- $\frac{Q_{inf}}{\text{sewer longitudinal area}}$ (m^3/day/(cm.km)) - **PI_{I4}** means infiltration flow per unit area of sewer wall. This indicator is related to the sewer wall area that is potentially subject to infiltration. It can be the wall area below groundwater level. In this case it was considered the total sewer wall area. Sewer longitudinal area is calculated as the sum, for all sewers of the measured reach, of the pipe perimeter times pipe length. EPA (2001) refers to that in USA this value can vary from 0.05 to 1.39 m^3/day/(cm.km). Tchobanoglous *et al.* (2003) refer that these values can range from 0.1 to 10 m^3/day/(cm.km).

Exfiltration. In the APUSS project five PI for exfiltration were established for performance assessment of impacts of exfiltration in sewer systems (Cardoso and Coelho, 2004). The following set of three PI is presented for the analysis of the case studies:

- $\frac{Q_{exf}}{Q_{avdwf}}$ (%) – **PI_{E1}** exfiltration flow expressed as a percentage of the daily mean dry weather flow. A drawback of this indicator is its dependency on the values of the dry weather flow. Amick and Burgess (2000) present values of experimental studies with values between 11.9% and 49%. Ellis *et al.* (2002) refer that probably this value is not greater than 10%.
- $\frac{Q_{exf}}{\text{sewer length}}$ (m^3/day/m) – **PI_{E2}** mean exfiltration flow per unit length of sewer. This indicator will give relevant results in systems where exfiltration takes place predominantly along the sewers. Literature values are between 0.000027 and 0.001 m^3/day/m (Amick and Burgess, 2000).
- $\frac{Q_{exf}}{\text{sewer longitudinal area}}$ (m^3/day/(cm.km)) – **PI_{E3}** mean exfitration flow per unit area of sewer wall. This indicator is related with the sewer wall area that is potentially subject to exfiltration. Sewer longitudinal area is calculated as the sum, for all sewers of the measured reach, of the pipe perimeter times pipe length. Literature values are between 0.08 and 1.20 m^3/day/(cm.km) (Amick and Burgess, 2000).

CASE STUDIES

Italian case study

Experimental catchment description. An experimental catchment, Torraccia, located in Rome has been investigated and is presented in Figure 1. Torraccia has about 85 ha, whose 55 ha are residential and 30 ha are rural. The sewer network is an egg-shaped combined system (1x1.2 m, 1.5x1.8 m and 1.5x2.1 m) laid about 4 to 9 m under the ground level. It is dated 14 years and pipe material is concrete. In Torraccia the mean groundwater level is 19 m below ground level. Torraccia was selected because it is considered representative of an urban area in Rome.

Experimental measurements campaigns description. Infiltration rate was assessed by application of the isotopic method (Kracht *et al.*, 2003), and exfiltration rate by QUEST (Rieckermann and Gujer, 2002) and QUEST-C (Rieckermann and Bares, 2003) methods. The isotopic method is based on hydrograph separation method; the two components (i.e., the sources of water drained by the investigated sewer system) identified were groundwater and drinking water. Submerged probe (Sigma 900max) for the level and velocity measurements and an automatic sampler (Sigma 900max) for taking wastewater from the sewer were installed at the outlet of Torraccia system (Figure 1). All the samples were analyzed in laboratory for the isotope $\delta^{18}O$ determination using the method by Epstein and Mayeda (1953) and infiltration was estimated by using the equation by Kracht *et al.* (2003). For infiltration assessment a one-day experiment was carried out in Torraccia. The estimated infiltration ratio is 0.14 ± 0.01 (ratio between infiltration and mean dry weather flow) and the infiltration flow rate is 3.22 ± 0.23 Ls^{-1}. The small infiltration values in Torraccia confirm the expectations, since groundwater level was under sewer invert levels during the experiment.

