Qualification et conception de sites de mesures débitmétriques en réseaux d'assainissement

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Qualification and design of flow meter measurement sites within sewer networks

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ABSTRACT

Measurement devices are more readily being implemented in sewer networks for a variety of purposes. Selecting the specific sites for conducting these measurements may prove difficult since the efficiency of available devices is heavily dependent on hydraulic conditions. Our research project makes use of numerical and experimental investigations in order to improve the representativeness of measurements performed in sewer networks, by taking into account the specificities of each particular site. The aim here is to develop a methodology for designing the instrumentation of a sewer section, including site qualification, sensor placement and post-processing of measurement results. This paper presents the framework of such a methodology, along with an application for assessing the influence of a 90° bend on velocity fields and the implications identified on flow measurements.

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RÉSUMÉ

Afin de répondre à des objectifs aussi bien techniques que réglementaires ou financiers, les besoins en instrumentation des réseaux d'assainissement sont en constante progression. Mais le choix des sites adaptés à l'implantation du matériel de mesures peut s'avérer délicat car les performances de ces matériels sont très tributaires des conditions d'écoulement. Les recherches en cours au GEMCEA combinent des études numériques et expérimentales afin de mieux décrire et prévoir les conditions hydrauliques dans les collecteurs. L'objectif à terme est de disposer d'une méthodologie d'aide à l'instrumentation, incluant la qualification des sites, l'implantation des capteurs et le post-traitement des mesures. Cet article présente d'abord les différentes étapes de la méthodologie. Celle-ci est ensuite illustrée par son application à l'influence d'un coude à 90° sur la répartition des vitesses, et ses implications sur une mesure de débit.

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INTRODUCTION

Sewer networks account for a considerable number of engineering facilities. According to data from the IFEN (French Institute for the Environment) **[1]**, 24.8 million housing units were connected to wastewater collection networks in France as of 2004, with a total linear network coverage exceeding 280,000 km. Moreover, financial estimations of the nation's system rehabilitation needs **[2]** amount to nearly €7 billion over the short term with annual outlays reaching €1 billion so as to keep up with system modernization needs.

These figures suggest the magnitude of the stakes involved when determining how to efficiently manage sewer networks, which constitute a major component in the area of urban water resources management both now and in the future **[3]**. System operations often differ substantially from hypotheses adopted during the design phase, especially regarding the flow rates actually conveyed through the system. The installation of networked measurement stations is thus a preferred component of any sewer system management policy **[4]**. Measurement results are interpreted on a deferred time scale and offer a precise view of sewer network performance over a one-year period, which makes it possible to create appropriate indicators focusing on discharge quantities, quality of effluent received at the plant and structural condition of the facilities **[2]**. Moreover, some of these sensors may be connected as input to real-time management systems, helping optimize the utilization of facility capacity, depending on specific circumstances and particularly during rainfall events.

This technical evolution is being backed by regulatory action (joint Ministerial decrees enacted on December 22, 1994 and June 22, 2007) and the adoption of new standards (EN 752 -2 & 7, NF P 15-900-2), which request in detailed terms facility managers to: supervise networks, evaluate network performance, respond quickly in the case of non-systemic malfunctions, and inform the project owner of improvements likely to enhance performance while increasing sewer collection reliability. Though the practice of installing sensors is becoming more widespread, it is still constrained by a lack of sites satisfying the prerequisites, such as a rectilinear network section (without any deposit accumulation), that ensure compliance with safety conditions for both personnel and equipment. Another constraint encountered involves the spatial representativeness of sensor measurements, and more specifically the velocity measurements carried out using Doppler effect sensors within the ultrasonic domain **[4, 5]**.

A research program was launched to develop an effective methodology for qualifying measurement sites and measurement equipment design; program goals consisted of:

– prequalifying a candidate site by highlighting cases that indicate a favorable profile, unfavorable profile, or potentially favorable while awaiting further investigations;
– qualifying the site according to the outcome of such investigations;
– establishing the procedure for a sensor installation campaign;
– defining the protocol to interpret sensor output, whereby measured values can be translated into the targeted physical magnitudes;
– evaluating the level of data uncertainty introduced.

The present article will describe such a methodology and follow up by demonstrating, on a selected example, the feasibility of these methodological underpinnings, namely the use of generic modeling. This approach involves models that yield results not necessarily dedicated to a single measurement site, but lead instead to a determination of velocity fields both inside circular collector pipes of any diameter and through diversions of any angle.

