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Enhancing hydraulic data reliability in sewers

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ABSTRACT

Recently, water utilities have been making considerable investments in sewers' monitoring; however, in most cases, assuring data reliability is yet a challenge. Often, hydraulic data is collected in sewers overlooking best practice aspects. Assuming confidence in data, while disregarding cautions verifications, might lead to inadequate uses of data. The paper presents a methodology aiming to narrow the gap between science and industry, regarding monitoring programs in urban drainage. A procedure to enhance hydraulic data reliability, in line with ISO/IEC 17025:2017, was developed, applied and validated, enabling a final evaluation on data and site adequacy and an overall identification of improvement opportunities. The availability of a valuable case study comprising 32 flowmeters from Portuguese utilities, in eastern Europe, presented an opportunity to create a story line, test the procedure's coherence, present it to the technical community and evaluate the constraints that utilities, in their everyday working context, are faced with. The procedure is presented in detail and a collection of examples of its application is shown. In the final evaluation, most monitoring stations' alignment with best practice requirements were either high (25%) or acceptable (44%), regarding their overall performance and compliance with both data and site adequacy. For all of them, improvement opportunities were identified.

Key words: data, hydraulic, monitoring, procedure, reliability, sewer

HIGHLIGHTS

- Assuring data reliability in sewers' monitoring is yet a challenge.
- A procedure to enhance hydraulic data reliability, in line with ISO/IEC 17025:2017, was developed, applied and validated.
- A final evaluation of data and site adequacy is provided.
- Graphical examples of data processing are provided.
- This step-by-step procedure may be readily replicated by other water utilities, enhancing confidence in data.

INTRODUCTION

Recently, water utilities have made considerable investments in sewer systems' monitoring (Yuan *et al.* 2019). Even though detailed guidance on planning and implementing flow surveys is available for a few decades (WRc 1987), only recently has permanent monitoring become more common (Wapug 2017). Monitoring in sewers has evolved significantly, mainly due to technological advances in sensors, instrumentation, online data acquisition, and data analysis tools. However, ensuring data quality is still a challenge (Campisano *et al.* 2013; EPA 2018; Yuan *et al.* 2019). Often, hydraulic measurements in sewers are carried out overlooking preliminary verifications that might contribute to overall data quality. Assuming confidence in such data may lead to using unreliable data, without expressing the associated uncertainty, which may negatively affect the decisions supported on these measurements. Neglecting quality insurance procedures is often due to unfamiliarity with what and how to measure. Frequently, utilities' technicians do not have specific training and skills in hydraulics and metrology and lack awareness of the limitations of each technology. Capacity building in water utilities, and training of personnel on measurement quality issues, is a step forward towards enhancing data reliability in the water sector.

Utilities need to monitor drainage systems for a variety of reasons including technical motivations, contractual obligations, financial, regulatory, or legal requirements. Regardless of the monitoring objectives, there are common requirements: data quality, addressing uncertainty, and assuring adequacy to the objective.

Identifying all possible sources of measurement uncertainty should be the starting point to enhance data quality (Almeida *et al.* 2021).

Data reliability and measurement quality benefit from international standards, namely related to measurement competencies. The ISO/IEC 17025:2017 (ISO 2017) is particularly relevant as it was designed to support accreditation of organizations carrying out measurement activities (for testing and calibration). This standard has two major parts, one on technical requirements (related to resources and processes) and another on management requirements. These requirements support the definition of procedures for evaluating data reliability in sewer hydraulics' monitoring.

ISO (2017) management requirements take into account equipment and software conformity, measurement traceability, maintenance and operational practices, integrity and robustness of the measurement systems (e.g. transduction and communication signals), and data processing.

From a technical point of view, many factors can significantly influence measurement accuracy, including local features such as sewage aggressive characteristics (mechanical and biochemical), confined space environment, low flows, or flow turbulence (WaPug 2017; Almeida *et al.* 2021). Free-surface flow is predominant in sewers, with far from optimal conditions (Bonakdari *et al.* 2007; Campisano *et al.* 2013). Additionally, high flow variability may occur, both in dry and wet weather. Dry weather flows are relatively predictable, whereas rain-derived inflows lead to sudden flow increase, eventually alternating between free-surface and pressure-flow (Almeida *et al.* 2021).

Human resources proficiency is also key to ensure data reliability. Frequently, water utilities struggle with identifying the best practices that ensure data has an appropriate level of confidence. They can benefit from a structured procedure for both internal purposes and outsourcing services.

The paper presents a methodology aiming at narrowing the gap between science and industry regarding monitoring programs in urban drainage. Specifically, a procedure to enhance hydraulic data reliability is developed, applied, and validated, adopting the ISO 17025 standard requirements (ISO 2017), enabling a final evaluation of data and site adequacy, as well as an overall identification of opportunities for improvement by water utilities.

METHODS

Overall description

The proposed methodology aims at the following objectives: (i) contribute to overall data quality and traceability; (ii) determine whether both the site and the data are adequate (to both the monitoring objectives and data intended use); and (iii) identify improvement opportunities to enhance data reliability.

The methodology has three phases, as presented in Figure 1. Phase 1 regards the development of a step-by-step procedure, which is applied in Phase 2, to a group of water utilities. Further on, in Phase 3, validation is made, including an assessment of the methodology's objectives.

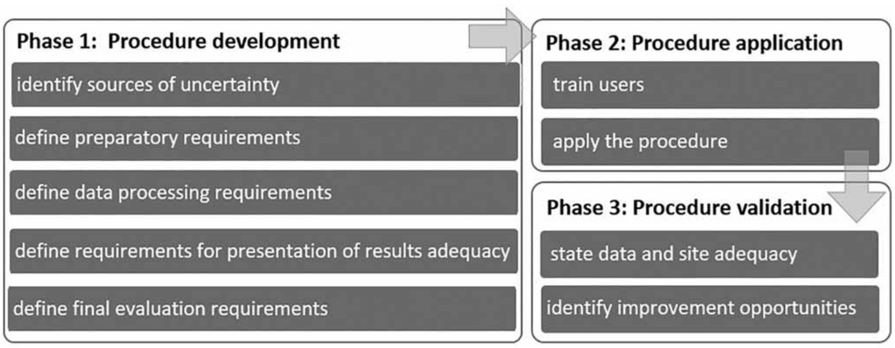

Figure 1 | Methodology to enhance sewer hydraulic data reliability.

