PERFORMANCES AND UNCERTAINTY OF TEMPERATURE METHODS FOR ILLICIT INFILTRATIONS AND INFLOWS ASSESSMENT IN STORMWATER SEWERS

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ABSTRACT

The term “illicit flows” refers to all those unexpected and unwanted waters that are drained by or discharged into the urban drainage systems. Unmanaged illicit flows may cause significant losses in functionality both to the sewer networks and to the wastewater treatment plants. This paper focuses on one of the main approaches for illicit flow individuation and estimation in sewers that is based on the joint use of flow probes and temperature sensors; such an approach is often chosen for practical aims, because of its simplicity, affordability and adaptability. In particular, this paper is meant to fulfill the still existing lack of a systematic method to assess a priori its performances in terms of reliability and accuracy, by rigorously implementing the general uncertainty analysis theory. Then, through some meaningful numerical case studies, it is shown how to minimize the uncertainty on the illicit flow estimation when just one flow probe is available for the field survey. But it also highlights the potential weakness of the field results when the illicit flow rates are too small and/or their temperatures are too close in comparison to the regular flow. This research has been carried out within the framework of the project “PerFORM WATER 2030”, funded by Regione Lombardia.

Keywords: sewer, illicit flow, infiltration and inflow, flow probe, temperature sensor, uncertainty.

1 INTRODUCTION

Sewer systems are extensive and aging structures, subject to cracks and misconnections during their operational lifetime. Illicit flows in sewer systems can be distinguished, depending on their source, into infiltrations and illicit inflows. The first are generally waters coming from aquifers or surface channels that can enter the network through cracked and broken pipes, leaky connections, or deteriorated manholes. The second are unauthorized and/or unintended connections delivering continuous or intermittent discharges to the sewer system. The temporal pattern of illicit flows can be constant or variable either in a random way or according to a regular time schedule, depending on their origin.

The presence of illicit flows in a sewer system causes lots of problems: network overload; increase of overflows; alterations of pumping systems functioning with arising energy costs and potential damages, especially if unexpected solid particles are transported; decrease of the efficiency of treatment plants due to flow dilution; and, last but not least, health and environmental problems.

Many regulations all over the world stress the importance to limit illicit flows into the stormwater sewers; it is very important not only to detect the so-called Infiltration & Inflow (I&I) into the drainage networks but also to understand their sources, trying to locate and quantify them. This knowledge is fundamental for the estimation of peak runoff [1] and the proper size of stormwater detention facilities [2]–[6] and Sustainable Urban Drainage Systems (SUDS) as like permeable pavements [7] and rainwater harvesting systems [8]–[10].

To this aim, the first step is usually the identification of the most critical areas and network sections, where further investigations must be developed at a local scale. The first step consist, most of the times, in the analysis of the night-time minimum of dry weather flows; after that, a number of different methodologies and technologies can be applied for the next

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level of the survey, depending on site conditions and resources availability: visual inspections and progressive sampling at manholes [11], smoke test and dye test [12], closed-circuit television camera (CCTV) inspections, Infra-Red camera [13], stable isotopes, polluting flows analysis, punctual measures of temperatures. In last decades, Distributed Time Sensing (DTS) technique has been successfully applied to locate I&I in sewers [14], [15]; it is based, too, on temperature measurements, but continuous in time and space; it allows to identify illicit flows for large distances without requiring access to private properties. Each one of these methodologies present some drawbacks: DTS requires cable installation into the sewer, dye and smoke tests are time consuming, visual inspections are – by definition – sensitive to human subjectivity, while methods based on sample analysis may be quite costly [16]; sometimes, a solution to improve the cost-effectiveness of a survey turns out to be the joint use of different technologies [17]. The method described in this paper needs punctual measures of temperature and flow rate, and can be performed indifferently by means of either DTS or simply temperature sensors coupled with flow probes: temperature anomalies, in fact, are generally indicators of illicit flows such as infiltration and inflow. The focus, here, is on the key aspect of the estimation of uncertainty about infiltrations or inflow rates calculated from the values of temperatures and in-sewer flow rates measured in the field, given the uncertainty of the temperature sensors and of the flow probes [18]. Then, the analysis of two meaningful numerical examples, described for each one of the three different general cases of interest for practical applications in real sewer systems, allows to evaluate the performances, in terms of accuracy and cost-benefits, which can be achieved by means of a given available set of temperature sensors and flow probes.

2 UNCERTAINTY ESTIMATION

Fig. 1 shows the reference scheme used in the following analysis.

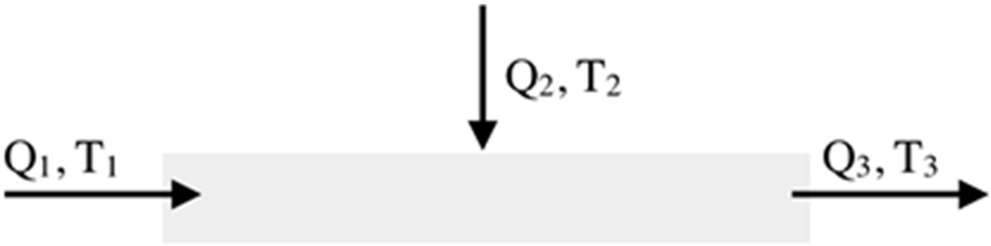

Figure 1: Scheme of reference for the analysis.