SITE QUALIFICATION METHODOLOGY

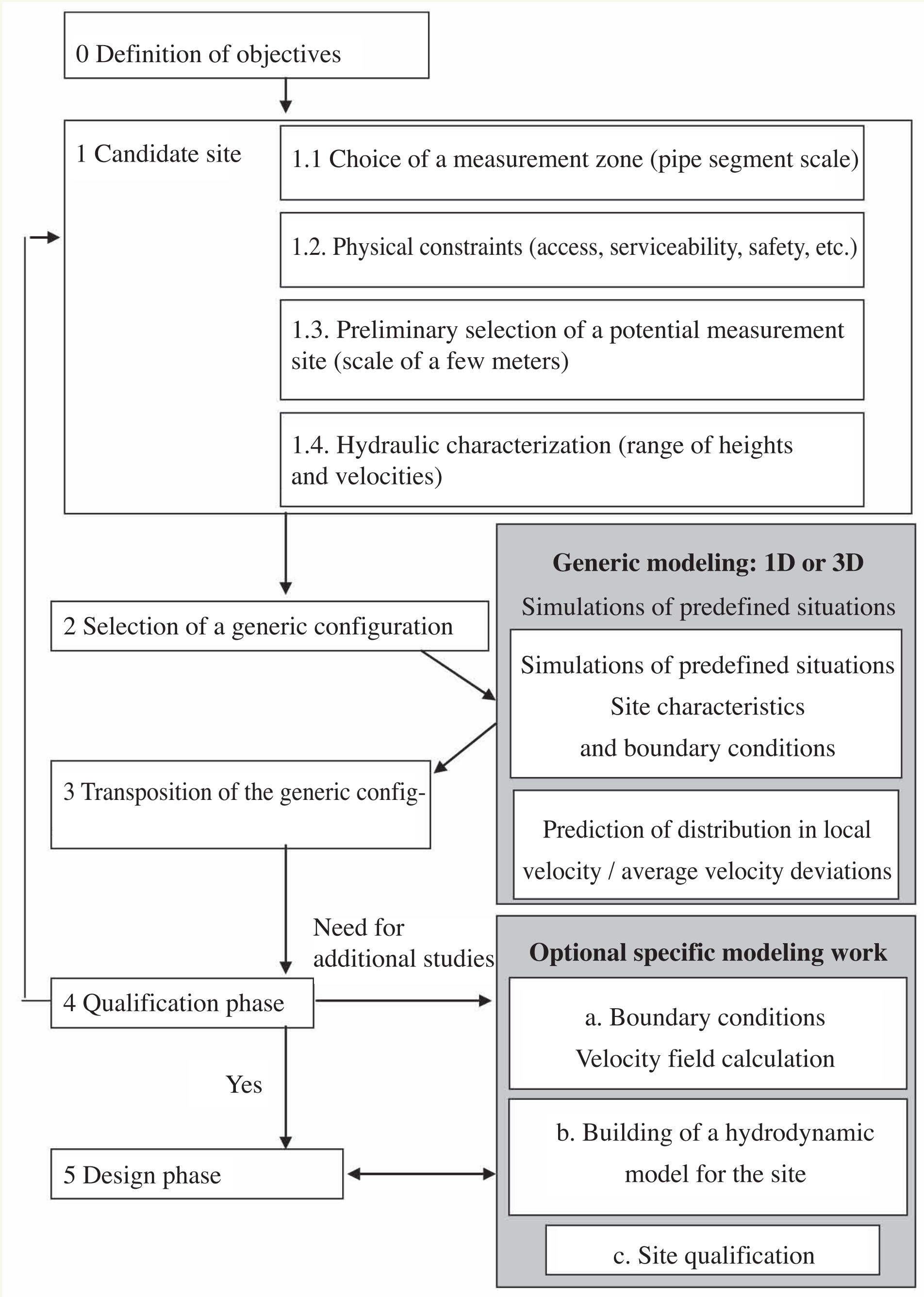
The measured parameters helpful to managing a sewer system are multifold, yet flow rates tend to be the key element, given that flow rates are critical not only to facility operations but to evaluating pollutant flows as well.

Moreover, the choice of measurement section within a system must acknowledge a number of constraints, including accessibility from the ground surface, safety issues, and service connection to energy and telecommunications networks. These demands placed on the configuration impose matching the measurement target with the instrumentation, in addition to severely limiting investment and operating costs.

Current practices encompass the steps of setting objectives and selecting the site (steps 0 and 1 in **Figure 1**), and these are to be combined with an empirical assessment of potential problems arising. Such practices tend to be satisfactory, yet difficulties persist, especially involving large-sized collector lines and/or non-standardized cross-sections. Regarding the various recurrent difficulties observed, the following needs to be stated:

– Those sites meeting all specification criteria are indeed rare, since the number of unique cases and conditions is fairly high. Compromises must be accepted, yet without necessarily being able to evaluate their consequences (see below);

Figure 1
A detailed view of the methodology proposed to qualify a flow meter measurement site and proceed with instrumentation design



– Verification of measurement results often proves difficult and infrequent at the lower end of the flow rate measurement range (i.e. dry weather rates), which in turn limits the ability to calibrate the average velocity calculation and to control uncertainties;
– Assessing the risks of silt or sediment deposition can, in certain cases, lead to (bad) surprises. Some sites do not display chronic sedimentation, yet might temporarily cause problems not easily anticipated or detected by means of simple observation.