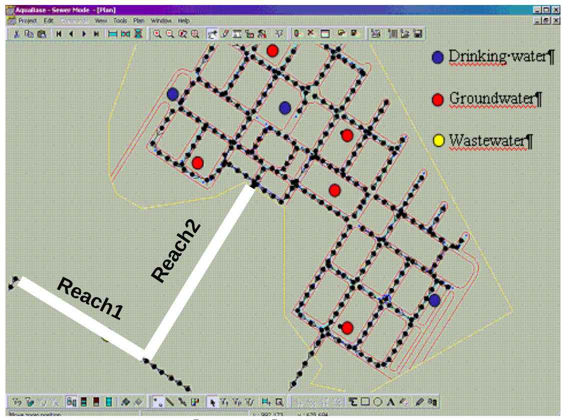

Figure 1. Torraccia sewer system and sampling points.

For the exfiltration assessed using the QUEST-C method two solutions of LiCl and NaBr were dosed into the wastewater pipe and the ion concentrations into wastewater samples taken at the end of the investigated reach were determined by means of Dionex Dx100 (anion column AS14 and cation column CS12). The mean exfiltration values for two reaches of 400 m (Reach1) and 480 m (Reach2) long pipes in Torraccia are summarized in Table 1. The small exfiltration values in Torraccia confirm the expectation since the investigated pipe backfilling was concrete and the structural state of the pipe was supposed to be good. Exfiltration ratio is the ratio between infiltration and mean dry weather flow.

Table 1. Torraccia mean exfiltration values by QUEST-C method.

	Reach1	**Reach2**
Exf. ratio [-]	-8.69	-1.73
Exf. rate [L s-1]	-2.45	-0.35

French case studies

Experimental catchments description. The two French Yzeron and Ecully catchments are located near Lyon, France. The Yzeron catchment has an area of 15 000 ha with increasing urbanization and imperviousness since 20 years. Its drainage system is combined, with a total length of 294 km and sewer sizes ranging from 200 mm circular pipes to 2 m egg-shaped pipes. In 1992, a diagnostic study revealed high infiltration rates linked to a degraded state of the sewer system. The Ecully catchment is smaller, with an area of 245 ha. The habitat is mostly residential. The imperviousness is evaluated to 46 % (De Bénédittis, 2004). Its drainage system is combined, with a total length of 15 km, a mean slope of 0.027 m/m, and sewer sizes ranging from 200 mm circular pipes to 1.8 m egg-shaped pipes.

Experimental measurements campaigns description. Infiltration and exfiltration rates have been measured using two of the methods developed within the APUSS project (De Bénédittis, 2004): the QUEST method based on NaCl mass balance for exfiltration (Rieckermann and Gujer, 2002) and the oxygen isotopic method for infiltration (Kracht *et al.*, 2003).

In the Yzeron catchment, one infiltration measurement campaign was carried out in 8 different locations (Figure 2) in December 2002. For each of the 8 investigated subcatchments, mean night and mean day infiltration flows, Qinf, were calculated (Table 2).

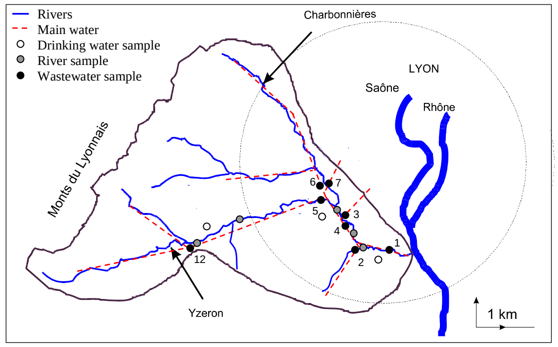

Figure 2. Sampling locations of infiltration measurements in the Yzeron catchment, France, December 2002 (De Bénéditis, 2004).

In Ecully, five infiltration measurement campaigns were carried out between December 2003 and June 2004 at the system outlet, giving a global estimation of the infiltration flow for the entire catchment. Seasonal variations of infiltration were observed (see upper part of Table 3).

Table 2. Results of infiltration measurements in Yzeron catchment (December 2004).