A generic portion of a sewer with undefined length and diameter can be considered as the control volume: inflow and outflow rates are respectively located in Sections 1 and 3 while in Section 2 an illicit entering flow rate is assumed (it can be generated from illicit connections, groundwaters or rainwater infiltrations). The six quantities of interest are the temperatures T_1, T_2 and T_3 and the flow rates Q_1, Q_2 and Q_3. Under the hypothesis of steady conditions, exploiting flow and energy conservation eqns (1), two of these six quantities can be calculated, if the remaining four are measured in the field:

$$\begin{cases} Q_1 + Q_2 = Q_3, \\ Q_1 \cdot T_1 + Q_2 \cdot T_2 = Q_3 \cdot T_3. \end{cases} \tag{1}$$

In the following analysis, three different cases are considered:

- Case A, which is typically related to infiltration of ground/rain waters: neither temperature nor flow rate of the illicit flow (Q_2 and T_2) can be measured; they are the unknown variables.
- Case B, which is typically related to illicit inflows: its temperature T_2 can be measured, while unknown variables are Q_2 and Q_1.
- Case C, which is typically related to illicit inflows, as well; its temperature T_2 can be measured, while unknown variables are Q_2 and Q_3.

Indeed, sometimes real situations can be quite different. For example, about case A, it may happen that a sensor for the measure of groundwater temperature can be located very close to the sewer, so that T_2 can be actually known; on the other hand, about case B and case C, due to the nature of the connection (e.g. a private property), it's not always easy to reach this punctual inflow and to measure its temperature T_2.

In general, if the measures of all the temperatures are available, for example when DTS is used, eqn (1) allows the estimation of the ratio between illicit flow rate Q_2 and one of the other flow rates in the pipe Q_1 or Q_3 [19]; but, of course, the two unknown flow rates can be both estimated only if one of the three flow rates is measured [20]. Discharge Q_2 is anyway the most important variable of the problem, by definition, as its knowledge drives the decisions about which kind of intervention is required to reduce the discovered illicit flow.

The computational procedure for uncertainty analysis, developed here for all the considered cases, allows to evaluate the performances which can be achieved, in terms of accuracy, in each one of the three above mentioned typical cases. In addition, this computational procedure is also the perfect tool to investigate and to compare the three cases, through some meaningful numerical examples, from the point of view of the reliability of the illicit flow estimations which can be obtained by field surveys. Based on such a comparison, it comes out which are, respectively, the most and the less favourable positioning schemes for temperature sensors and flow probes. It is assumed in each example that all the flow meters have the same relative uncertainty (expressed as %) while all the temperature sensors have the same absolute uncertainty (expressed as °C). By the way, the uncertainty about flow rates can also keep into account small short-term oscillations and variations and also transient storage effects [21], while the uncertainty about the temperatures can keep into account also the variations due to the thermic interactions between, on the one hand, the stream and, on the other hand, the channel walls and the air above the stream surface.

2.1 Case A

Unknown variables are illicit flow Q_2 and its temperature T_2; they can be estimated rearranging flow and energy conservation eqn (1):

$$Q_2 = Q_3 - Q_1, \tag{2}$$

$$T_2 = \frac{Q_3 \cdot T_3 - Q_1 \cdot T_1}{Q_2}. \tag{3}$$

Eqn (3) can be made dimensionless and written as:

$$\frac{T_2}{T_3} = \frac{Q_3}{Q_3 - Q_1} - \frac{Q_1}{Q_3 - Q_1} \cdot \frac{T_1}{T_3}. \tag{4}$$

The relative uncertainty of illicit flow results:

$$\frac{U(Q_2)}{Q_2} = \left[\frac{U(Q)}{Q}\right]_{1;3} \cdot \alpha, \tag{5}$$

with $\alpha = \sqrt{2 \cdot \left(\frac{Q_1}{Q_2}\right)^2 + 2 \cdot \left(\frac{Q_1}{Q_2}\right) + 1}$ and $\left[\frac{U(Q)}{Q}\right]_{1;3}$ is the relative uncertainty of the flow rate measurements, having assumed the same value for both the two measured flow rates Q_1 and Q_3. The relative uncertainty of estimated temperature T_2 results:

$$\frac{U(T_2)}{T_2} = \sqrt{\left[\frac{U(Q)}{Q}\right]_{1;3}^2 \cdot \left(\frac{(T_1 \cdot Q_1)^2 + (T_3 \cdot Q_3)^2}{(Q_2 \cdot T_2)^2} + \alpha^2\right) + [U^2(T)]_{1;3} \cdot \frac{1}{T_2{}^2} \cdot \alpha^2}. \tag{6}$$

In particular, $[U^2(T)]_{1;3}$ is the uncertainty of temperature measurements, having assumed that it has the same value for both the two measured temperatures T_1 and T_3.