Phase 1 – Procedure development

In this phase, a set of criteria is specified, within several steps. This specification is based on ISO (2017) requirements, literature review, and previous experience of the development team. Before starting, *possible sources of uncertainty* are identified. Some are site-specific (technical aspects related to each site and the selected equipment) while others are site-transversal (those that may affect the monitoring system as a whole and are common to several sites).

As a result, procedure development is structured in the following steps: *preparatory requirements*, *data processing*, *presentation of results adequacy*, and *final evaluation*.

Getting into *preparatory requirements*, both the objective of the monitoring program and the intended use of data are the pillars for most subsequent decisions, so should be clearly stated at the beginning. Further on, several management tasks regarding the monitoring system and site characteristics are recognized, mainly addressing the already identified sources of uncertainty.

Data processing refers specifically to the actions triggered after data collection and aims to understand data, detect anomalous situations and explain them (OTHU 2009). It should be based on clear and well-structured rejection and acceptance criteria (Bertrand-Krajewski *et al.* 2000a; OTHU 2009). Decisions should consider context information on the monitoring program, sites, and catchment basins (WAPUG 2017) and its inherent procedures and results must be recorded to allow traceability, process repeatability, and transparency (EPA 2018; Almeida *et al.* 2021). Protocols should be applied to every monitoring site and should regard data collected on the site and also data obtained from neighbouring sites, both for present and historical records (Allit 1999; OTHU 2009; EPA 2018).

Afterward, the requirements for *presentation of results adequacy* are defined, aiming at assessing site and data adequacy to the monitoring objectives and data intended uses, previously defined in preparatory requirements.

The last step involves the definition of requirement regarding the *final evaluation* of the previous steps.

Phase 2 – Application to a study case

A set of monitoring systems are required to apply and validate the procedure. Preferably, selected monitoring systems should be diverse and be real cases managed by water utilities, as the purpose is to develop a procedure for application by water utilities and promote knowledge transfer between researchers and the water industry. A process of knowledge co-creation, involving 'experts' and 'users' is applied (Roux *et al.* 2006), to overcome the difficulties faced by the utilities during the application, while contributing to improving the procedure.

Even if some steps of the procedure had been applied previously (Almeida 1999; Brito 2012; Cardoso *et al.* 2020), the availability of a substantial and valuable study case presents an opportunity to create a storyline, develop a coherent procedure, present it to the technical community, and test it.

This phase has two steps, *training users* on the procedure and *application of the procedure*.

Phase 3 – Procedure validation

Procedure validation includes a wrap-up with a clear statement on *data and site adequacy* before data is made available for further studies or tasks, and with a clear identification of *improvement opportunities*.

STUDY CASE

The development of the procedure was undertaken in collaboration with 19 Portuguese water utilities, representative of the Portuguese reality and in charge of urban water systems of different typology and network extension (between 32 km and 2,180 km for wastewater systems). Among the participants, one utility covers the whole urban water cycle (water supply, wastewater and stormwater drainage, urban streams, and bathing waters). In terms of drainage, the vast majority is responsible only for wastewater service, with five utilities also responsible for stormwater service. Over 2/3 of the utilities are responsible for wastewater collection, and the remaining for wastewater transport and treatment.

All utilities installed at least one rain gauge and flowmeter. In all, 32 flowmeters and 18 rain gauges were included in the study case (see Figure 2). The majority are located near Lisbon, the country's main city.

The flowmeters were installed in pipes with diameters ranging from 200 mm to 3,000 mm. For this sample, flow ranges were quite variable, as shown in Table 1. These sites were mostly designed for free-surface flow; in four sites, electromagnetic equipment was installed to monitor pressurized flow.

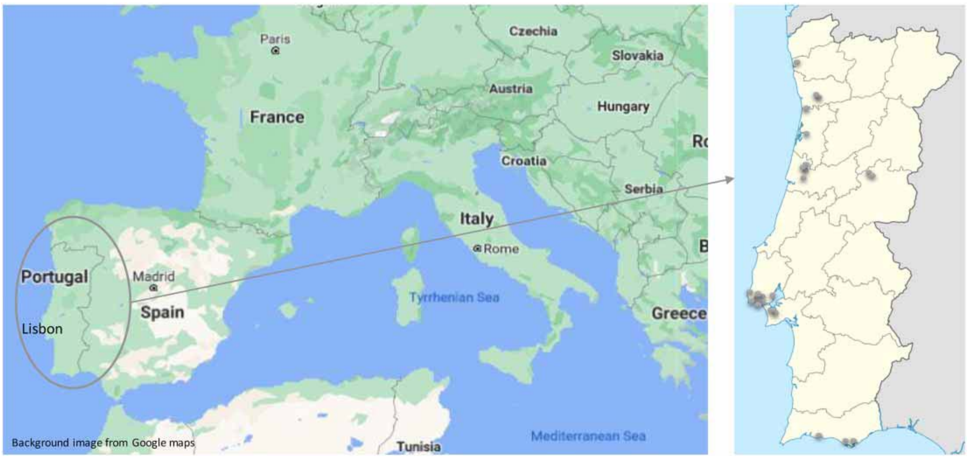

Figure 2 | Location of the flowmeters (•) in the study case.

Table 1 | Statistics on flow in the 32 flowmeters in the study case

	Minimum flow (ls^{-1})	Average flow (ls^{-1})	Peak flow (ls^{-1})
Min	0.8	3.8	21.3
Percentile 25	7.3	16.7	124.1
Percentile 50	17.0	39.7	209.7
Percentile 75	65.3	176.4	1,170.0
Max	555.4	2,768.0	9,071.0

The vast majority of the participants had no previous experience in data monitoring in drainage systems or had only undertaken short-term campaigns, but with minor participation in the process. The main questions raised by the participants were whether they were using data properly, if data was trustworthy and how to increase confidence in data. To some extent, stressing so assertively that 'data reliability starts way before data collection and continues after that' was rather unforeseen for most participants.

These combined conditions make this study case adequate to develop the procedure reported herein. The participants received training regarding implementation of a monitoring program, following the steps in Figure 3 (adapted from Almeida *et al.* 2021).

