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Ultrasonic device for real-time sewage velocity and suspended particles concentration measurements

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ABSTRACT

In the frame of a technological research and innovation network in water and environment technologies (RITEAU, Réseau de Recherche et d'Innovation Technologique Eau et Environnement), our research group, in collaboration with industrial partners and other research institutions, has been in charge of the development of a suitable flowmeter: an ultrasonic device measuring simultaneously the water flow and the concentration of size classes of suspended particles. Working on the pulsed ultrasound principle, our multi-frequency device (1 to 14 MHz) allows flow velocity and water height measurement and estimation of suspended solids concentration. Velocity measurements rely on the coherent Doppler principle. A self developed frequency estimator, so called Spectral Identification method, was used and compared to the classical Pulse-Pair method. Several measurements campaigns on one wastewater collector of the French city of Strasbourg gave very satisfactory results and showed smaller standard deviation values for the Doppler frequency extracted by the Spectral Identification method.

A specific algorithm was also developed for the water height measurements. It relies on the water surface acoustic impedance rupture and its peak localisation and behaviour in the collected backscattering data. This algorithm was positively tested on long time measurements on the same wastewater collector.

A large part of the article is devoted to the measurements of the suspended solids concentrations. Our data analysis consists in the adaptation of the well described acoustic behaviour of sand to the behaviour of wastewater particles. Both acoustic attenuation and acoustic backscattering data over multiple frequencies are analyzed for the extrapolation of size classes and respective concentrations. Under dry weather conditions, the massic backscattering coefficient and the overall size distribution showed similar evolution whatever the measurement site was and were suggesting a global wastewater particles behaviour. By comparison to sampling data, our data analysis lead to the characterization of two particle groups: the ones occurring during rain events and the ones typical of wastewater under dry weather conditions. Even with already encouraging results on the several weeks of data recorded on several wastewater collectors, the validation of our data inversion method is still under progress.

Key words | acoustic, suspended solids, velocity, water height

INTRODUCTION

All around the globe, the wastewater policies are becoming increasingly stringent (European Union 2000; Federal Water Pollution Control Act 2008). Some key components

of the wastewater and pollution regulation are real-time sewer networks surveys. Their aim is a good knowledge of the flow characteristics. Many types of gauging systems are

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currently implemented in wastewater networks; they mainly allow measurement of water height, flow velocity, flow rate and give an estimation of the total suspended solids concentration. Unfortunately the online, real-time, availability of these data is seldom.

This paper deals with the development of a specific stand-alone ultrasonic instrumentation dedicated to sewer systems which allows online monitoring of:

- The water height.
- The velocity profile, which combined with the water height and the flow bed knowledge gives the flow rate.
- The granulometric size classes distribution of suspended solids.

The required specifications of our instrumental development were the combined possibility of flow rate measurements with 5% accuracy on open channels with diameters going from 0.3 to 1 m and velocities up to 3 m/s *and* concentration measurements of suspended solids with granulometric estimation.

BASIC METHODOLOGY

Instrument description

The instrument's global topology can be seen in Figure 1. It consists of two distinct parts, a submersible frame which is placed in the flow and a data management platform which remains on shore. Both are connected by a power supply and communication wire. The submersible frame contains the transducers and the sequencing, emission-reception and the digitalisation electronics. The data management platform, in charge of data treatment and storage can be accessed by a personal computer or can be directly connected to a network.

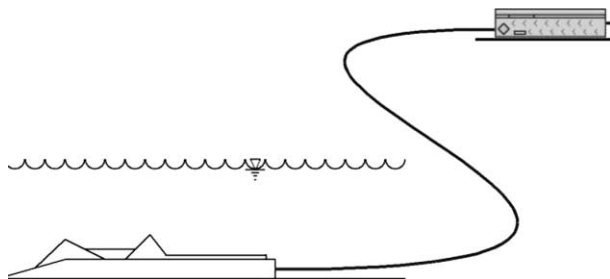


Figure 1 | Schematic layout of the MES-FLUX.



Figure 2 | Picture of the frame and the open data management platform.