2.2 Case B

Unknown variables are the incoming flow rate Q_1 and the illicit flows Q_2, while all the temperatures and the downstream flow rate Q_3 are measured. Flow rates Q_1 and Q_2 can be estimated by the following eqns:

$$Q_2 = Q_3 \cdot \frac{\Delta T_{31}}{\Delta T_{21}}, \tag{7}$$

with $\Delta T_{31} = T_3 - T_1$ and $\Delta T_{21} = T_2 - T_1$.

Once the discharge Q_2 has been obtained, Q_1 can be evaluated from the flow conservation eqn (1):

$$Q_1 = Q_3 - Q_2 = Q_3 \cdot \left(1 - \frac{\Delta T_{31}}{\Delta T_{21}}\right). \tag{8}$$

The dimensionless expressions of eqns (7) and (8) result, respectively:

$$\frac{Q_2}{Q_3} = \frac{\Delta T_{31}}{\Delta T_{21}}, \tag{9}$$

$$\frac{Q_1}{Q_3} = 1 - \frac{\Delta T_{31}}{\Delta T_{21}} = \frac{\Delta T_{23}}{\Delta T_{21}}. \tag{10}$$

Relative uncertainties of estimated flow rates Q_2 and Q_1 result, respectively:

$$\frac{U(Q_2)}{Q_2} = \sqrt{\left[\frac{U(Q)}{Q}\right]_3^2 + [U^2(T)]_{1;2;3} \cdot \beta}, \tag{11}$$

$$\frac{U(Q_1)}{Q_1} = \sqrt{\left[\frac{U(Q)}{Q}\right]_3^2 \cdot \left(\left(\frac{Q_2}{Q_1}\right)^2 + \left(\frac{Q_3}{Q_1}\right)^2\right) + \left(\frac{Q_2}{Q_1}\right)^2 \cdot [U^2(T)]_{1;2;3} \cdot \beta}, \tag{12}$$

with $\beta = \frac{1}{\Delta T_{31}{}^2} \cdot \left(1 + \left(\frac{\Delta T_{32}}{\Delta T_{21}}\right)^2 + \left(\frac{\Delta T_{31}}{\Delta T_{21}}\right)^2\right)$ and $\Delta T_{32} = T_3 - T_2$.

In particular, $[U^2(T)]_{1;2;3}$ is the uncertainty on temperature measurements, having assumed that it has the same value for all of the three measured temperatures T_1, T_2 and T_3, while $\left[\frac{U(Q)}{Q}\right]_3$ is the relative uncertainty of the measured flow rate Q_3.

2.3 Case C

Also Case C assumes the knowledge of all temperatures T_1, T_2 and T_3, but it differs from Case B because it considers Q_3 instead of Q_1 as unknown variable. Resulting equations to estimate Q_2 and Q_3 can be obtained rearranging eqns (1):

$$Q_2 = Q_1 \cdot \frac{\Delta T_{31}}{\Delta T_{23}}, \tag{13}$$

$$Q_3 = Q_1 + Q_2 = Q_1 \cdot \left(1 + \frac{\Delta T_{31}}{\Delta T_{23}}\right), \tag{14}$$

with: $\Delta T_{23} = T_2 - T_3$.

Dimensionless expressions of eqns (13) and (14) result, respectively:

$$\frac{Q_2}{Q_1} = \frac{\Delta T_{31}}{\Delta T_{23}}, \tag{15}$$

$$\frac{Q_3}{Q_1} = 1 + \frac{\Delta T_{31}}{\Delta T_{23}} = \frac{\Delta T_{21}}{\Delta T_{23}}. \tag{16}$$

Relative uncertainties on estimated flow rates Q_3 and Q_2 result, respectively:

$$\frac{U(Q_2)}{Q_2} = \sqrt{\left[\frac{U(Q)}{Q}\right]_1^2 + [U^2(T)]_{1;2;3} \cdot \gamma}, \tag{17}$$

$$\frac{U(Q_3)}{Q_3} = \sqrt{\left[\frac{U(Q)}{Q}\right]_1^2 \cdot \left(\left(\frac{Q_1}{Q_3}\right)^2 + \left(\frac{Q_2}{Q_3}\right)^2\right) + \left(\frac{Q_2}{Q_3}\right)^2 \cdot [U^2(T)]_{1;2;3} \cdot \gamma}, \tag{18}$$

with $\gamma = \left(\frac{1+\left(\frac{\Delta T_{31}}{\Delta T_{23}}\right)^2+\left(\frac{\Delta T_{21}}{\Delta T_{23}}\right)^2}{{\Delta T_{31}}^2}\right)$; $\left[\frac{U(Q)}{Q}\right]_1$ is the relative uncertainty of the measured flow rate Q_1.