Our work program seeks to streamline the guidelines specific to flow meter installation and, where need be, simplify protocol so as to enable measurements at sites exhibiting suboptimal conditions while maintaining control over result uncertainty. This effort has entailed modeling flows, with an emphasis on velocity distribution within a given sewer line volume. Knowledge of this distribution is critical to identifying the representativeness of flow rate measurements derived from velocity sensors. The velocity field adjacent to the line bottom also serves to evaluate sedimentation risks.

Since the hydrodynamic model is quite sophisticated to implement in an operational setting, we have sought to develop an intermediate methodology between current empirical practices and a systematic modeling of measurement sites. **Figure 1** provides a detailed description of this methodology, with the second and third steps lying at the core and presumably requiring the preliminary completion of generic models. These models would need to depict standard configurations in parametric form, thus facilitating the eventual transposition to real-world situations. When reaching step 4 therefore, the site can be either rejected with a return to step 0 or else qualified with continuation to step 5, during which the measurement point is designed. Another option would be to consider the case uncertain, which leads to introducing a specific modeling approach.

METHODOLOGY FEASIBILITY

The methodology feasibility study **[7]** focuses on the generic model (see Step 3) by considering the case study of velocity field evolution in a collector line downstream of a pipe elbow, in order to determine the radius of influence of such a singularity or, on the other hand, the zone with a profile favorable to installing a flow meter for the purpose of measuring velocity.

Singularity index and extent of influence

To quantify the influence of a particular singularity on the velocity field, we propose adopting a singularity index at the level of cross-section S_x, which is to be based on the average quadratic deviation between a given discretized velocity field and a developed field, as normalized by average velocity:

$$I_{sx} = 100 \times \frac{\sqrt{\sum_n \left(U(x,y,z) - U(\infty,y,z)\right)^2}}{n\bar{U}} \quad (1)$$

where $U(x,y,z)$ is the local velocity in the abscissa section x, calculated from the exit of the elbow bend **(Fig. 2)**; $U(\infty,y,z)$ the velocity in a cross-section where the flow is fully developed; and $\bar{U}$ the average velocity in the cross-section.

For information, if the same calculation protocol were applied to compare a uniform field with a developed field, a value of 2.8% would be obtained for a circular cross-section 1.5 m in diameter filled at 55% of capacity. This value might seem small, yet in fact it reflects strong transverse and vertical velocity gradients. Further downstream of this singularity (the notion of downstream infinity will be applicable in the following discussion), velocity equals $U(\infty,y,z)$, and the index should equal zero; due to numerical diffusion however, a zero index value is very difficult to obtain. Moreover, for this bent circular collector pipe, simulations indicate that an index value of 0.2% corresponds to the fact that just 10% of the wetted surface area is exposed to a local velocity $U(x,y,z)$ that differs by more than 10% with respect to velocity $U(\infty,y,z)$. In addition, this 0.2% value corresponds to the deviation existing between the developed profiles calculated by a single-phase model (where the free surface condition is replaced by a rigid hanging side) and by a two-phase model (where the free surface is modeled).

The singularity index must not therefore be interpreted in absolute value terms, but instead in terms of variations and position within the 0.2%–3% interval. For the following discussion, the 0.2% value will conventionally define the radius of influence downstream of a bend, also known as the re-establishment length and denoted L_R.

Parameterization considerations

The numerical study is intended to identify parameters with the most sensitive effect on the singularity index and to describe this effect in the most generic form possible, by expressing the singularity index as a function of the parameters yet to be defined, with preference for an adimensional form.

Among the set of parameters capable of varying in actual configurations and exerting an influence on the re-establishment length, let's cite the following:

– size of collector pipe
– cross-sectional shape
– material roughness
– pipe bend angle
– bend radius
– filling height
– flow velocity
– slope of the apron.

Even when combining the practical range of variations applicable to each parameter with just a few procedures, the resulting array is still multifaceted and incompatible with the computation time required for each simulation. To explore this avenue further, we established a number of parameters, including:

– cross-sectional shape: circular
– roughness: 2 mm
– angle: 90°.

The circular shape is standard and encompasses a large number of potential scenarios. The roughness effect was tested during a preliminary step and found to remain limited. As for the 90° angle, it would appear to be the least favorable. For the bend radius, we introduced a three-value range: 6 m, 9 m, and 12 m.

