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Acoustic profilers and pollutant flux measurements in urban hydrology

Profileurs acoustiques et mesure des flux polluants en hydrologie urbaine

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RÉSUMÉ

Les réglementations européennes et nationales demandent de recouvrer le bon état écologique des milieux récepteurs en 2015. Il est donc primordial de minimiser des rejets de polluants non traités au milieu récepteur, ce qui implique une bonne gestion des réseaux d'assainissement urbain et donc une connaissance précise des débits et des charges polluantes transitant dans les collecteurs. Des méthodes traditionnelles de mesures existent. Ainsi, par exemple, les débitmètres à effet Doppler ou les cordes de vitesses permettent d'obtenir une mesure de vitesse en continu mais des questions demeurent sur l'échantillonnage spatial du champ de vitesses. Les prélèvements suivis d'analyses permettent de connaître les concentrations en polluants mais de manière discrète. Les profileurs permettent théoriquement d'obtenir en continu et simultanément des profils de vitesse et d'intensité rétrodiffusée. Ce qui correspond à une connaissance plus détaillée, tant spatialement que temporellement, des champs de vitesses et de polluants. Cet article présente l'étude expérimentale entreprise en vue de préciser les potentialités des profileurs ultrasonores. Après quelques rappels de théorie, les matériels mis en œuvre et les expérimentations effectuées sont détaillés. Ensuite les résultats sont présentés et discutés par rapport à ceux obtenus avec des méthodes plus usuelles. Enfin les pistes de travaux complémentaires sont exposées.

MOTS-CLÉS

Techniques acoustiques, flux polluants, vitesse, matières en suspension

ABSTRACT

As European and national regulations request to recover the quality of receiving waters in 2015, the pollution discharged from sewer networks must be significantly reduced. This implies an accurate knowledge of the flow rates and pollutant loads conveyed in sewer channels. Traditional methods are available. For example, acoustic Doppler flow-meter can continuously record the mean velocity but questions are remaining on the spatial representativity of such measures. Sampling and analyses give the pollutant concentration but continuous measurements are impossible. Acoustic profilers allow continuous measurements of velocity and intensity profiles and then to a much more precise, in a spatial and temporal point of view, of pollutant fluxes. This study aims at testing the capabilities of acoustic Doppler profilers. After some theory, this paper presents a PC-ADP (Sontek) profiler and the experiments conducted. The results are presented and compared with those obtained with traditional methods. Some recommendations are given for further researches.

KEYWORDS

Acoustic techniques, pollutant fluxes, velocity, suspended solids concentrations

1 INTRODUCTION

When the European and national regulations request to recover the quality of the receiving waters in 2015, a minimisation of the pollution discharged from sewer networks is needed. A wise management of networks and a minimisation of the pollution discharged into receiving waters need an accurate knowledge of the flow rates and pollutant loads conveyed in sewers.

In sewage flow analysis, the traditional methods are based on well known techniques such as acoustic Doppler flow-meters and total suspended solids sampling as well as analysis. Although those methods give satisfaction for common gauging campaign, their implementation is rather difficult. First of all, sewer measurements give a lot of constraints: safety, dry weather conditions, time consuming for sampling and analysing, etc... Moreover, simultaneous measurements of velocity profile remain difficult and simultaneous measurements of velocity and suspended solids concentration remain impossible. The acoustic Doppler profilers present an interesting alternative that need to be validated.

This experimental study further contributes to that purpose. This paper first gives a brief review of the main equations. Next, the Pulse Coherent Acoustic Doppler Profiler (PC-ADP Sontek) is presented. It was used in a real urban sewer and the results were compared with those obtained with a two dimensional velocity and total suspended solids sampler. The results show the great improvement given by the profiling techniques in term of simultaneity and time saving.

2 THEORY

An acoustic transducer emits ultrasonic beams (3 or 4 depending on the constructors) that are reflected in all directions by the targets that are presented within the fluid. The shift between the emitted and reflected frequencies is used to calculate the flow velocity, with the assumption that the particles and the fluid move at the same velocity.

$$V \cos(\alpha) = \frac{c \Delta f}{2 f_0} \quad (1)$$

With $\Delta f = f_1 - f_0$, c is the acoustic beam velocity, f_0 the emitted frequency, f_1 the backscattered Doppler frequency shift received by the transducer. Figure 1 illustrates how a commonly used acoustic flow-meter measures the velocity of the black particle.