Figure 2 shows the open data management platform along with the submersible unit on the right (seen in operation on Figure 3). The global dimensions of the frame are about $260 \times 75 \times 45 \text{ mm}^3$. The three specifically oriented transducers are used for velocity, water height and suspended solids concentrations measurements on the well known pulsed ultrasound principle (Takeda 1999).

The biggest broadband transducer of mean frequency 1.8 MHz is used for monostatic velocity and water height measurements. It has a slope of 75° with the stream direction which allows higher velocity values for a given Doppler frequency. This first transducer and a second one, equally oriented, of mean frequency 9.2 MHz, are also used

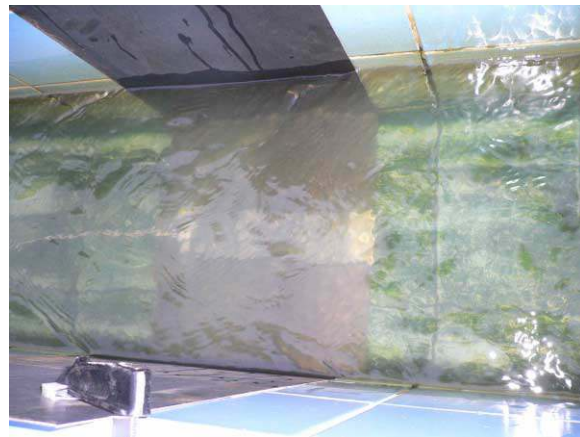


Figure 3 | Operation in a sewer outflow.

for the suspended solids concentration measurements. The third and last transducer, centred on 4.5 MHz, makes an angle of 70° with the direction of the other transducers. It is used for the collecting of complementary data at another diffusion angle for granulometric measurements. The concentration measurements are made on frequencies ranging from 1 to 14 MHz over all the transducers.

Pulsed ultrasound principle

By range gating, the instruments that operate on the pulsed ultrasound principle can easily provide measurement profiles (see Figure 4). Their working principle allows precise knowledge of the position in the flow of a given data at a given time stamp. Periodically, an ultrasonic pulse is emitted into the medium. This signal is backscattered by the particles suspended in the flow. Received by the transducer, the backscattered signal received by the transducer is conditioned, amplified and sampled in order to extract the information on the velocity and the concentration of suspended solids. These values are estimated on a succession of measurement volumes by windowing the backscattered signal in several blocs related to several measurement depths.

WATER HEIGHT ESTIMATION

The water height measurements are made with the 1.8 MHz transducer and rely on the acoustic impedance rupture of

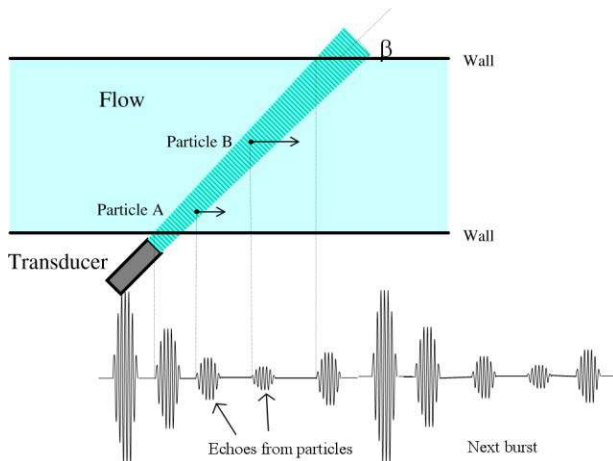


Figure 4 | Pulsed ultrasound principle, here with transducer set out of the flow.