		Isotopic method ($\delta^{18}O$ method)		
Point	Period	b (%)	Q_{dwf} (m^3/h)	Q_{inf} (m^3/h)
1	N	0,86	2012	1728
1	D	0,75	2351	1756
2*	N	1,01	199	202
2*	D	1,00	239	238
3	N	0,44	67	30
3	D	0,24	117	28
4	N	0,78	964	756
4	D	0,75	1386	1035
5	N	0,88	231	203
5*	D	0,89	268	239
6	N	0,85	631	534
6	D	0,72	658	470
7	N	0,60	112	67
7	D	0,32	197	64
12	N	0,81	249	201
12	D	0,92	249	229

Table 3. Ecully: results of infiltration (catchment scale) and exfiltration (reach scale) measurements.

Date of measurement campaign	Q_{inf} (m^3/h)	Uncertainty ΔQ_{inf} (%)
17/12/2003	41.75	11.74
27/04/2004	41.74	5.22
28/04/2004	38.08	4.86
17/05/2004	35.23	3.24
04/06/2004	23.80	3.67
Date of measurement campaign	Q_{exf} (m^3/h)	**Uncertainty** ΔQ_{exf} (%)
25/07/2003	10.85	3.12
31/10/2003	6.61	1.81
28/11/2003	2.51	2.49
25/06/2004	15.89	3.31
9/07/2004	11.29	0.68
22/07/2004	15.06	2.17

Six exfiltration measurement campaigns have also been carried out in Ecully on a 838 m sewer reach using NaCl mass balance method between July 2003 and July 2004 (see lower part of Table 3). Sewer wet wall area was calculated as the sum, for all sewers of the measured reach, of the product of pipe perimeter times pipe length.

RESULTS AND DISCUSSION

Results

Infiltration. The PI presented before were applied to the case studies in order to assess the performance of the sewer systems regarding infiltration and exfiltration impacts. Figure 3 to Figure 6 show the results obtained for infiltration after application of the PI at a catchment scale. In these figures the performance of the different systems can be compared in the same graph. In the case of the Yzeron catchment, the PI was calculated for 8 subcatchments and also for the entire catchment as a simple mean.

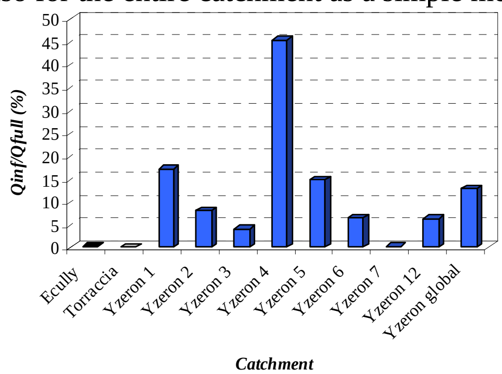

Figure 3 – Proportion of the full section flow capacity used by the infiltration flow PI_{I1}.

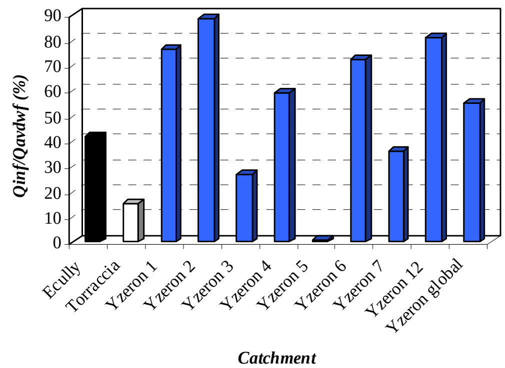

Figure 4 – Infiltration flow as a percentage of the daily mean dry weather flow PI_{I2}.