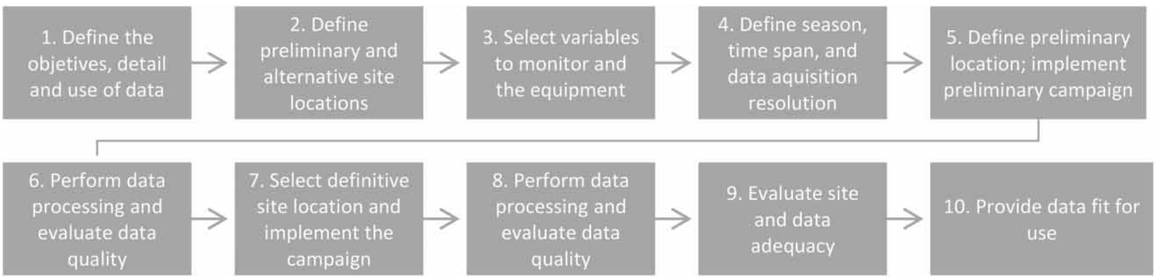

Figure 3 | Monitoring program steps.

Regarding the *objective* of the monitoring programs, all utilities had a technical motivation, aiming at performance assessment. Concerning *use of data*, all utilities were, in a broader sense, targeting undue inflows in the drainage system – but different types of undue inflows. One of the flowmeters was installed in a stormwater system, and the utility was willing to detect sanitary or industrial undue inflows. One flowmeter monitored a combined system. The other 30 flowmeters were installed in the sanitary system and utilities were aiming at other specific undue inflows e.g. infiltration, rainwater inflows, or tidal water.

The selection of the *variables to monitor* depends on the monitoring objectives, on the site's location and hydraulic conditions, on the available equipment, its installation and operation costs, and on the required reliability (Almeida *et al.* 2021). Utilities mostly aimed at hydraulic quantities, for flow characterization (mostly from the measurement of water height and velocity, and some monitored hydrostatic pressure) and precipitation (for characterization of rain events' impact). Some utilities monitored water quality quantities, namely to detect and characterize variations in the water quality matrix (due to industrial or saltwater inflows) and water consumption volume (to address the relationship between wastewater volume and expected sanitary water volume). A few utilities characterized the surrounding water environment, namely by gathering data on tidal height, water quality in local water bodies, and groundwater level using piezometers. One utility had a deeper insight into solid wastes characterization, as solids deposition and sewer blockage were a serious concern.

For hydraulic monitoring in sewers, utilities considered several aspects when *selecting the equipment*, such as quantities to be measured and expected measuring ranges, physical characteristics of the installation site and whether the installations were to be temporary or permanent (Almeida *et al.* 2021).

Overall, different technical solutions were available for hydraulic monitoring. Most sites were equipped with multisensory portable meters (velocity Doppler, hydrostatic pressure, and water height ultrasonic sensors). In a few sites, as referred, electromagnetic flowmeters were installed.

All rain gauges installed were tipping bucket type.

For the *preliminary location* of the sites, the manufacturer's technical specifications were available for most equipment solutions. The equipment's internal safety (given e.g. the occurrence of pressurized flow), presence of explosive gases, and transportation of large solids, were taken into account. The location of a sensor in the pipe, either regarding its longitudinal or cross-sectional reference was also important, as accuracy often depends on this geometry (Mignot *et al.* 2012). A straight upstream pipe, without singularities, away from any bend or elbow, obstacle, confluence, or flow distribution device, is advisable. However, sometimes even when fulfilling the equipment's technical specifications, the site may be proven inadequate, which reflects on data quality. To overcome this, several supporting recommendations were made to the utilities for selecting preliminary site locations, regarding, among others: conditions of access to and inside the manhole; adequacy of hydraulic and environmental conditions; historical operation and maintenance records (Almeida *et al.* 2021).

During procedure application, other actions supported the utilities' monitoring programs, such as:

– methodological guidelines were established;
– equipment and sites' selection were supervised and the teams were trained to verify installation conditions;
– audits were undertaken (one audit per utility);
– documentation produced by the utilities was reviewed and improvement opportunities were continuously identified; and
– access to software tools, to support data processing, was provided.

PROCEDURE DEVELOPMENT

Sources of uncertainties in urban drainage hydraulic monitoring

A lower value of measurement uncertainty contributes to higher confidence in the monitoring process. Measurement uncertainty is sometimes confused with the uncertainty of the measuring equipment. The latter is only one of the contributions, and sometimes not the most meaningful. As mentioned, sensors in sewers are located in an aggressive environment; data is transmitted through an equipment chain and the original value of the variable can be corrupted.

According to USBR (2001), an accuracy of around 10% was considered acceptable in sewers given the difficulty of achieving good installation conditions. Bertrand-Krajewski *et al.* (2000b) report that in France a standard uncertainty of 50%–100% was frequent. Harmel *et al.* (2006) point out a moving layer of sediments as the main contribution to uncertainty in flow measurement. Yen *et al.* (2015) illustrate how measurement uncertainty in data can propagate to uncertainty on output results. Ribeiro *et al.* (2009) carried out the evaluation of standard uncertainty in multisensory measurement, based on water height and velocity, with flow determined by the Continuity equation (Equation (1)) as around 230 litre per second (ls^{-1}). Uncertainty values were reported between 6.5% and 11.0% (Ribeiro *et al.* 2009). Bertrand-Krajewski *et al.* (2000a) carried out uncertainty propagation to evaluate the expanded uncertainty in free-surface flow. This was done for pipe diameters over 1.0 m, with uniform flow and variable pipe roughness, based on Equations (1) or (2), the Gauckler-Manning-Strickler equation. For comparison between different pipe diameters, the water height (h) was divided by the pipe's diameter (D); expanded uncertainty was evaluated for given dimensionless relative water heights (h/D). The expanded uncertainty stabilized, for a relative water height above 0.25, in 18% for Equation (1), and at 15% for Equation (2).

$$F = S\,(h) \cdot U \tag{1}$$

$$F = K_S\,(h) \cdot S\,(h) \cdot R_h(h)^{\frac{2}{3}} \cdot J^{\frac{1}{2}} \tag{2}$$

where F: flow (cubic meter per second, m^3s^{-1}), S: flow section area (square meter, m^2), h: water height (meter, m), U: average flow velocity (meter per second, ms^{-1}), K_s: roughness coefficient (meter cubic root per second, $m^{1/3}s^{-1}$), R_h: hydraulic radius (m), J: unitary hydraulic head loss (-).