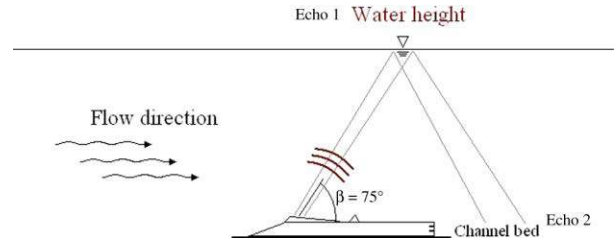


Figure 5 | Ultrasonic beam propagation.

the water/air interface. For water height measurement, the instrument is installed on the bottom of an open flow channel. The emitted ultrasonic beam makes a 75° angle with the horizontal water level. The beam propagates in the medium and is strongly reflected by the water/air interface which corresponds to water height. A large amount of the beam energy is reflected as depicted in Figure 5. A part of it will be reflected once again by the channel bottom and will lead to multiple echoes (Figure 5).

The presence of the multiple echoes makes the signal analysis difficult. As can be seen on the amplitude profile of Figure 6, the amplitude of the channel bed echo might be as strong as the one produced by the water height. Its strength depends on the water surface agitation.

The first step of the data analysis is the identification of the peak in the backscattered amplitude profile. It is obtained by the localization of the measurement volumes with the highest energies. Once identified, the peaks are characterized by their position and their amplitude. Figure 7 shows the extrapolated water height for the identified peak

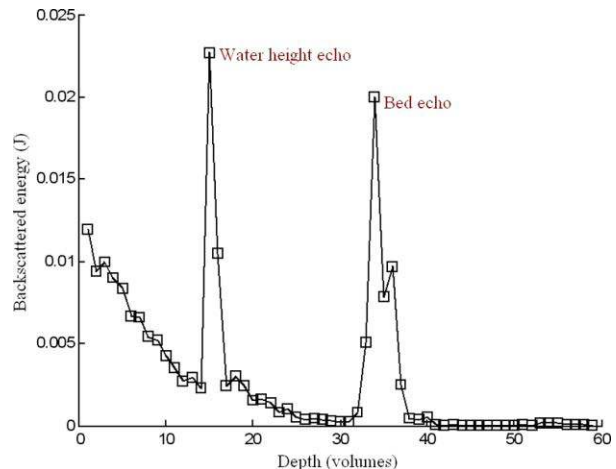


Figure 6 | Typical amplitude profile.