3 BEST PERFORMANCES IN ILLICIT FLOWS ESTIMATION

A trivial observation is that, of course, the more the temperatures T_1, T_2 and T_3 are similar, the less it is possible to get a reliable estimation of the illicit flow Q_2 in Case B and in Case C. Apart from this, one of the main targets of this paper, as already said, is to find out which is the best positioning of temperature sensors and flow probes in real sewer systems, when their task is to estimate illicit flow rates. With reference to the cases here discussed, in other words, the aim is to find out which one between Case A, Case B and Case C is the best in terms of accuracy and reliability of the illicit flow estimation. To do this, relative uncertainty of the measures of illicit flow rate Q_2 and temperature T_2 must be compared for the three cases; in particular, two different sets of assumptions for measurement uncertainty of flow rates and temperatures are here considered, respectively $U(Q_i) = 5\%$, $U(T_i) = 0.5°C$ and $U(Q_i) = 10\%$, $U(T_i) = 1°C$. Two examples for each case are carried out. Examples 1 can be considered as the benchmark: incoming flow rate Q_1 and illicit flow Q_2 are equal. Instead, Examples 2 is aimed to model a situation in which Q_2 is significantly smaller than Q_1.

3.1.1 Example 1

At first, unknown variables are estimated from measured data through eqns (2) and (3) for Case A1, eqns (7) and (8) for Case B1 and eqns (13) and (14) for Case C1:

Case A1: Q_1 = 50 l/s, Q_3 = 100 l/s, T_1 = 20°C, T_3 = 18°C → Q_2 = 50 l/s, T_2 = 16°C
Case B1: Q_3 = 100 l/s, T_1 = 20°C, T_2 = 30°C, T_3 = 25°C → Q_1 = 50 l/s, Q_2 = 50 l/s
Case C1: Q_1 = 50 l/s, T_1 = 20°C, T_2 = 30°C, T_3 = 25°C → Q_2 = 50 l/s, Q_3 = 60 l/s

Then, through eqns (5) and (6) and considering the uncertainty values assumed for the measured quantities, relative uncertainties for Q_2 and T_2 in the three cases A1, B1 and C1 have been estimated (Table 1).

Graphical results for Cases A1, B1 and C1 for the assumed uncertainty values for flow rates and temperatures equal to $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$ are shown in Figs 2–4.

Table 1: Assumed and calculated uncertainties of illicit flow rate and temperature in Example 1.

Case	Assumed uncertainties for flow probes and temperature sensors	Calculated relative uncertainty $U(Q_2)/Q_2$	Calculated relative uncertainty $U(T_2)/T_2$
A1	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	11%	18%
	$U(Q_i) = 10\%$; $U(T_i) = 1°C$	22%	37%
B1	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	13%	2%
	$U(Q_i) = 10\%$; $U(T_i) = 0.5°C$	26%	3%
C1	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	25%	2%
	$U(Q_i) = 10\%$; $U(T_i) = 1°C$	50%	3%

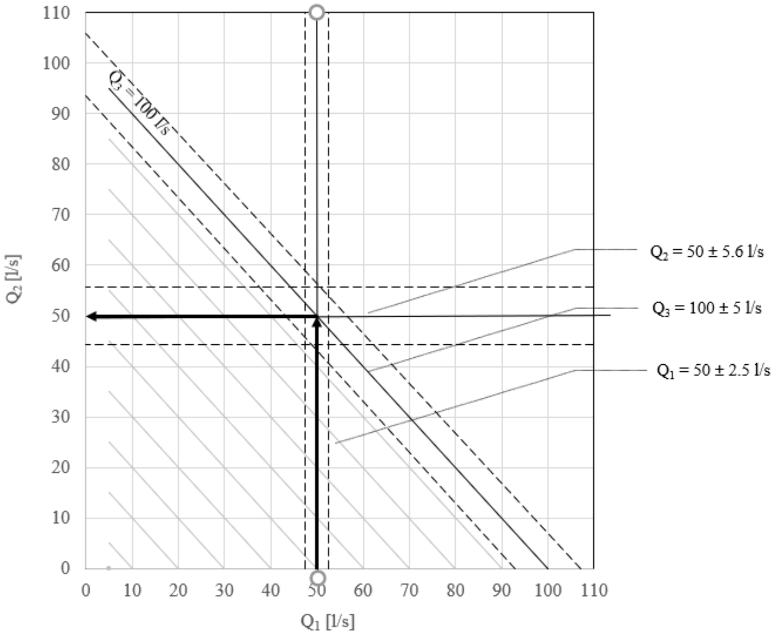

Figure 2: Graphical representation of Case A1 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