For the collector size, we tested the two values of 0.8 m and 1.5 m to span a wide range of situations.

This range may be subsequently extended depending on the results obtained. The effect of filling height was examined in detail over the range 0.66 m to 1.2 m, for a filling rate of between 44% and 80%; associating this parameter with an average upstream velocity corresponds to a uniform flow for a 0.04% slope.

Moreover, the effect of average velocity was studied over a range of 0.7 m/s to 1.2 m/s, which corresponds to input conditions according to a uniform flow profile, as determined by water height and a slope varying from 0.04% to 0.1% for a 50% filling rate of a 1.5 m-diameter collector pipe. This range is somewhat narrow and may subsequently be extended.

For the collectors studied herein (see **Table 1**), flow is turbulent and the Reynolds number $Re = \frac{UD_h}{\nu}$ is greater than 10^{+5}, where D_h is the hydraulic radius, $g = 9.81$ m·s^{-2} the gravitational acceleration, and $\upsilon = 10^{-6}$ m^2·s^{-1} the kinematic viscosity of water.

Table 1
Case study examples.

Geometry	Diameter (m)	Filling rate (%)	Average velocity (m/s)	Radius of curvature (m)
Circular	1.5	44	0.65	6
Circular	1.5	44	0.65	9
Circular	1.5	44	0.65	12
Circular	1.5	44	0.85	9
Circular	1.5	44	1.00	9
Circular	1.5	44	1.15	9
Circular	1.5	51	0.73	9
Circular	1.5	59	0.77	9
Circular	1.5	75	0.80	9
Circular	1.5	80	0.83	9

Numerical modeling

This study has run the CFX industrial computing code in order to calculate velocity fields in a straight vertical cross-section of sewer pipe. Three-dimensional flow modeling is based on both the mass and motion quantity conservation equations for an average Reynolds number and incompressible flow:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j}\right) \tag{3}$$

where x_i represents the Cartesian coordinates, U_i the velocity components in the x_i direction, ρ the mass density, P the pressure, ν the kinematic viscosity, and $-\overline{u_i u_j}$ the Reynolds tensor components, which describe the effects of turbulent fluctuations on average flow and raise a closure problem with respect to the system of equations. Turbulence models are intended to close the system, by adopting a set of hypotheses that allow determining the Reynolds constraints and hence solving the system.

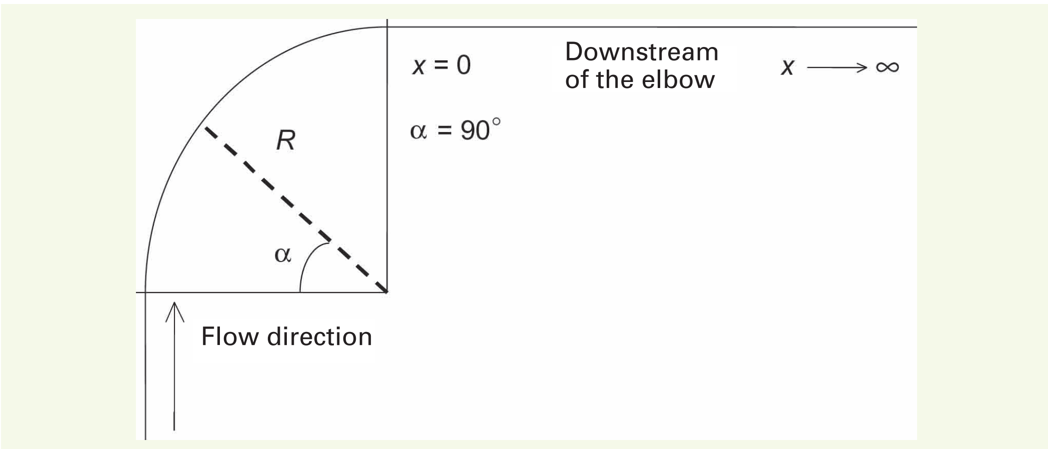
The computation code relies on a finite volume method with tetrahedral control volumes and a structured Cartesian mesh. The computation domain comprises a circular collector pipe and extends 50 m in length upstream of the elbow and 120 m downstream **(Fig. 2)**.

The upstream boundary conditions are water height h and uniform velocity $\overline{U}$ throughout the cross-section. The upstream length is sufficient to obtain, based on this information, a developed velocity field. A hydrostatic pressure condition is applied downstream (constant water height over the entire length). Flow near the solid walls is modeled by means of a constitutive law, which remains a function of the type of wall **[8]**.

Given the anisotropic nature of flows running inside narrow free-surface channels, we decided to use the turbulence model proposed in **[9]**.