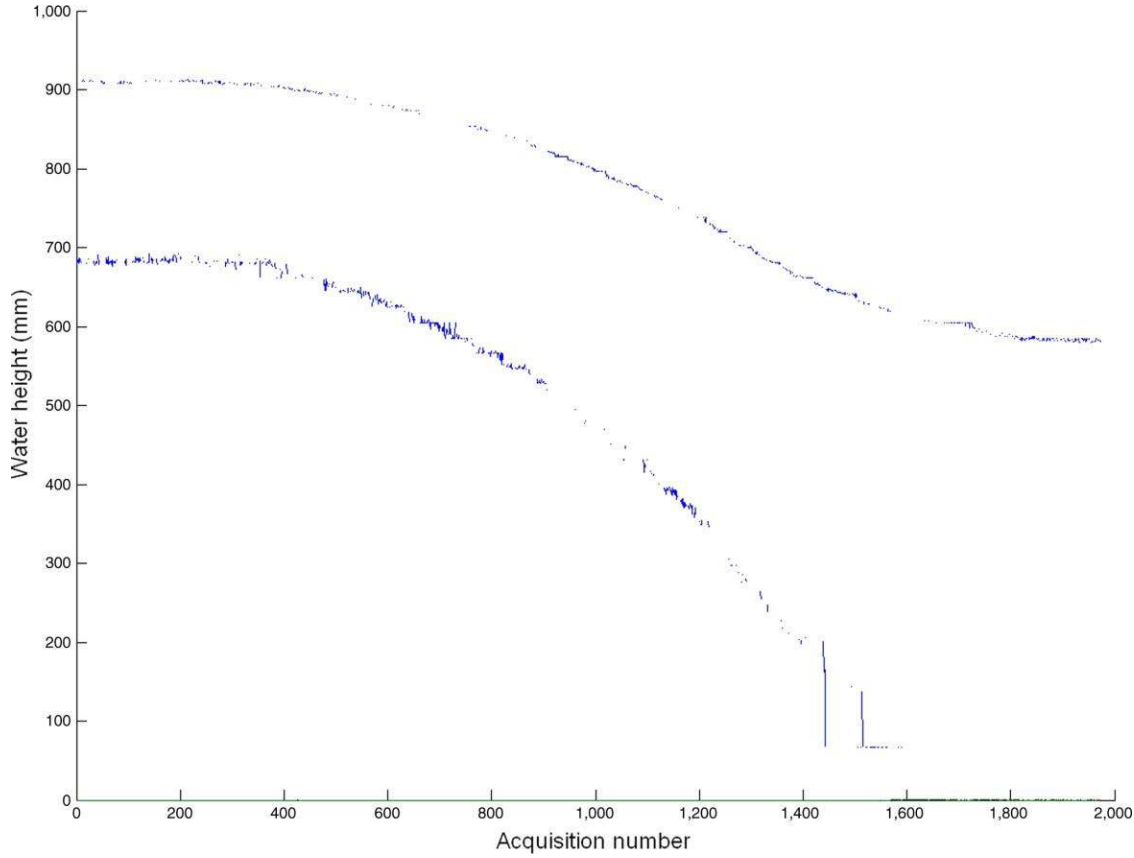


Figure 7 | Typical evolution of water height and bed echo as observed in a wastewater collector.

values in a wastewater collector of the French city of Strasbourg over a time period of about 12 hours. The upper curve corresponds to the real water height and the second one is the bed echo from a foregoing pulse. It can clearly be seen that the bed echo gives more disparate amplitude values as the real water height.

The effective differentiation between the water height and the bed echo is made on the basis of two criterions which are the variation of peak position and the standard deviation of the peak amplitude. The combination of both criterions ensures the correct water height identification.

VELOCITY PROFILES

By using a pulsed ultrasonic beam, the estimation of the flow velocity can be achieved at different depths along the profile of the backscattered beam. The measurement chord

is made of the succession of volumes with dimensions depending on the beam width and the duration of the observation window (Yu *et al.* 2006). The signal strength within each volume is a function of the number of suspended particles in the volume, their size and their velocity. The Doppler frequency shift of the acoustic signal depends only on the particles velocity. Several methods are used to extract the Doppler information from the volume's acoustic backscattering signature. The coherent Doppler method is implemented in our instrument. This method uses the observed phase shift of the acoustic signal of a same volume during consecutive emission–reception cycles (Takeda 1995). Each cycle generates a data sample by volume. This method allows good spatial resolution with low variance. Its major disadvantage is the velocity / depth limit due to the signal sampling.

An estimator allows the calculation of mean Doppler frequency f_D , thus the flow velocity V in the corresponding