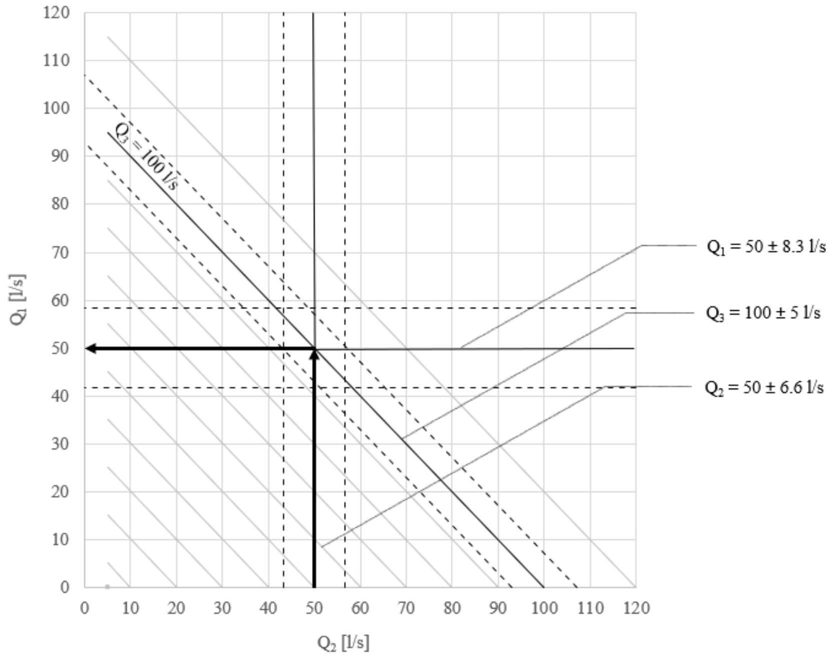

Figure 3: Graphical representation of Case B1 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

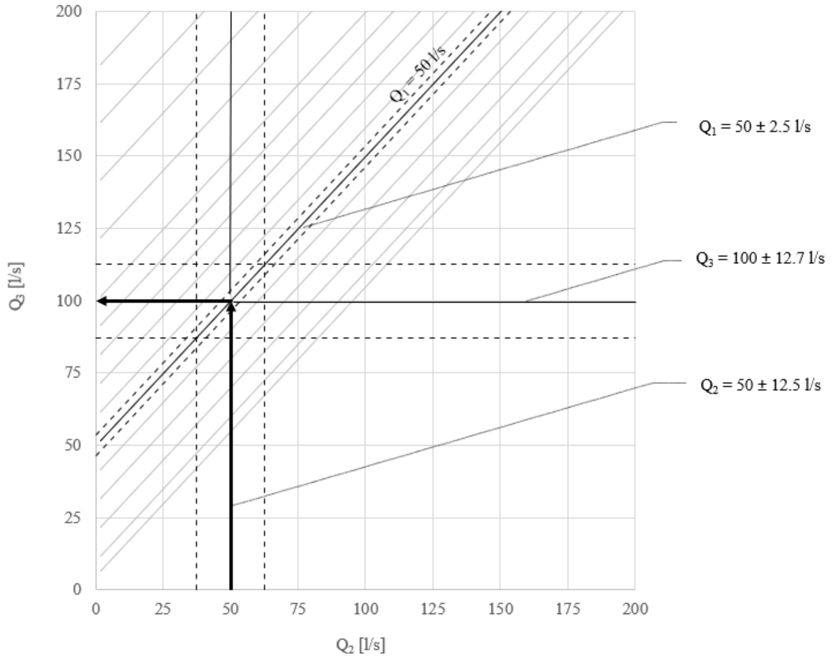

Figure 4: Graphical representation of Case C1 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

According to eqns (5), (11) and (18), a basic remark is that the values of the relative uncertainty $U(Q_i)/Q_i$ and of the absolute uncertainty $U(T_i)$ play the role of a multiplying coefficient in the expressions giving the relative uncertainty of the illicit flow $U(Q_2)$, in all of the three cases: so, in practice, doubling both the relative uncertainty of the measured flow rates $U(Q_i)/Q_i$ and the uncertainty of the measured temperature $U(T_i)$, the relative uncertainty $U(Q_2)/Q_2$ doubles. Beyond this, even more important is that it comes out that, fixed all the other parameters, the smallest relative uncertainty for illicit flow estimation $U(Q_2)/Q_2$ is for Case A1: this happens just because the sought flow rate Q_2 is calculated directly from the balance equation; differently, for cases B and C, flow rate Q_2 comes from energy conservation equation together with balance equation, with four measured quantities (and their own uncertainties) involved. But, on the other hand, flow probes are generally much more expensive than temperatures sensors; for this reason, Case B and Case C can be significantly less expensive than Case A, as they require just one flow probe instead of the two required in Case A. With reference to relative uncertainty of illicit flow temperature, Case A1 has the greatest uncertainty $U(T_2)$, since it is not measured directly in the field, while Case B1 and Case C1 have the smallest one, since T_2 temperatures are measured in the field in both of these cases. In conclusion, taking apart the operational aspects related to installation and running in each specific site, Case B1 could be seen as a kind of compromise in terms of cost-benefits, requiring a less expensive setup in comparison to Case A1 but having a better efficiency in comparison to Case C1.