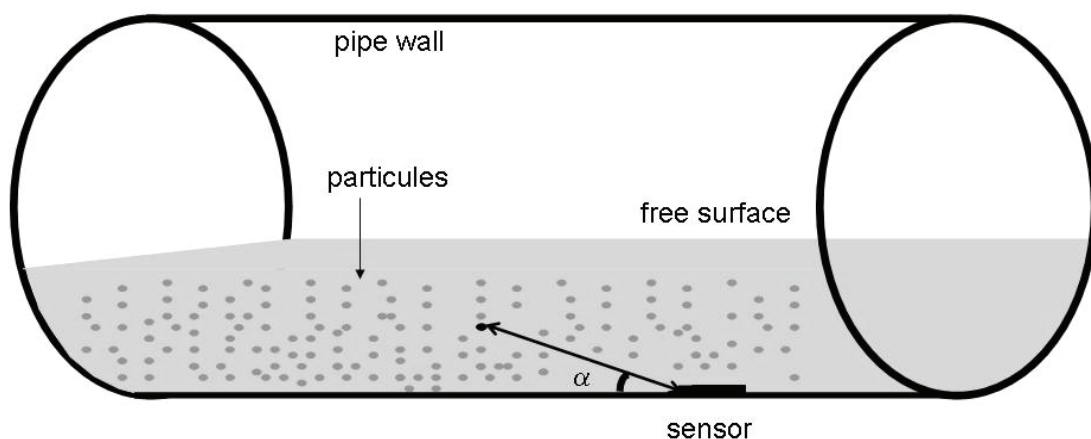


Figure 1 : Velocity measurement with an acoustic Doppler flow-meter as those commonly used in sewers

The wave reflected to the emitter can be analysed to characterize the fluid properties. Lurton (2002) proposed a law to relate the particles properties to the backscattered intensity.

$$NR = NE + IC - 2PT \quad (2)$$

where NR is the backscattered intensity (dB), NE is the emitted intensity measured at 1 m of the emitter (dB), IC is the target indicator and characterizes the ability of the targets to send the ultrasonic wave back (dB), PT characterizes the attenuation of the beam through the water (dB).

Various authors like Thorne and Hanes (2002), Hoitink and Hoekstra (2005), Tessier (2006) argue that the particles nature (mineral or organic) has an essential influence on the target indicator IC that can be modelled through by:

$$IC = 10\log_{10}(C_m) + 20\log_{10}(f(\rho_p, a, k, c, \dots)) \quad (3)$$

where C_m is the concentration in $\text{kg}\cdot\text{m}^{-3}$ and ρ_p mass per volume ratio in $\text{kg}\cdot\text{m}^{-3}$, a the particles radius, k the wave number. The ultrasounds celerity c is equal to $1480 \text{ m}\cdot\text{s}^{-1}$ at 20° C . This parameter is function to the water temperature, salinity and depth (Coppens, 1981). For waste water flows, the influence of the last two parameters is negligible.

Thorne et al. (1993) proposed a quantification of the attenuation :

$$PT = 10\log_{10}(\psi R) + \alpha R \quad (4)$$

where ψ quantify the cylindrical dispersion near the emitter (Fresnel distance), α is the attenuation factor such as $\alpha = \alpha_w + \alpha_p$ with α_w the clear water factor and α_p the particles factor

Fishers and Simmons (1977) proposed a law to calculate α_w in maritime context. Admiraal and Garcia (2000) adapted it for river flows (they do not consider pressure and salinity) :

$$\alpha_w \approx (55.9 - 2.37T + 0.05 \times T^2) 10^{-15} f_0^2 \text{ (Pa/m)} \quad (5)$$

where T is the water temperature ($^\circ\text{C}$) and f_0 the emitted signal frequency (Hz).

The dampening coefficient α_p is due to viscosity for small particles (Urlick et al., 1948) but it is related to diffusion phenomenon for bigger particles (Sheng and Hay, 1988), (Thorne, 1993). A literature review showed that, by fitting experimental results, a relatively simple expression of coefficient α_p has been established for sand rigid particles (Thornes et Hanes, 2002)

$$\alpha_p = \frac{1.1k_\alpha x^4}{1 + 1.3x^2 + 4/3k_\alpha x^4} \frac{C_m}{a\rho_p} \quad (6)$$

with $k_\alpha=0.18$ and $x=2\pi a/\lambda$. where λ the wave length. Though waste water particles are not sand the use of this expression permits the estimation of the order of magnitude for the attenuation coefficient. An experimental study (Larrarte and François, 2008) showed that the attenuation of ultrasonic beams by waste waters particles is negligible.

3 EXPERIMENTAL STUDY

Acoustic profilers were developed to obtained velocity profiles in a really brief time. The profiler used in this study was a PC-ADP made by Sontek for shallow water applications. Three transducers are located every 120 degrees on the measuring head and they make a 15 degrees angle with the vertical direction (Figures 2 and 3). Due to the 15 degrees angle of the transducers, the radius of the cell i located at d_i m is:

$$\Delta = d_i \tan(15^\circ) \quad (7).$$

For example, $\Delta = 0.52 \text{ m}$ at 1 m from the measuring head. Then, this cell encompassed 25% of the

cross section of the measuring site. Thus vertical and transverse profiles correspond to mean values on a big part of the cross section and are not studied here. The emitted frequency is 1500 kHz, the blank (dead) zone is 0.1 m long and each horizontal measuring cell is 0.02 m high. The three beams can be combined to obtain the three components of the velocity of the particles, and then the water velocity. The measurement frequency can be chosen, various tests showed that a good compromise between measure quality and amount of data to be analyzed can be obtained with a 5 s time step.