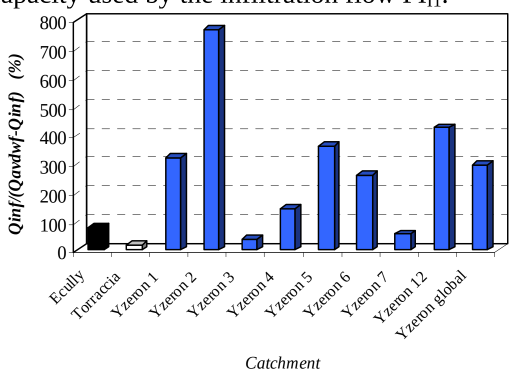

Figure 5 – Infiltration flow as a percentage of the daily mean domestic wastewater PI_{I3}.

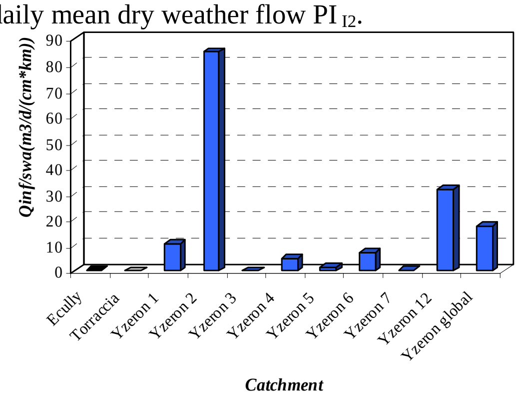

Figure 6 – Infiltration flow per unit sewer wall area PI_{I4}.

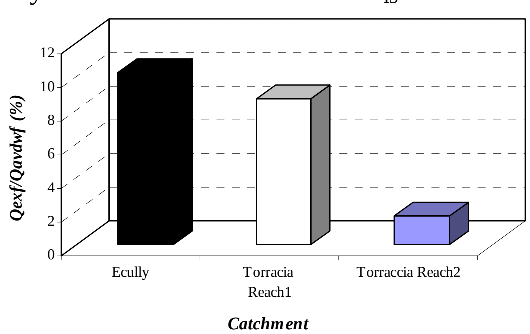

Figure 7 – Exfiltration proportion of dry weather flow PI_{E1}.

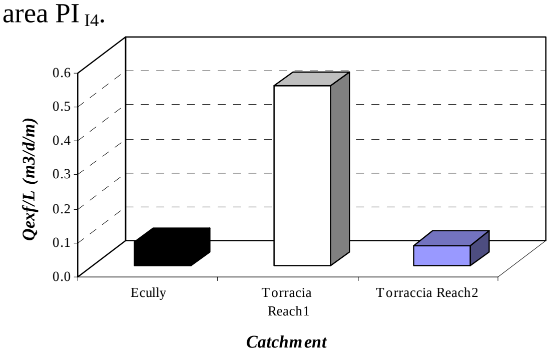

Figure 8 – Exfiltration flow per unit sewer length PI_{E2}.

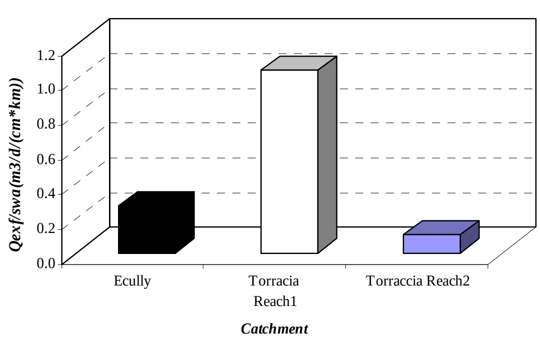

Figure 9 – Exfiltration flow per unit sewer wet wall area PI_{E3}.

Exfiltration. With respect to exfiltration, the same analysis is presented in Figure 7 to Figure 9 for the three PI presented before. The exfiltration analysis was only performed in the sewer reaches where information and data was available. For Yzeron catchment there was no exfiltration data. For Torraccia there was data on the two reaches presented before.