3.1.2 Example 2

At first, unknown variables are estimated from measured data through eqns (2) and (3) for Case A1, eqns (7) and (8) for Case B1 and eqns (13) and (14) for Case C1:

Case A2: $Q_1 = 50$ l/s, $Q_3 = 60$ l/s, $T_1 = 20°C$, $T_3 = 18°C$ → $Q_2 = 10$ l/s, $T_2 = 8°C$
Case B2: $Q_3 = 100$ l/s, $T_1 = 23°C$, $T_2 = 30°C$, $T_3 = 25°C$ → $Q_1 = 71.4$ l/s, $Q_2 = 28.6$ l/s
Case C2: $Q_1 = 71.4$ l/s, $T_1 = 23°C$, $T_2 = 30°C$, $T_3 = 25°C$ → $Q_2 = 28.6$ l/s, $Q_3 = 100$ l/s

Then, through eqns (5) and (6) or simply starting from assumed uncertainties, relative uncertainties of Q_2 and T_2 in the three cases A2, B2 and C2 are estimated in Table 2.

Graphical results for Cases A2, B2 and C2, for assumed uncertainties of flow rates and temperatures equal to $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$, are shown in Figs 5–7.

Table 2: Assumed and calculated uncertainties of illicit flow rate and temperature in Example 2.

Case	Assumed uncertainties	Calculated relative uncertainty $U(Q_2)/Q_2$	Calculated relative uncertainty $U(T_2)/T_2$
A2	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	39%	111%
	$U(Q_i) = 10\%$; $U(T_i) = 1°C$	78%	222%
B2	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	32%	2%
	$U(Q_i) = 10\%$; $U(T_i) = 0.5°C$	64%	3%
C2	$U(Q_i) = 5\%$; $U(T_i) = 0.5°C$	44%	2%
	$U(Q_i) = 10\%$; $U(T_i) = 1°C$	89%	3%

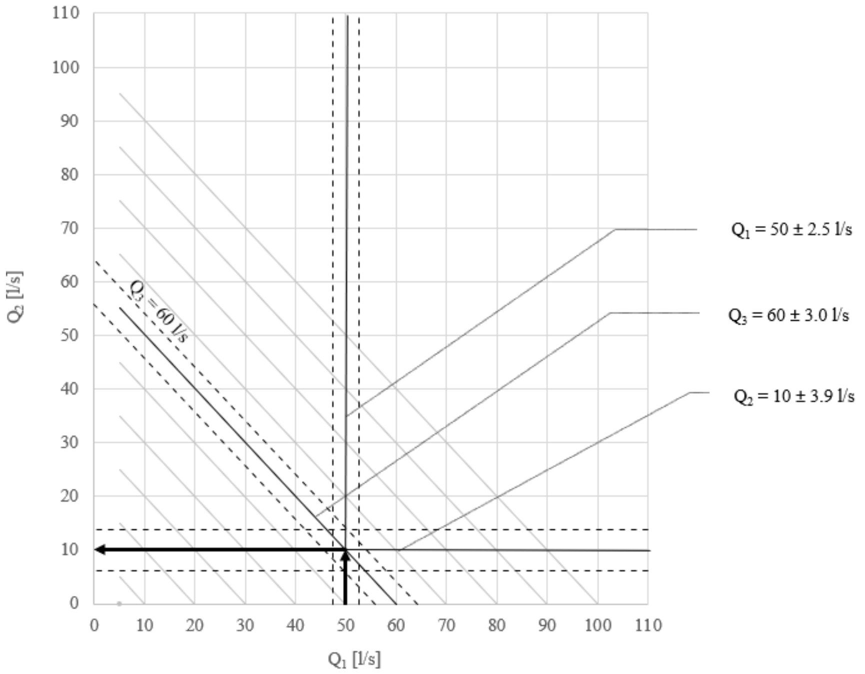

Figure 5: Graphical representation of Case A2 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