Henriques *et al.* (2007) also evaluated uncertainty propagation in flow measurement with an electromagnetic meter in free-surface flow. For instance, for a flow rate of 10 ls^{-1}, a 5% expanded uncertainty was obtained.

Harmel *et al.* (2006) presented an analysis of uncertainty propagation in small hydrographic basins related to, among others, flow measurement. The authors carried out an extensive bibliographic review on the procedures commonly associated with each source of uncertainty. Only uncertainty associated with data processing was not considered. Three scenarios were identified: I – best possible scenario; II – typical scenario; III – worst-case scenario.

Scenario I represented a chain of procedures with high-quality control, without financial or technical resources restrictions and ideal hydrological conditions. On the opposite, scenario III refers to a chain of procedures with low-quality control, significant resource constraints, and adverse hydrological conditions. In scenario I, velocity and water height measurements were taken at various cross-sectional points, in dry weather, in a pre-calibrated structure, and subject to periodic calibrations. A 3% standard uncertainty was obtained.

Scenario II corresponds to a situation of flow measurements in a small river basin, with a stable uniform cross-section and upstream reach, with a moderate effort in quality assurance and control. Standard uncertainties were reported between 6 and 19%.

In scenario III, Equation (2) was used, based on a single water height measurement in a sewer with a moving sediment layer and variable cross-section. A 42% standard uncertainty was obtained.

Monitoring conditions in sewers with stormwater flows (either combined, separate stormwater or separate sanitary sewers with undue connections) may be compared with those described by Harmel *et al.* (2006) in scenarios II and III.

Several sources of uncertainty are reported (Bertrand-Krajewski *et al.* 2000a; Bonakdari *et al.* 2007; JCGM 2008; Campisano *et al.* 2013; ISO 2017; WaPug 2017; Almeida *et al.* 2021). The most relevant are:

– questionable equipment selection, equipment uncertainties, and calibration uncertainties;
– inadequate method for calculating flow;
– measurement environment such as the presence of solids, physical and biochemical conditions;
– unsuitable sensor installation;
– absence of a pre-campaign or inadequate campaign representativeness;
– unfit technical skills in hydraulics, electronics, computing, and metrology;
– undocumented or improper equipment maintenance and data processing; and
– absence of document management and traceability.

Determination of uncertainty is a not common practice in urban drainage monitoring. Since it is not an easy task, identification of major sources of uncertainty contributes to raising awareness of the problem and motivates monitoring teams to tackle each of the identified sources to minimize its contribution, and enhancing data quality.

Preparatory requirements

Preparatory requirements consist of checking whether identification and control of site and system characteristics were made. It consists of confirming if steps 1 to 5 of Figure 3 were adequately undertaken, and if, within this process, the identified sources of uncertainty were minimized.

In alignment with ISO (2017), the following criteria were detailed in Almeida *et al.* (2021): *objectives and use of data; document management and traceability; human resources; influencing conditions* (including context information and pre-campaign implementation)*; methods definition* (for hydraulic calculations, data processing, equipment installation, and maintenance)*; equipment characterization, suitability and installation requirements; sampling representativeness* (identification of expected patterns, sampling interval, campaign duration and time of the year, and synchronisation of records).

Most criteria focus on individual monitoring sites, but some are site-transversal. This is the case of *document management* and *human resources*. Regarding *methods*, some aspects are site-specific, others are site-transversal.

Regarding *sampling representativeness,* sampling interval, campaign duration and time of the year have to be identified and their adequacy to the phenomena under observation ought to be verified (Almeida *et al.* 2021).

For the *sampling interval*, for hydraulic variables in the sewer, a recommendation was made for a data acquisition interval of at least 5 minutes. As for precipitation, the tipping occurrence ought to be registered with a resolution below 1 second.

Moreover, in sewer monitoring, it is important to know whether data was collected in wet or dry weather periods. However, this distinction should be based not only on precipitation data but also on a correlated analysis with flow data.

Drainage systems receiving rain-derived inflows have variable retention times in the system. This variation increases with the dispersion of contributions in the upstream catchment area. The main sources of rain-derived inflows are direct rainwater connections or groundwater infiltration. Therefore, flow records can deviate significantly from dry weather patterns both during and after a precipitation event. The time-lapsed until the complete hydrograph recession can be significant (Wapug 2017), depending on drainage basin characteristics. On the other hand, if an event with low precipitation volume or duration occurred, rain-derived inflows might not occur. Rainwater may infiltrate or be retained in surface depressions.

Concerning *campaign duration and time of the year*, independent of the objectives, at least three precipitation events ought to be available. To simulate wet weather flows, this number should be higher (WaPug 2017). Although short-term flow surveys are quite common, these have several limitations: extreme precipitation and flooding events may not be registered; dry weather data may not depict seasonality; baseflow variations (rainfall-induced infiltration, in longer wet periods, associated with saturated soils) may not be captured.

A balance must be reached between desired data and existing restrictions (such as seasonal availability and budget constraints).

The recommendation for the participants was for the inclusion of at least 5 wet weather events with different average and maximum intensity, rain volume, and duration. Given the average characteristics of drainage catchments, relevant wet weather events were collected for precipitation intensities greater than 5 mm/h and rain volumes above 5 mm in 30 min periods. A wet weather event included the whole period from the beginning till the end of precipitation plus the recession period of the hydrograph. In some cases, this might comprise several precipitation periods.

In dry weather, foul flows present a daily pattern, repetitive and relatively predictable, closely related to water consumption.

For mathematical modelling, including 2 dry weather days used to be recommended, which could go up to 5 to improve data confidence, or if the dry weather pattern varies (Saul 1997). As referred, this may occur due to base flow variability because of, for example, infiltration, weekly or seasonal variation. Usually, dry weather patterns vary between weekdays and weekends. Socio-economic characteristics, basin occupation, and the type of prevailing economic activities also interfere with the pattern (Enfinger & Stevens 2007; Loureiro *et al.* 2015).

Within the study case, identification of dry weather patterns was carried out using flow data in periods without rainfall and after complete hydrograph recession (after precipitation) had occurred. Since there was considerable variability throughout the year and throughout the week, data was separated as dry season and wet season, weekdays and weekend days, as recommended by Enfinger & Stevens (2007). A recommendation was made for the inclusion of at least 15 dry weather weekdays (for an expected pattern for working days), 10 dry weather weekend days (for a weekend or holiday pattern), and of a 1-year record if identification of seasonal variations in dry weather were sought. Depending on the drainage catchments' characteristics, these minimum periods could be extended.