Discussion

Infiltration. Considering Figure 3 to Figure 6 it is possible to draw the following conclusions:

- For the global **Ecully** catchment, the contribution of infiltration is very high representing a flow additional to domestic wastewater of about 77% (**PI_{I3}**) and corresponds to about 40% (**PI_{I2}**) of the dry weather flow that will reach the WWTP. **PI_{I4}** shows a value of 0.3 m^3/day/cm/km. However, this has no impact on the hydraulic capacity of the system as **PI_{I1}** presents a value of 0.3%.
- For the global **Torraccia** catchment, the contribution of infiltration represents an additional flow to domestic wastewater of about 18% (**PI_{I3}**) and corresponds to about 15% (**PI_{I2}**) of the dry weather flow that will reach WWTP. There are no impacts on the hydraulic capacity of the system as **PI_{I1}** presents a value of 0.06%. **PI_{I4}** shows a value of 0.1 m^3/day/cm/km. This means that infiltration has no relevant impact on the system performance.
- For the global **Yzeron** catchment, the contribution of infiltration represents a additional flow to domestic wastewater of about 300% (**PI_{I3}**) and corresponds to 55% (**PI_{I2}**) of the dry weather flow that will reach WWTP. There are impacts with regard to the hydraulic capacity of the system as **PI_{I1}** presents a value 13% but not very significant. **PI_{I4}** shows a value of 18 m^3/day/cm/km. All PI are out of the range of the values from literature. This reflects the fact that the Yzeron sewers are in a bad structural state as detected some years ago by the Great Lyon Sewer Department, and rehabilitation projects are under preparation at the moment.
- Comparing the performance of the different catchments/subcatchments, it is clear that Yzeron2 shows significant problems as a consequence of infiltration. PI for Yzeron2 are 22 times higher than for Ecully and Torraccia. In spite of PI_{I2} is 88% and PI_{I3} is 767%, the value for PI_{I1} is 8%. PI_{I4} presents a value of 85 m^3/day/cm/km, much higher compared to other catchments and excessive. This means that this catchment presents severe infiltration problems and that impacts are higher in terms of costs. It seems that there are no hydraulic problems. On contrary, Yzeron4 presents the values of PI_{I2} of 59%, PI_{I3} of 144% and PI_{I1} of 45%. In this case besides the impact on costs, there are also problems with hydraulic capacity. In general, Yzeron catchment presents significantly higher values for the PI than Ecully and Torraccia. Yzeron seems to have bigger problems related to infiltration occurrence than Ecully. Torraccia presents the lowest PI values and seems to have no problems related to infiltration.

Exfiltration. Considering now Figure 7 to Figure 9, it is possible to conclude that, regarding exfiltration, **Ecully** presents the highest **PI_{E1}** value, though it is close to **Torraccia Reach1** value, meaning that about 10% of the dry weather flow is lost. **Torraccia** presents a big difference in the value of this PI for Reach1 8.7% and Reach2 1.7%, but they are within literature values. **PI_{E2}** and **PI_{E3}** are higher than the literature values and the highest value is for **Torraccia Reach1**. In this case **Reach1** seems to have more problems regarding exfltration. The use of PI when comparing different systems or different sewers can support the prioritization of rehabilitation actions.

CONCLUSIONS

- The presented methodology aims to support sewer systems rehabilitation by using infiltration and exfiltration performance indicators (PI), as a means of aggregating information on system characteristics and experimental data from monitoring or modelling, and translate it into performance values. This allows sewer operators to compare either different systems performance or monitor the time evolution in the system in a standardised and quantified way. This performance assessment can support the decision on when and where rehabilitate, depending on the selection criteria (hydraulic, environmental, economic, etc.).
- The application of PI for infiltration and exfiltration depends on available data, which means that on the one hand the approach can be applied at pipe or larger scales; on the other hand the quality and uncertainty of PI results depend on the quality an uncertainty of data used. Possible next steps would consist to account for uncertainties in I/E rates and in sewer characteristics in the evaluation of the PI and of their own uncertainties and to establish a robust classification for PI based on more case studies.
- Any assessment using PI must consider a set of PI and not only one, in order to give a global view with significant information.

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