To keep computation times compatible with systematic testing, the free surface is depicted by a rigid hanging side. While this simplification does not extend to representing the "dip phenomenon", i.e. the fact that maximum velocity lies beneath the free surface in the developed flow zone through a narrow channel, it was still selected for four main reasons:

Figure 2
Modeled domain



– The zero shear rate condition at the free surface is well reproduced by this type of numerical simulation and, as a consequence, has been used by various authors **[10-12]** to numerically simulate free-surface flow;

– While remaining within the non-developed flow zone, the secondary currents of the first type of Prandtl are critical and the "dip phenomenon" is absent, as could be experimentally verified **[13]**;

– Numerical results are in good agreement with experimental findings **[13]**;

– In the zone where flow is developed, the average quadratic deviation between single-phase and two-phase simulation results is small (less than or equal to 0.2% depending on water height).

RESULTS

These simulation results allow describing the influence of an elbow by distinguishing 3 zones downstream of the elbow:

❶ a highly heterogeneous zone: the vortex is produced by a centrifugal force that creates secondary currents of the first Prandtl type. A single and substantial vortex exists, with the maximum velocity of secondary currents $U_S = \sqrt{v^2 + w^2}$ on the order of 10% to 25% of maximum velocity U_{max} within the cross-section, where v and w are the velocity components in the transverse and vertical directions, respectively;

❷ a transition zone: the heterogeneity is minimal, but flow is not fully developed; just a single vortex remains, yet velocity U_s is on the order of 2% to 3% of maximum velocity;

❸ a zone where flow is developed: medium vortices are produced by the effect of Reynolds constraints. Two contra-rotating currents can be observed centered in the middle of the cross-section with a decreasing vertical velocity mid-section (velocity U_s equals roughly 2% of maximum velocity).

Influence of filling height

In this study, both the diameter and radius of curvature have been fixed. **Figure 3** shows the velocity fields at ten times the free-surface width downstream of a 90° bend, featuring a 9 m radius of curvature in a 1.5-m diameter circular collector with an input velocity corresponding to the average value in a uniform flow regime created by a 0.04% slope.

It can be seen that the velocity fields are not symmetrical with respect to the median vertical plane of the collector, in addition to the fact that maximum velocities U_{max} are offset in the direction towards the outerwall regardless of water level.

The singularity indices, lying between 1 and 1.6, correspond to velocities extending locally from 70% at the inner wall to 100% of maximum velocity at the level of the outer wall. We have been able to verify that the ratio of average velocity $\bar{U}$ to maximum velocity in the cross-section remains between 0.85 and 0.87 for the range of water levels investigated, which is in agreement with the range listed in Standard NF EN ISO 748 regarding velocity field exploration methods.

Figure 4 indicates that for a given radius of curvature, diameter and slope, the singularity index immediately downstream of an elbow is greater with lower water height. **Figure 4** also shows that this index decreases and tends towards a common value beyond a width 20 times that at the free surface downstream of the elbow. Note that the index only drops below the threshold value, regardless of water height, at 35 times the free surface width, i.e. 3.5 times further downstream than what was listed in the sensor manufacturer's specifications **[14]**.

Figure 3

*Velocity field U_i/U_{max} at 10*B downstream of an elbow on a 1.5-m diameter collector for various water levels.*