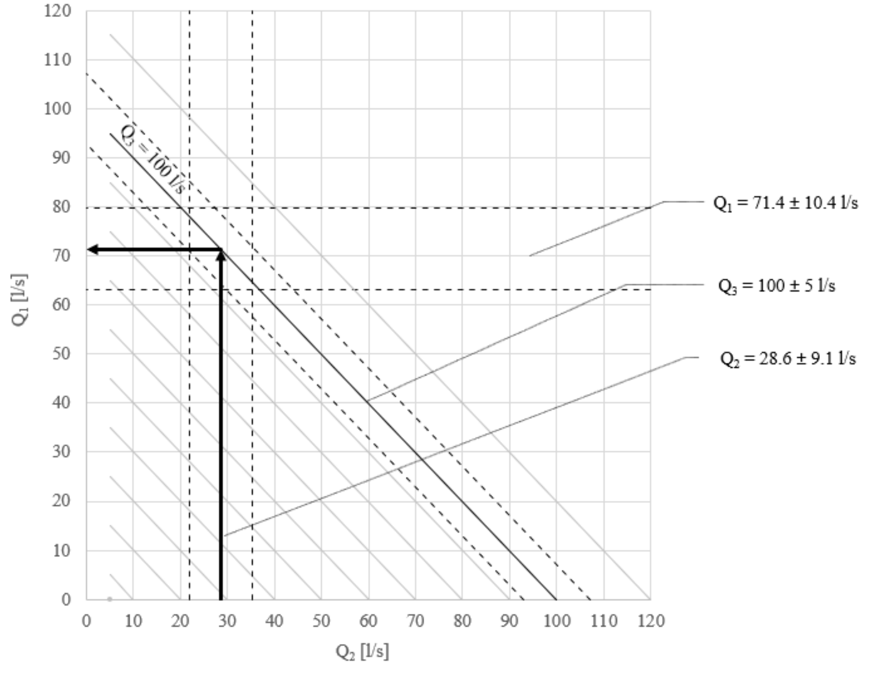

Figure 6: Graphical representation of Case B2 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

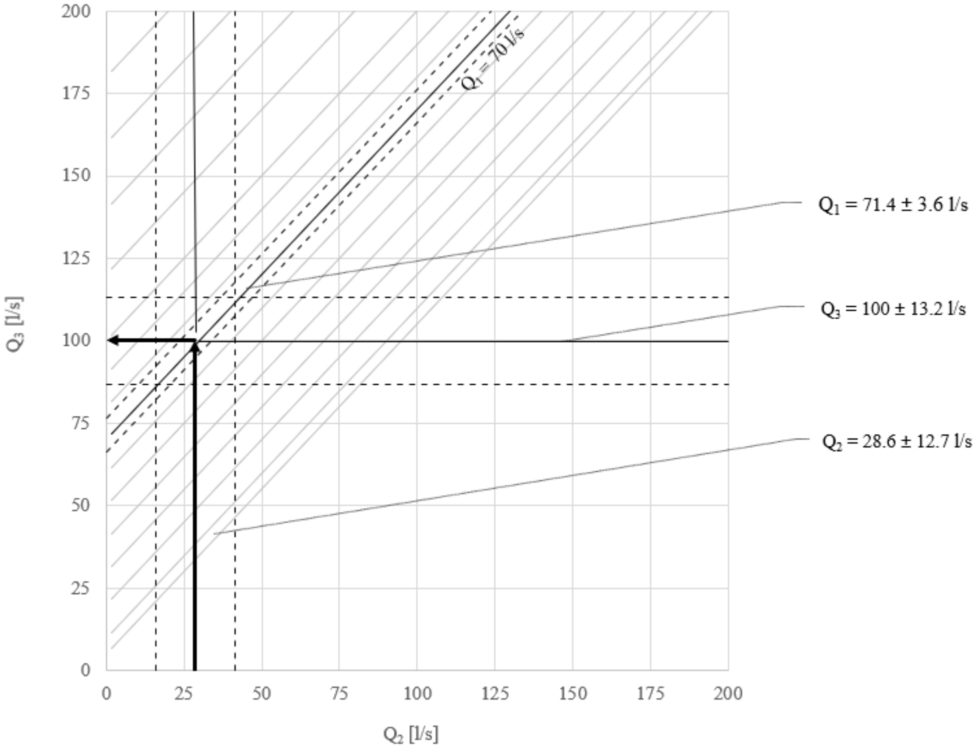

Figure 7: Graphical representation of Case C2 with $U(Q_i) = 5\%$ and $U(T_i) = 0.5°C$.

According to Table 2, Case B2 turns out to be, although slightly, the most suitable, having the lowest relative uncertainty concerning both flow rates and temperatures. Another key outcome is that relative uncertainties of flow rates and temperatures are systematically much higher in comparison with those of Example 1 reported in Table 1; this means that, for a given case (no matter if Case A, Case B or Case C), when illicit flow Q_2 and upstream flow Q_1 are not too different then the resulting relative uncertainties are lower than what they are when Q_2 is quite (or much) smaller than Q_1.

4 CONCLUSIONS

This paper is meant to offer a support to operators involved in planning and executing field surveys for the estimation of illicit inflows in sewers in steady conditions. As a matter of fact, this paper has described the mathematical procedures required to estimate both illicit flows and their temperatures by means of a proper set of temperature sensors and flow probes. It has also provided a detailed description of the mathematical procedures to assess the uncertainty of these estimated illicit flow rates and temperatures.

In addition, the numerical examples developed for the three typical cases of practical interest has pointed out that the more the illicit flows and the sewer flow are different, the less it is possible to estimate them in a reliable way. It has also emerged that when just one single flow probe is available for the field survey and the suspected connection is not accessible, to minimize the uncertainty on the illicit flow estimation it is better to place the available flow probe upstream instead of downstream the sewer trunk under investigation.

REFERENCES

[1] Becciu, G. & Paoletti, A., Random characteristics of runoff coefficient in urban catchments. *Water Science and Technology*, **36**, pp. 39–44, 1997.