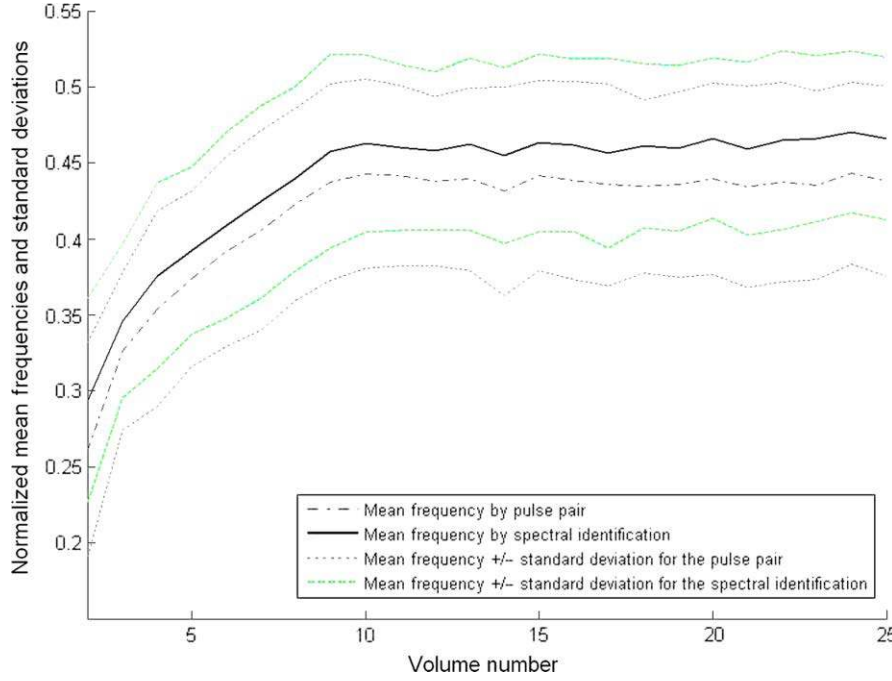


Figure 8 | Doppler frequency estimators comparison.

volume according to:

$$V = \frac{c \cdot f_D}{2f_0 \cdot \cos \beta}$$

where c is the speed of sound in the medium, f_0 the carrier frequency and β the angle between the flow and the ultrasonic beam. This instrument only measures the velocity relative to the transducer, which is resolved into the along channel (streamwise) direction. The velocity profile is obtained on the measurement chord and its integration over the flow section gives the flow rate.

Two different estimators have been used for the Doppler frequency estimation: the well known Pulse-Pair method (Miller & Rochwarger 1972) and a self developed Spectral Identification method (Fischer *et al.* 2008). The two methods have been compared on the same data set, for measurement volumes going from flow bed (volume 1) to water height as shown on Figure 8:

As predicted by theory, a difference in the mean Doppler frequency values exists. The results also show a smaller standard deviation for the Spectral Identification method.

Several measurements campaigns have been done so far. For example, the instrument was deployed for several

weeks in a wastewater collector of Strasbourg. This location was of great interest because of its large section and important water height, the typical velocities and suspended solids concentrations. The instrument was located in the collector bottom and was measuring velocities on a chord of 50 volumes going from the bottom to the water surface.

On the spectrum visualisation of Figure 9, one can observe the Doppler frequency dispersion mainly due to the turbulences generated by the frame's position which was very close to the bottom of the collector but not in contact.

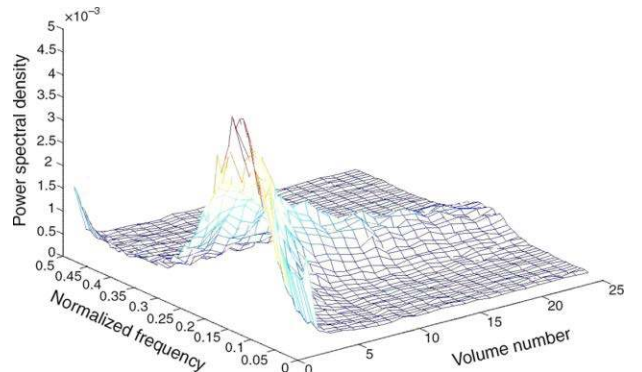


Figure 9 | Experimental Doppler spectrum obtained in a wastewater collector.

SUSPENDED SOLIDS CONCENTRATIONS

One problem with the use of ultrasound to characterize suspended solids is the huge variety of materials that can be found under this generic term. These materials have very disparate acoustic behaviour. Nevertheless, their acoustic signal analysis in terms of the well known behaviour of sand (Thorne & Hanes 2002), qualitatively reflects the size evolution of the suspended particles.

On a theoretical basis, the relation between the transducer's emission voltage $V_{e,j}$ at the frequency j and the reception voltage $V_{t,j}$ can be written as:

$$\left(\frac{V_{t,j}(r)}{V_{e,j}(r)}\right)^2 = G_j^2 \frac{3}{32} c \Delta t_j \left(\frac{R}{r}\right)^2 \left[\sum_{i=1}^n \sum_{k=1}^p \beta_{v,j,i,k} C_{v,i,k}(r) \right] \times g_j^2 \left(\frac{r}{x_{c,j}}\right) \exp\left(-4 \int_0^r \left[\alpha_j + \sum_{i=1}^n \sum_{k=1}^p \alpha_{v,j,i,k} C_{v,i,k}(r) \right] dr\right)$$