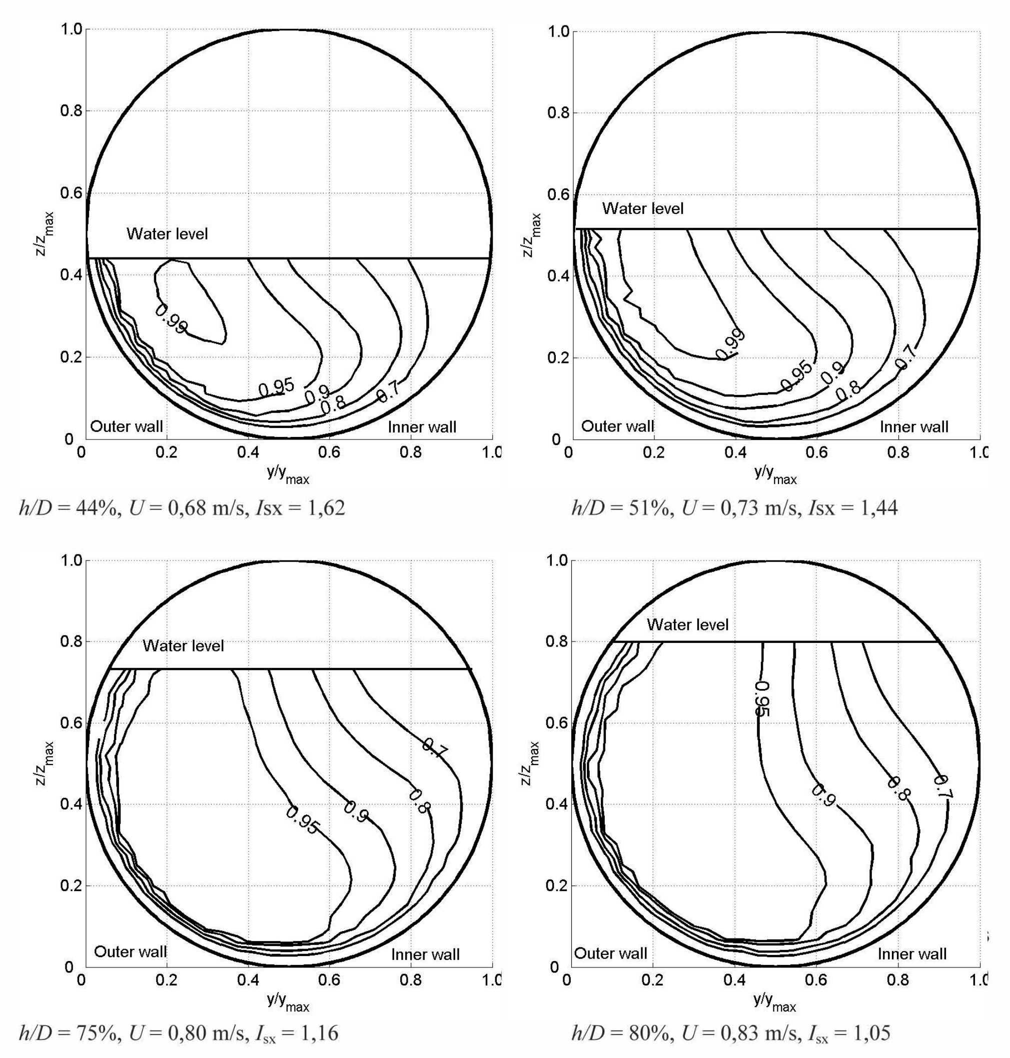
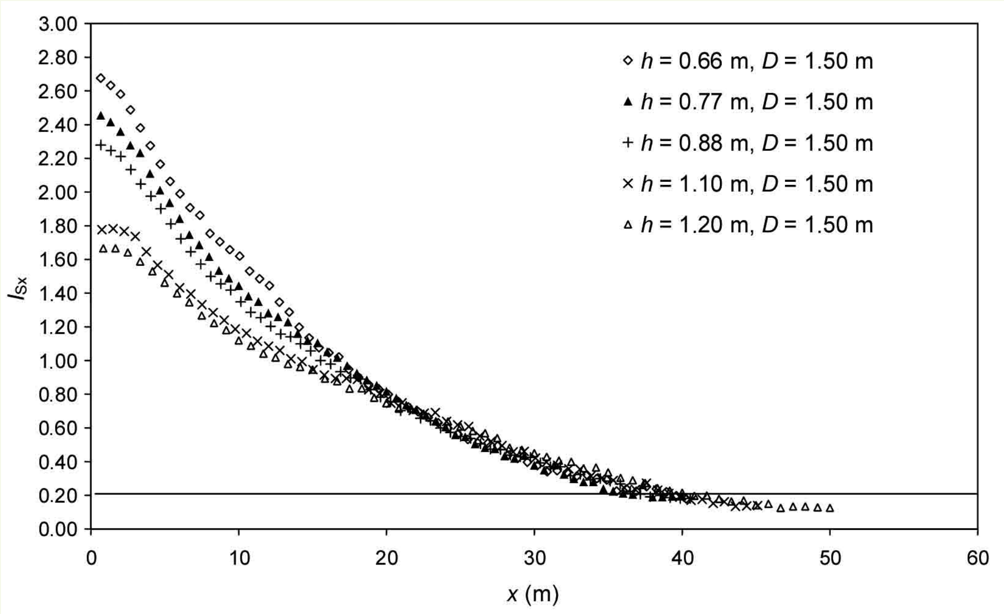