[2] Becciu, G. & Raimondi, A., Probabilistic analysis of spills from stormwater detention facilities. *WIT Transactions on the Built Environment*, vol. 139, WIT Press: Southampton and Boston, pp. 159–170, 2014. DOI: 10.2495/UW140141.

[3] Becciu, G. & Raimondi, A., Probabilistic analysis of the retention time in stormwater detention facilities. *Procedia Engineering*, **119**(1), pp. 1299–1307, 2015. DOI: 10.1016/j.proeng.2015.08.951.

[4] Becciu, G. & Raimondi, A., Probabilistic modeling of the efficiency of a stormwater detention facility. *International Journal of Sustainable Development and Planning*, **10**(6), pp. 795–805, 2015. DOI: 10.2495/SDP-V10-N6-795-805.

[5] Raimondi, A. & Becciu, G., On pre-filling probability of flood control detention facilities. *Urban Water Journal*, **12**(4), pp. 344–351, 2015. DOI: 10.1080/1573062X.2014.901398.

[6] Raimondi, A. & Becciu, G., On the efficiency of stormwater detention tanks in pollutant removal. *International Journal of Sustainable Development and Planning,* **12**(1), pp. 144–154, 2017. DOI: 10.2495/SDP-V12-N1-144-154.

[7] Marchioni, M. & Becciu, G., Experimental results on permeable pavements in urban areas: A synthetic review. *International Journal of Sustainable Development and Planning*, **10**(6), pp. 806–817, 2015.

[8] Becciu, G., Raimondi, A. & Dresti, C., Semi-probabilistic design of rainwater tanks: A case study in Northern Italy. *Urban Water Journal*, **15**(3), pp. 192–199, 2018. DOI: 10.1080/1573062X.2016.1148177.

[9] Raimondi, A. & Becciu, G., Probabilistic modeling of rainwater tanks. *Procedia Engineering,* **89**, pp. 1493–1499, 2014. DOI: 10.1016/j.proeng.2014.11.437.

[10] Raimondi, A. & Becciu, G., Probabilistic design of multi-use rainwater tanks. *Procedia Engineering*, **70**, pp. 1391–1400, 2014. DOI: 10.1016/j.proeng.2014.02.154.

[11] Butler, D. & Davies, J., *Urban Drainage*, CRC Press, 2004.

[12] Hoes, O.A.C., Schilperoort, R.P.S., Luxemburg, W.M.J., Clemens, F.H.L.R. & Van de Giesen, N.C., Locating illicit connections in storm water sewers using fibre-optic distributed temperature sensing. *Water Research*, **43**, pp. 5187–5197, 2009.

[13] Lepot, M., Makris, K.F. & Clemens, F.H.L.R., Detection and quantification of lateral, illicit connections and infiltration in sewers with Infra-Red camera: Conclusions after a wide experimental plan. *Water Research*, **122**, pp. 678–691, 2017.

[14] Nienhuis, J., de Haan, C., Langeveld, J., Klootwijk, M. & Clemens, F.H.L.R., Assessment of detection limits of fiber-optic distributed temperature sensing for detection of illicit connections. *Water Science and Technology*, **67**(12), pp. 2712–2718, 2013.

[15] Schilperoort, R.P.S., Gruber, G., Flamink, C.M.L., Clemens, F.H.L.R. & van der Graaf, J.H.M.H., Temperature and conductivity as control parameters for pollution-based real-time control. *Water Science and Technology*, **54**(11–12), pp. 257–263, 2006.

[16] Panasiuk, O., Hedström, A., Marsalek, J., Ashley, R.M. & Viklander, M., Contamination of storm water by wastewater: A review of detection method. *Journal of Environmental Management*, **152**, pp. 241–250, 2015.

[17] Beheshti, M. & Saegrov, S., Detection of extraneous water ingress into the sewer system using tandem methods: A case study in Trondheim city. *Water Science and Technology*, **79**, pp. 231–239, 2019.

[18] Lazzarin, A., Orsi, E. & Sanfilippo, U., A statistical analysis on experimental calibration data for flowmeters in pressure pipes. *Journal of Physics Conference Series*, **882**, 2017. DOI: 10.1088/1742-6596/882/1/012015.
[19] Beheshti, M. & Saegrov, S., Quantification assessment of extraneous water infiltration and inflow by analysis of the thermal behaviour of the sewer network. *Water,* **10**, pp. 1070–1087, 2018.
[20] Schilperoort, P.S. &. Clemens, F.H.L.R., Fibre-optic distributed temperature sensing in combined sewer systems. *Water Science and Technology*, **60**(5), pp. 1127–34, 2009.
[21] Schmid, B.H., Innocenti, I. & Sanfilippo, U., Characterizing solute transport with transient storage across a range of flow rates: The evidence of repeated tracer experiments in Austrian and Italian streams. *Advances in Water Resources*, **33**(11), pp. 1340–1346, 2010. DOI: 10.1016/j.advwatres.2010.06.001.