where G_j is the gain of the instrument, c the speed of sound in the medium, Δt_j the pulse emission duration, R the transducer's radius, g_j the near field correction, $x_{c,j}$ the near field distance, α_j the water attenuation coefficient, $C_{v,i,k}$ the volumic concentration and $\alpha_{v,j,i,k}$ and $\beta_{v,j,i,k}$ coefficients for attenuation and backscattering behaviour respectively. The coefficients are both function of the suspended particles size (subscript i), of the particle shape, acoustic impedance (subscript k) and insonifying frequency (subscript j). Rewriting the previous equation, a ratio can be expressed as below. This ratio is directly linked to the particle mixture:

$$T_j(r) = \frac{(V_{t,j}(r))^2}{(V_{e,j}(r) G_j)^2 c \Delta t_j \frac{3}{32} \left(\frac{R}{r}\right)^2 g_j^2 \left(\frac{r}{x_{c,j}}\right) \exp(-4 \alpha_j r)} = \left[\sum_{i=1}^n \sum_{k=1}^p \beta_{v,j,i,k} C_{v,i,k}(r) \right] \exp\left[-4 \int_0^r \sum_{i=1}^n \sum_{k=1}^p \alpha_{v,j,i,k} C_{v,i,k}(r) dr\right]$$

All the terms on the left of the second equals sign are measurable, like the gain or the near field correction which both were determined from laboratory measurements, or are known as the pulse duration. Thus the

previous equation can be simplified to:

$$T_j(r) = \beta_{p,j}(r) \exp\left[-4 \int_0^r \alpha_{p,j}(r) dr\right]$$

with:

$$\beta_{p,j}(r) = \left[\sum_{i=1}^n \sum_{k=1}^p \beta_{v,j,i,k} C_{v,i,k}(r) \right] \alpha_{p,j}(r) = \sum_{i=1}^n \sum_{k=1}^p \alpha_{v,j,i,k} C_{v,i,k}(r)$$

Without any preliminary knowledge about the particle mixture's composition, the T_j equation won't be sufficient to extract all the unknown coefficients. Therefore, we assume that the particle distribution, independently of their size, is uniform along the beam. Thus, there's no distance dependency of the backscattering and attenuation coefficients and consequently their values can easily be extracted from the T_j equation. However, the attenuation coefficient is usually a small value. Hence its estimation error might be huge in regard to its mean value. Only the profiles obtained for frequencies above 6 MHz give significant attenuation information. In its current configuration, our instrument gives only a single exploitable profile for attenuation at 11.7 MHz.

Another assumption is an identical size distribution of all particles whatever the value of their density is. On the basis of the semi-empirical formulae describing the behaviour of sand, the backscattering coefficient becomes:

$$\beta_{p,j} = \sum_{i=1}^n \beta_{v,j,i} C_{v,i} = \frac{C_m}{\rho_{mean}} \sum_{i=1}^n F_{j,i} \gamma_i$$

C_m stands for the total massic concentration in kg/m³. The mean density of all particles is ρ_{mean} and γ_i stands for the fraction of the i th size class. The mean value of the ratio of the form function by the particle radius over 5 diameters classes (12, 30, 70, 170 et 400 μ m) is given by the following expression where a_s is the particle radius:

$$F_{j,i} = \left\langle \frac{f_{j,i}^2}{a_s} \right\rangle_i$$

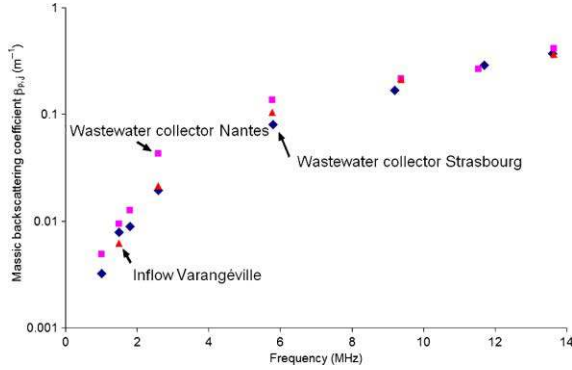


Figure 10 | Massic backscattering coefficient as a function of frequency for different measurement localizations.