Figure 4

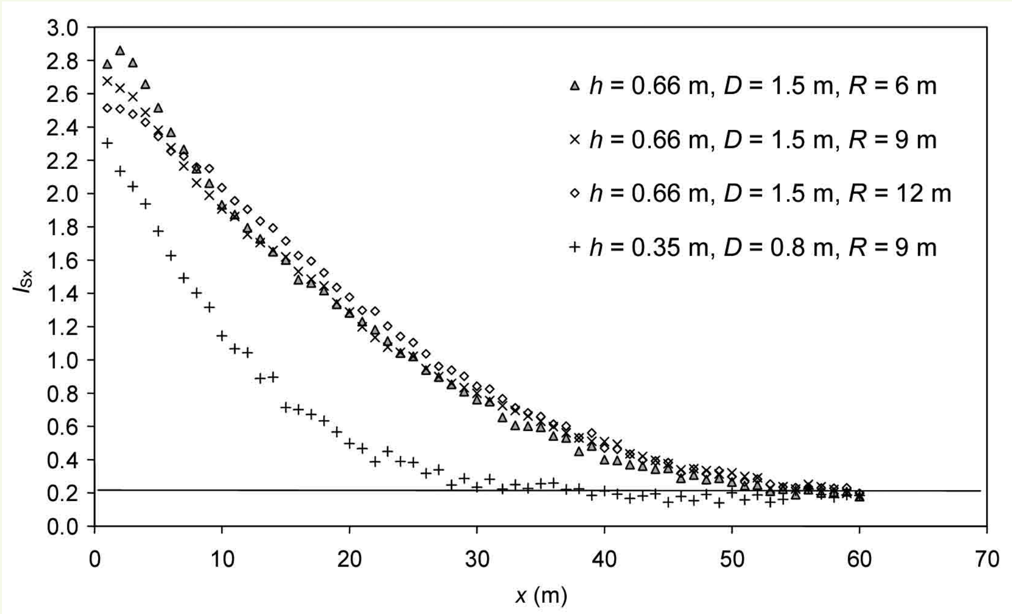
Influence of water height on the singularity index for a collector with a 1.5-m diameter, 9-m radius of curvature and 0.04% slope.



Influences exerted by diameter and radius of curvature

Figure 5 illustrates that for a given filling rate (0.44), the radius of curvature only exerts a small impact on the singularity index, except at very short distances downstream of the elbow. Further downstream, the index tends towards the common value of 0.2. It is also observed that for a given radius of curvature *R*, the diameter *D* of the sewer pipe significantly influences the singularity index up to a distance equal to 20 times the free surface width downstream of the elbow.

figure 5
Influence of both elbow radius and diameter on the singularity index for h/D *= 44%*

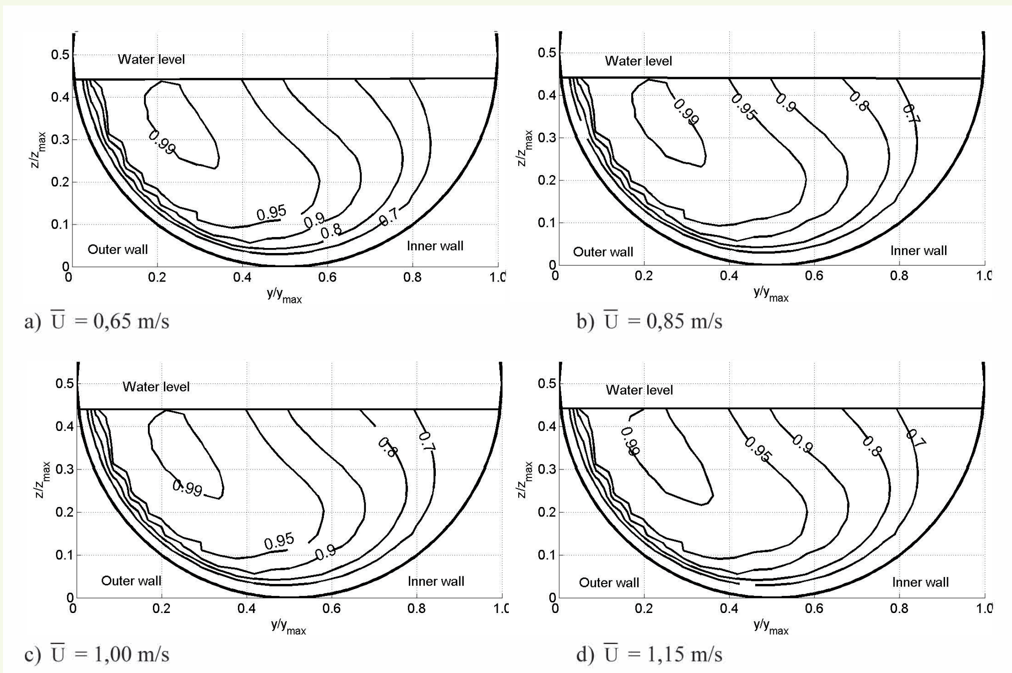


Influence of average velocity or slope

Figure 6 shows that for the targeted range, i.e. 0.70 m/s to 1.20 m/s, the imposed upstream velocity exerts no influence on the adimensional velocity field U/U_{max}. This result is noteworthy for the transposition of generic models, yet would still need to be confirmed over a wider range of velocities.