Data processing

Data processing integrates the *preliminary assessment*, *analysis and validation,* and quantification of *validated data*. Figure 4 indicates the features within each criterion.

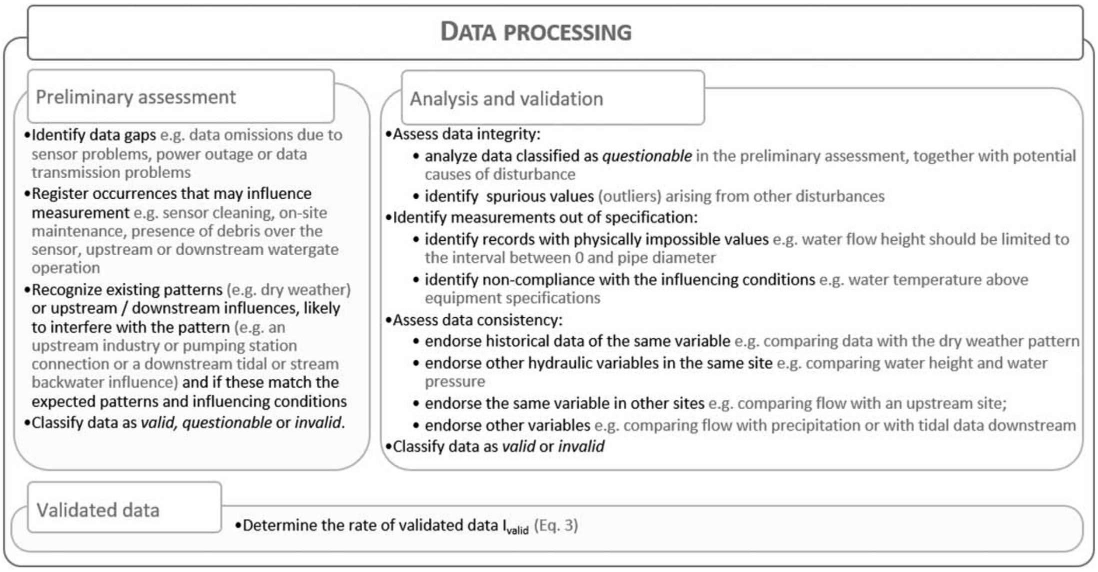

Figure 4 | Criteria regarding data processing.

Within data *preliminary assessment*, a global overview on data is made, mainly to acknowledge existing data (i.e., expected records within the collected data) and the circumstances that might explain data variation. After *preliminary assessment*, only data claified as questionable or valid proceed.

Data *analysis and validation* consist of the interpretation and approval of data based on complementary information. Training was made; for example, on outlier analysis and the interpretation of upstream and downstream influence on flow data. To support *data consistency* assessment, specific tools (for processing precipitation data, identifying wet weather events, and determining dry weather flow patterns) were developed to analyse collected data and, when available, historical data.

After *analysis and validation*, only data classified as *valid* is available for further uses (i.e., validated data). Such availability is assessed by the *rate of validated data* I_{valid} (Equation (3)):

$$I_{valid}\ (\%) = \frac{\text{number of records within validated data}}{\text{number of expected records within collected data}}. \quad (3)$$

Presentation of results adequacy

With *presentation of results adequacy*, overall outcomes appropriateness is assessed, for each measurement site, by assessing *site suitability* towards the measurement objectives and validated *data suitability* for the data uses defined in the project.

Figure 5 specifies the items to go through within these criteria (Almeida *et al.* 2021).

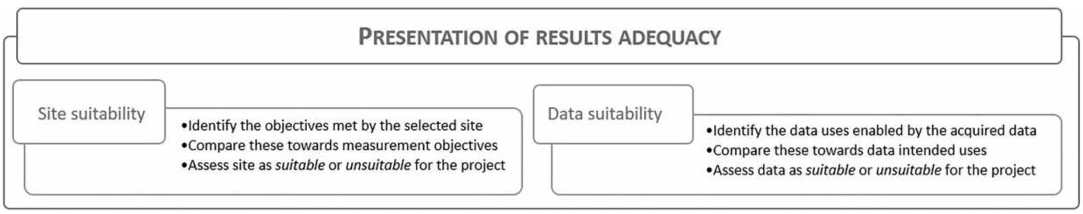

Figure 5 | Criteria regarding presentation of results.

Final evaluation

Final evaluation consists of assessing the alignment between the sites' results and the criteria within the previous steps. This alignment is classified as *high*, *acceptable,* or *reduced*, regarding overall performance and compliance with both data and site adequacy.

Utilities should assess the performance levels for each monitoring site and the whole monitoring system. It should be weighted whether the worst-rated criteria are correctable or not. In the first case, the monitoring campaign might be extended (e.g. if the equipment was not properly maintained, or if sampling was inadequate). In the second, the equipment should be re-installed or relocated and data should either be rejected or be classified as appropriate to other uses, but not for the intended uses in the project.

Each monitoring station is finally assessed as a whole, considering simultaneously site and data suitability and the larger context given by the monitoring system.

RESULTS AND DISCUSSION

Utilities within the study case applied the procedure and determined the performance levels for each criterion. For the vast majority, the sites' location (88%) was considered adequate for the monitoring objectives. However, some of the selected equipment was considered inadequate for the objectives (19%) or was poorly installed or could benefit from minor corrections (22%).

In Figure 6, a few examples of poorly installed sensors are presented.

Figure 6 | Examples of sensors poorly installed in sewers. (a) Sensor in a supporting ring, top of the pipe (b) Sensor in a supporting ring, bottom of the pipe (c) Sensor above the pipe, in the manhole wall.

In Figure 6(a), the supporting ring is placed at the rear end of a pipe, disregarding a minimum distance to the downstream manhole. The sensor is reading water height and velocity in the transition between uniform flow and critical flow, infringing this equipment's measurement principle. Readings ought to be collected in uniform flow. In Figure 6(b), sensor misalignment to the pipe's longitudinal axis is notable. In Figure 6(c), hydraulic conditions disregard manufacturer recommendations and measurement guidelines, which assume the flow is stable. Given sensor positioning in a manhole section receiving two lateral connecting pipes, water surface disturbance is evident.