The form function itself is calculated from (Sheng & Hay 1988; Crawford & Hay 1993; Thorne *et al.* 1993a):

$$f_{\infty,j} = C_0 \frac{1.1x^2}{1 + 1.1x^2}, \quad \text{where } x = k_j a_s$$

with

$$C_0 = 1.1 \left[1 - 0.25 \exp(-((x - 1.4)/0.5)^2) \right] 1 + 0.37 \exp(-((x - 2.8)/2.2)^2)$$

Previous contributions make the resolution of the T_j equation possible. From there, the granulometric distributions and the massic concentrations of suspended particles are estimated. A second step in the data analysis is the use of the attenuation data. The attenuation

coefficient can be written:

$$\alpha_{p,j} = \sum_{i=1}^n \alpha_{v,j,i} C_{v,i} = \frac{C_m}{\rho_{\text{mean}}} \sum_{i=1}^n A_{j,i} \gamma_i$$

The mean massic attenuation factor can be expressed in a similar way as previously:

$$A_{j,i} = \left\langle \frac{3\chi_j}{4a_s} \right\rangle_i$$

As for backscattering, a common model exists for the normalized total scattering section χ_j . Under the same assumption as previously that wastewater suspended solids behave as sand, its value might be obtained through the modified high-pass model (Crawford & Hay 1993; Thorne *et al.* 1993b; Sheng & Hay 1988; Richards *et al.* 1996) for attenuation under its usual form:

$$\chi_j = \frac{1.1(4/3)0.18x^4}{1 + 1.3x^2 + (4/3)0.18x^4}$$

On this basis, the attenuation is recalculated and compared to the one obtained by analysis of experimental data through the T_j equation.

Figure 10 shows the evolution of the massic backscattering coefficient on three different French localizations, two wastewater collectors, one at Nantes, the other at Strasbourg and the inflow of a wastewater treatment plant

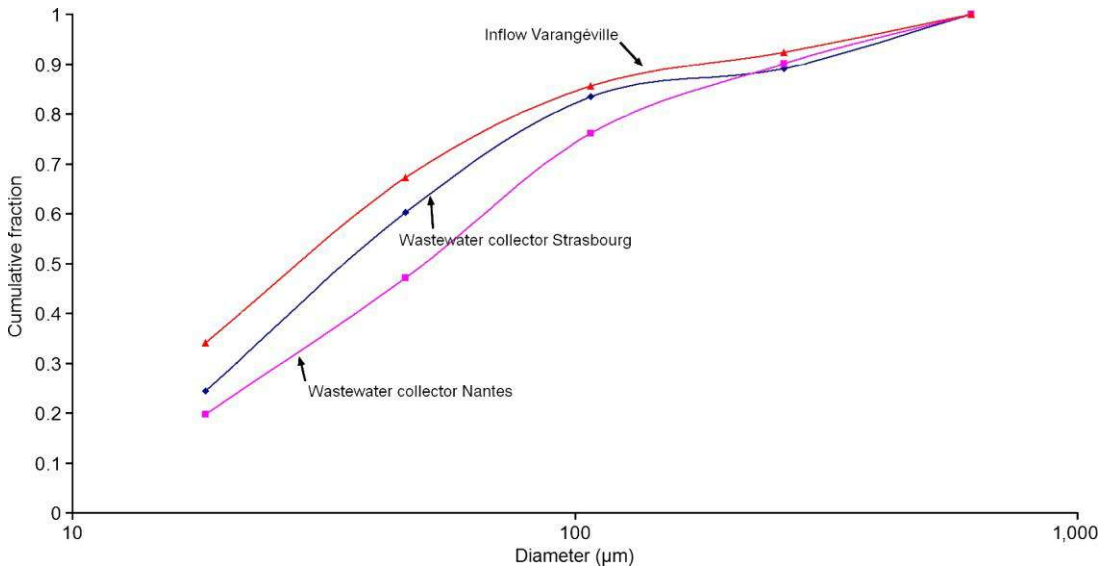


Figure 11 | Daily cumulative fraction of particles as a function of size and localization.