Figure 6
Velocity field U_i/U_{max} *at 10*B downstream of an elbow with constant water level for various upstream velocities* $\bar{U}$ *.*

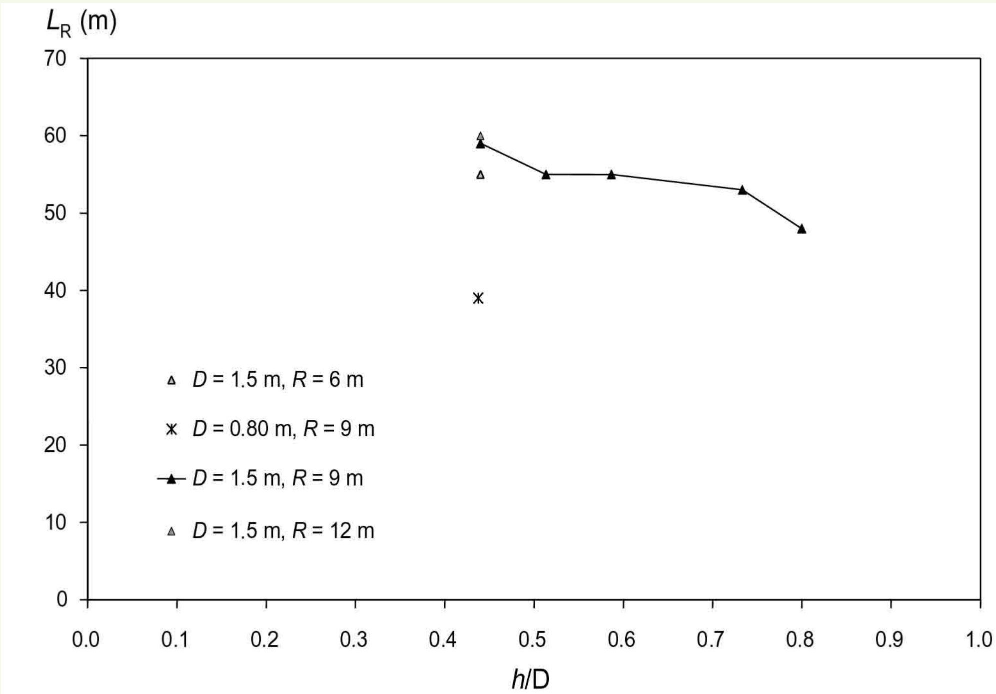
a b
c d



Attempt at generalization

Figure 7, which was derived for a slope equal to 0.04% and its associated velocity, indicates that for a given collector pipe diameter and radius of curvature, the re-establishment length decreases slightly with filling rate. For a given filling rate, this length is directly influenced by collector diameter since it drops by 33% when the diameter is halved. It is essential to point out that Dean's number, which is typically defined for flows in closed pipes as the quotient of tube radius divided by elbow radius of curvature, does not lead to a generic formulation of the results displayed below. In time, it would be necessary to express these results with respect to the adimensional numbers yet to be identified.

figure 7
Influence of filling rate on the re-establishment length



CONCLUSION

Incorporating the hydraulic setting is a critical aspect in the design of a measurement point within a sewer collection system, and moreover the measurement cross-section must be chosen in conjunction with an appropriate method and technology. Regarding the example developed herein, the targeted method has been based on measuring average velocity through an entire cross-section. This method can potentially be adapted to a wide array of site configurations, yet the various technologies available all remain sensitive to the spatial distribution of velocities through a section. The prediction of this distribution at a given site for an entire range of hydraulic loadings has required introducing hydrodynamic models, once the particular site proves to be somewhat complex. These studies might also be somewhat cumbersome to conduct. We sought to evaluate the possible contributions of a "generic" modeling of standard configurations in order to approximate the hydraulic behavior of special sites corresponding to these configurations.

On a given example, we examined the benefit and feasibility of adopting such an approach, which entails setting the re-establishment distance of a developed velocity profile downstream of a unique type of singularity, specifically an elbow on a circular sewer collector pipe. A single-phase representation of free surface flow depicts well the major modification in secondary currents caused by the singularity. After creating a singularity index of the velocity field and proposing a conventional definition of re-establishment length, we were able to identify the set of most influential parameters, namely filling rate and collector pipe diameter. The influence of radius of curvature seems to be less pronounced, while average velocity has a negligible impact over these test value ranges.

Progress is still needed to refine the expression of results in an adimensional form and assess the influence of other parameters, such as the bend angle of the elbow or cross-sectional shape.

The next step could consist of extending the approach by a parameterization of the re-establishment length of a developed field, in addition to the velocity field in cross-sections located within the disturbed zone. This information could then be combined with a knowledge of spatial sampling carried out by sensors, in order to: optimize sensor implementation inside a given cross-sectional configuration, and specify the corrections to be applied to measurements for the purpose of evaluating both the average velocity and result uncertainty.

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