For almost every site (those that complied with site and equipment adequacy), representative dry weather patterns were studied (78%), mostly both for weekdays and weekends. Representative rain events were identified in most rain gauges (95%), with up to 37 events in one location.

Figure 7 presents two examples of data processing results, namely for preliminary assessment.

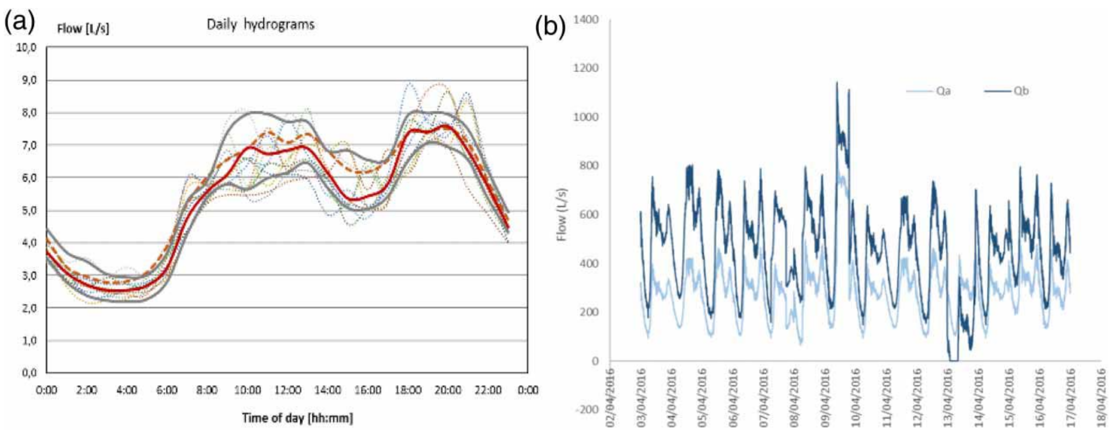

Figure 7 | Examples of data processing results – preliminary assessment. (a) hourly flow for dry weather days, 15-days data (b) 5-min flow upstream (light blue) and downstream (dark blue), 2-weeks data.

Figure 7(a) presents the daily pattern for dry weather flow in one flowmeter. In grey, the limiting 25- and 75-percentiles for hourly data are presented; in continuous red, the hourly median flow; in dashed red, the average flow; in several colours, the hourly data for the several dry weather days under study. As expected, the dry weather flow pattern is very similar to a common water supply pattern. Flow is lower in night hours, ascends in the morning to a daily peak, and then again in the evening for another peak. This recognition of existing patterns allows for a comparison with expected patterns.

Figure 7(b) presents data from two flowmeters installed in sewers in the same drainage basin. Flow coming from the upstream flowmeter (light blue) is transported along the sewer, which receives several connections on the way, and passes through the downstream flowmeter (dark blue). Flow records are expected to be parallel in time, as the contributions through the day are similar but higher in the downstream flowmeter. The expected almost parallel progress in time is only interrupted on the 13th of April. The utility confirmed with its operational records that a discharge had occurred between the two sites. This verification allowed explaining and accepting of data for that day.

In Figure 8, a few examples of data processing results are presented, namely for analysis and validation criteria.