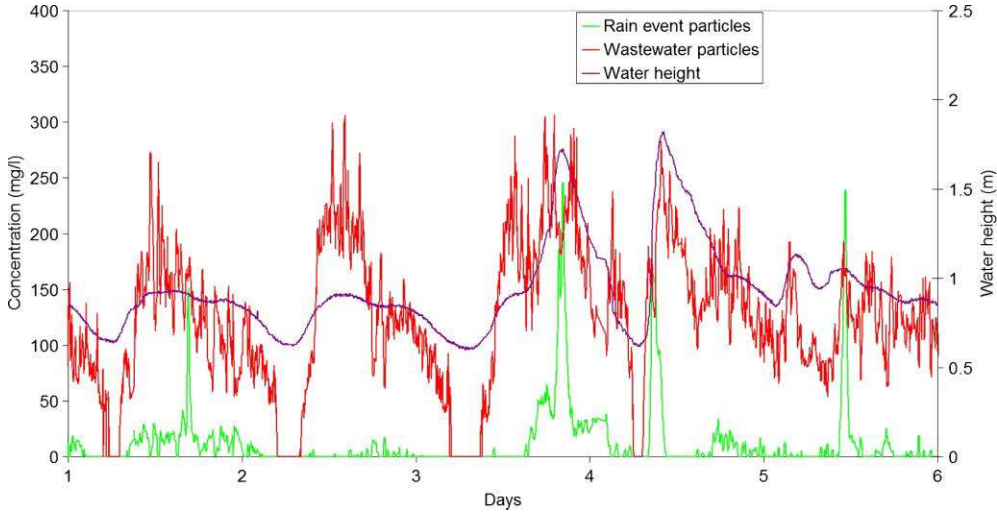


Figure 12 | Suspended solids concentration evolution.

at Varangéville. All measurements were made during dry weather conditions. They show similar values and shape for the three totally different measurement localizations. Also the overall size distribution is similar on all sites (Figure 11).

However, the estimated values given by the resolution of the T_j equation were shown to be 12 times smaller than the massic concentration values obtained by sampling. To fit this observation, the attenuation is calculated as mentioned previously and the concentration values are consequently adjusted. In fine, our current analysis allows a suspended solids classification in two categories: dry weather (standard conditions) and rain event suspended solids. To fit the concentration obtained by sampling, the data analysis is adjusted through:

$$\begin{aligned} \beta_{p,j} &= C_m[0.24(1 - \delta) + 0.08\delta]\sum_{i=1}^n F_{j,i}\gamma_i \\ \alpha_{p,j} &= C_m[0.625(1 - \delta) + \delta]\sum_{i=1}^n A_{i,j}\gamma_i \end{aligned} \quad \text{with } \sum_{i=1}^n \gamma_i = 1$$

δ is the fraction of dry weather wastewater suspended solids. Figure 12 gives a direct application of this new system. It shows the total concentration evolution for dry weather suspended solids and rain event suspended solids for a period of 5 consecutive days in the wastewater collector of Strasbourg. It clearly shows the known dry weather particle concentration evolution: nightly decrease and early morning increase due to human activity. There is also good rain event particles identification as correlated to water height.

CONCLUSIONS

Two prototypes of the described instrument exist. One of them is used for various in situ measurement campaigns. The second exemplar is used for laboratory measurements and algorithm betterment. They showed good agreement with other gauging methods for velocity, water height, daily concentration evolution of suspended particles and rain event discrimination.

In their current state, velocity and water height algorithms are satisfactory. A generic formula for flow calculation exists but has still to be implemented and validated. However, the suspended solids granulometric analysis has still to be improved. The several approximations leading to the inversion of the diffusion and the attenuation data have to still to be massively validated by comparison to sampling data. Some general elements of comparison are described in another article: (François *et al.* 2008).

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