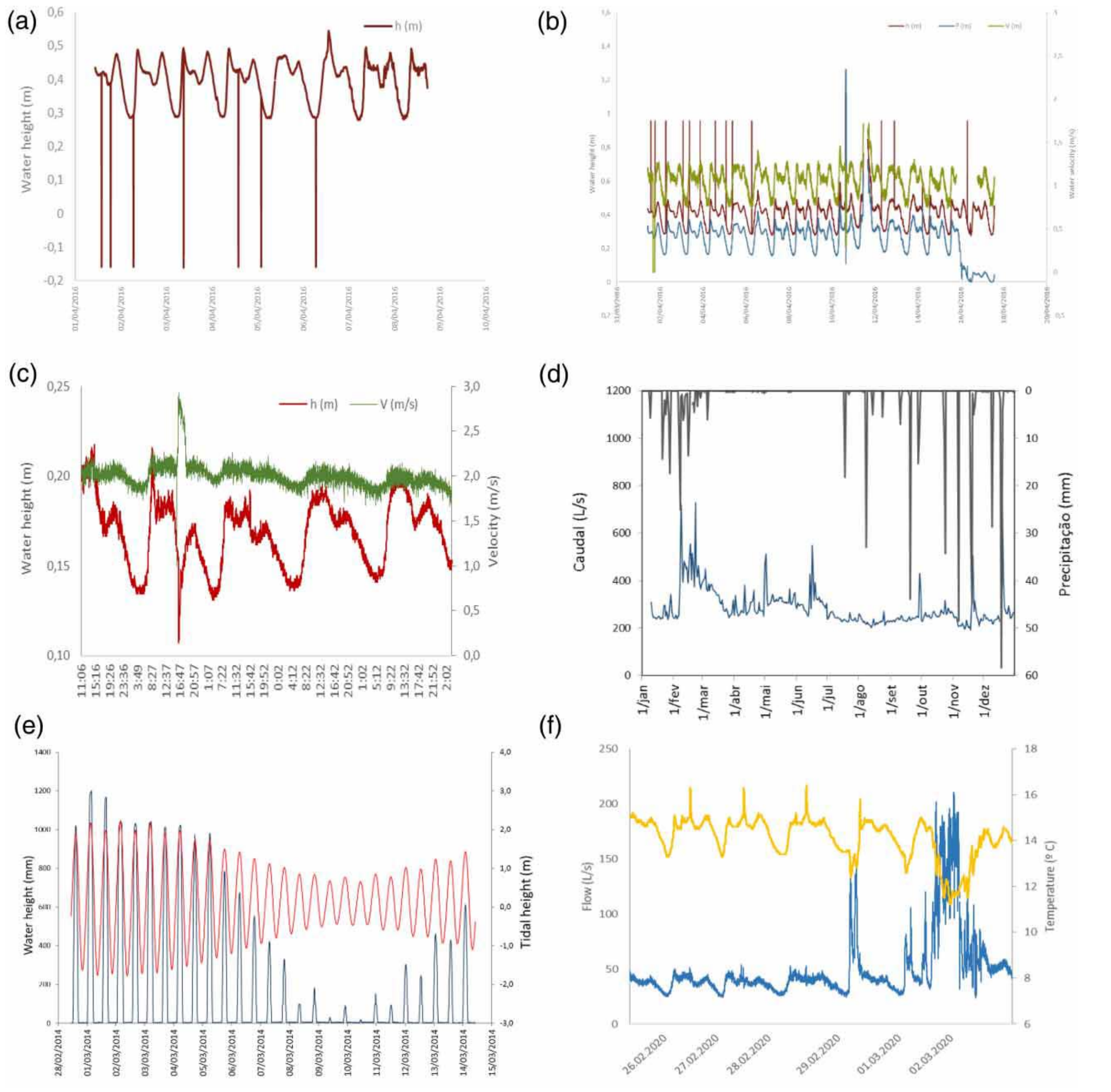

Figure 8 | Examples of data processing results – analysis and validation. (a) 3-min average water height given by an ultrasonic sensor, 1-week data (b) 5-min average velocity (green) and water height given by an ultrasonic (red) and a pressure sensor (blue), 18-days data. (c) 1-min average velocity (green) and water height given by an ultrasonic sensor (red), 5-days data. (d) Daily flow (blue) and precipitation (grey), 1-year data. (e) Hourly water (blue) and tidal (red) height, 2-weeks data (f) 1-min flow (blue) and water temperature (yellow), 1-week data.

In Figure 8(a), water height data presented some erroneous readings. Measurements were out of specification: water height should be limited to the interval between 0 and the pipe diameter, and negative values are physically impossible. These occasional records were rejected.

In Figure 8(b), the results in a multisensory flowmeter are presented: the water height given by two sensors (ultrasonic and pressure sensors) on the left axis and the water velocity on the right axis. Some erroneous readings are perceived in the ultrasonic water height, as those did not occur in the pressure readings. A data gap occurred in velocity so, for this time frame, the flow had to be calculated using the Manning-Strickler equation (Equation (2), which requires only water height data) instead of the continuity equation (Equation (1), which requires both water height and velocity data). A diversion in pressure sensor readings, towards the last day, is evident when compared with the other two sensors. The pressure sensor's operational conditions had to be checked.

Figure 8(c) presents results from another multisensory flowmeter: the water height on the left axis and the water velocity (on the right axis). On the second day, an unexpected diversion from the pattern occurred: water height suddenly dropped, while velocity suddenly increased. This might be explained by the occurrence of an upstream partial blockage that was later washed off. Data was accepted and the occurrence was later confirmed by the operational team.

In Figure 8(d), 1-year daily flow (in the left axis) and precipitation data (in the right axis in reverse order) are presented. The flow meter was installed in a sanitary sewer, which is designed to transport only flow from internal household, commercial or industrial connections, and not from stormwater connections. It is evident that there is an unexpected inflow increase during and after rain events. This was probably coming from undue rainwater connections or infiltration.

In Figure 8(e), changes in water height in a pipe presented a cyclical pattern in a few days' time windows, which was not explained by any of the variables the utility was already monitoring. Being installed in a coastal area, the comparison with tidal height demonstrated a connection between the two, which was a sign of undue coastal water inflows.

In Figure 8(f), this very detailed flow and water temperature data also illustrates how comparing different variables permits interpreting a deviation in flow records. Records were mostly parallel during dry weather. However, water temperature drops significantly when the flow rises suddenly, due to the entrance of a colder flow. This may be a sign of undue stormwater connections, as wastewater is usually warmer than rain.

Endorsing other variables, in addition to hydraulic and water quality variables, can allow for deeper analysis in the data processing. For example, after determining the dry weather pattern, an average daily flow per capita may be calculated. Comparing such results with the design specifications (of the sewers upstream the monitoring section) allows flagging monitoring frailties previously undetected or unexpected inflows (either higher or lower). In the study case (for the sub-sample of six sites for which the contributing population equivalent was available), dry weather average daily flow per capita ranged from 114 to 174 litres/inhabitant/day. This range is quite aligned with Portuguese average per capita values.

Utilities were able to complete data processing on most sites (88%). As an example, Figure 9 presents an excerpt of a monitoring report, where performance levels on *preparatory requirements* are presented by a utility that was assessing 3 flowmeters. Again, some criteria are site-specific (e.g. equipment) while others are site-transversal (e.g. human resources).

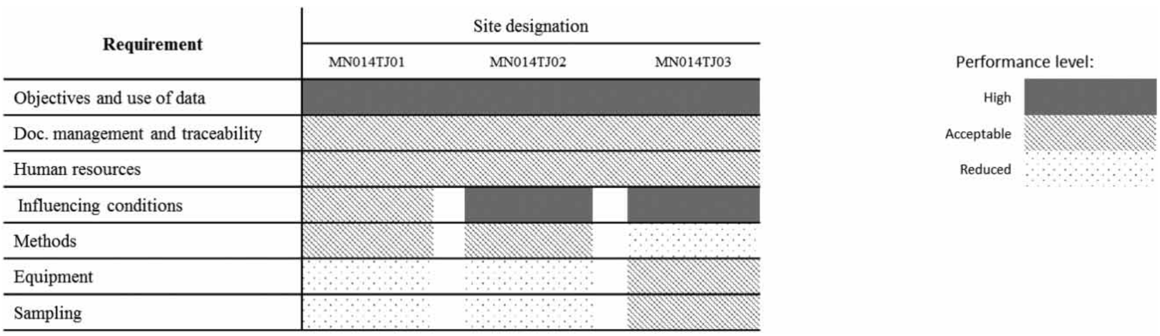

Figure 9 | Final evaluation on preparatory requirements (example from one utility).

Figure 10 displays an overview of performance levels assigned to all monitoring sites in the study case. For each requirement, the percentages of sites with a high, acceptable, and reduced performance level are presented.

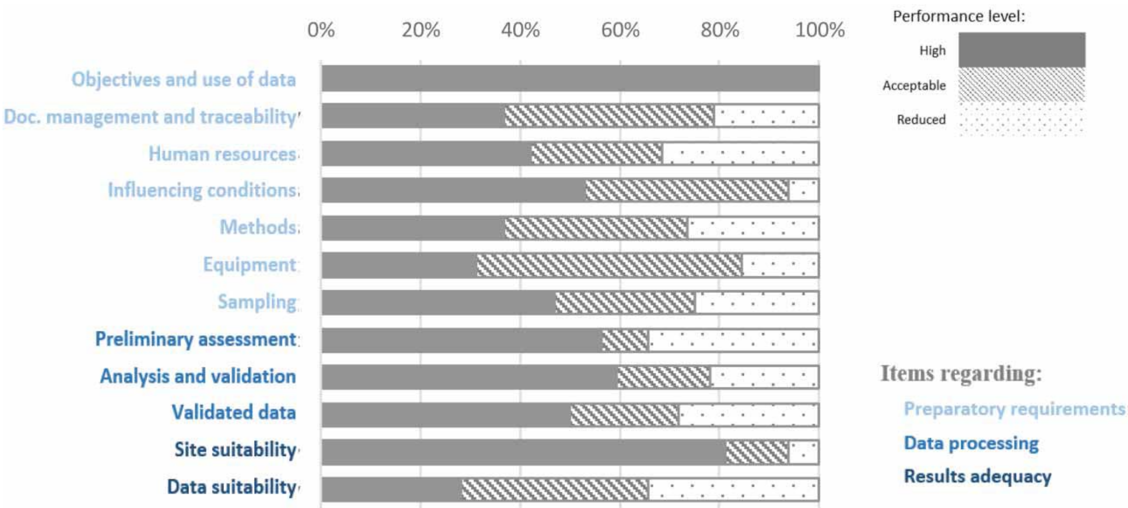

Figure 10 | Performance levels for all monitoring sites.

Overall, the declaration of *objectives and use of data* were considered *high* level for all the sites. Human resources were considered *high* level for 42% of the utilities and an additional 26% considered this criterion *acceptable*. For most sites, the majority of the criteria within preparatory requirements were classified between *acceptable* and *high* level (68%–100%).

Criteria within data processing had very similar *high* level results (50%–59%).

Within results adequacy, most sites were considered *high* level (81%), but the same did not occur for *data suitability*, with only 28% *high* level sites, and only 66% either *high* or *acceptable*.

Each monitoring station was also assessed as a whole, considering simultaneously site and data suitability. All in all, most sites were considered high level, but the same did not occur for data suitability. Most monitoring stations' alignments with best-practice requirement were either *high* (25%) or *acceptable* (44%), and the analysis of the performance levels allowed the identification of improvement opportunities. In Allit (1999), about 50% to 70% of measurement sites were technically unacceptable, mostly due to: the absence of qualified technical personnel; the non-implementation of pre-campaigns; inadequate installation; failure to comply with the maintenance protocol. Specific aspects within each criterion were targeted, analysed, and discussed with the utilities, and specific improvement opportunities were identified.

Among the 32 flowmeters, two had a final recommendation for uninstalling and nine for minor installation corrections. For the 14 sites with an *acceptable* performance level, seven could upgrade to *high* level if the utilities improved their *preparatory requirements*. For most sites with a *reduced* performance level (10 in total), it is necessary to improve site suitability and equipment selection and installation.

Besides that, some utilities have to work on preparatory requirements (mostly in human resources) or inadequate sampling (mostly by assuring campaign representativeness of both dry and wet weather).

Before going through the final evaluation, utilities were questioned about the main obstacles to overcome they already perceived:

- lack of human resources (95% of the utilities) or of specific qualifications (85%);
- concerns when choosing the right equipment for specific hydraulic variables (85%); and
- absence of internal operational (77%) or maintenance procedures (77%).

These are in line with the overall acknowledgment made on the results, after the complete application of the procedure.

Additional constraints include the lack of a detailed procedure for equipment installation and of technical background to identify the methods to determine derived variables in data processing (e.g. how the flow will be determined from water height measurements), which would also help utilities to better understand if they're choosing the right equipment and if it is properly installed.

The need to improve data traceability was also clear, mainly through centralized access to data and the documented communication with service providers.

To acknowledge the benefit of applying the procedure, a simulation exercise on the performance levels was done in the case scenario 'what would the final evaluation be if the utilities had not applied the procedure?'. The obtained results were self-evident: only 9% of the sites would have been *high* level sites, 41% *acceptable* and 50% would have been of a *reduced* performance level. This starting point partially justifies the obtained performance levels, and there is still a long path to go before they all upgrade to *high* level results.

Nevertheless, the results are reassuring. Capacity building stood out as a lever for improving data reliability. The utilities within the study case are mostly small or medium-size utilities with general financial constraints. A large majority, before entering the process, were only familiar with the one-off aspects of preparatory requirements, had virtually no data processing capabilities, and no ability to perform determination of results adequacy. Typically, in the beginning, they showed too much confidence in data without any prior verification. Even so, the progress shown by the teams involved was noteworthy. Most of the criteria were met by the utilities and, above all, the aspects to be improved by each one are now clearly identified.

The ISO (2017) standard was found to be quite structuring and goes beyond technical aspects which frequently don't act alone to condition date adequacy, as was evident in the study case. In some utilities, this standard is being adopted in water quality laboratories, so internal articulation of technicians working in the sewer system with colleagues from other departments, who are familiar with management processes, was identified as an opportunity.

CONCLUSIONS

A methodology regarding monitoring programs in urban drainage was presented. Specifically, a procedure to enhance hydraulic data reliability was developed, applied to a study case, and validated. A final evaluation of data and site adequacy was done. Several graphical examples of data processing illustrate the procedure. In the study case, most sites were considered high level (meaning that equipment and manhole selection and sensor installation were mostly well done), but the same did not occur for data suitability (meaning that e.g. sample representativeness or data processing could be improved). In all, alignment with best-practice requirement was either high (25%) or acceptable (44%), and this analysis allowed the identification of improvement opportunities.

Capacity building was proven to be a step forward towards enhancing data reliability.

The authors consider the methodology narrows the gap between science and industry. Knowledge sharing and collaboration with utilities was a tool to improve the procedure. Utilities were involved in the development and compromised with specific actions to enhance data reliability, and the research partner committed with the utilities' needs to take a step forward.

In summary, methodology objectives were met: overall data quality and traceability were improved; both site and collected data adequacy (to monitoring objectives and data intended use) were assessed; and targeted and specific improvement opportunities to enhance data reliability were clearly stated, at the end.

Outputs of this application are currently being used to determine performance metrics by the participating utilities. The results were encouraging. The opportunity to replicate the methodology to other water utilities managing drainage systems and to other contexts within the water community is envisaged, namely to, for example, monitor water quality or hydraulic variables in urban streams.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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