3 transducers



Logical box

Figure 2 : The measurement head and logical box of the profiler

As an oceanographic device, the PC-ADP was made to measure downward from the free surface (figure 2). A part of the emitted beams goes vertically and is reflected by the bottom of channel before the main fraction that has been directed with a 15° angle. This generates side lobe interference on a h_b height (Simpson, 2001), (Le Coz et al., 2008) where the measurements are biased by, with :

$$h_b = (1 - \cos(15^\circ))h = 0.03h \quad (8)$$

with h the water depth under the PC ADP

Measurements were performed in the French city of Nantes, on a site called "Jardin des Plantes" that received some 150,000 equivalent-inhabitant effluents. The sewer had an egg-shaped section with a bank and a typical dry weather water levels below 0.80 m. Its velocity is around 0.46 m/s. The walls are constructed by good quality concrete. This site is located in a public garden and installed with an experimental device called "Hydre". It was developed to allow measurements from the ground level regardless of the water level in the sewer (figure 3). One of its major functions is to measure both the velocities and suspended solids fields in a short time interval (Larrarte and Cottineau, 2008). Its measuring head has been equipped with 2 flow-meters and a sampling pipe. To avoid practical metrological problem related to drifting material clogging the sensors, the measurement head is also equipped with a compressed air pipe close to the flow-meters in order to clean those materials. The flow-meters used are Nivus PVM-PD which emits at 750 kHz. Hydre functions to scan the entire area from sewer bottom to a maximum level of 1.5 m (zone which corresponds to about 90% of the yearly observed water level configurations).

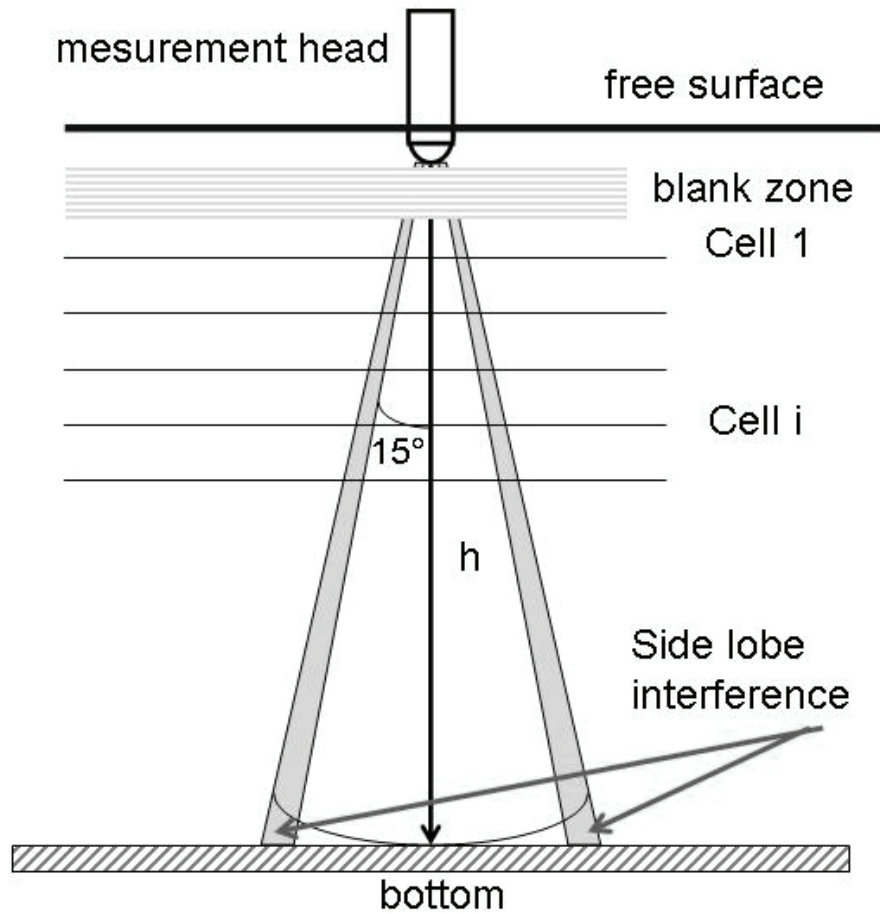


Figure 3 : Scheme of the profiler and parameters

The profiler was fixed on Hydre (figure 4), so that its position in the transverse and vertical directions were easy to manage.

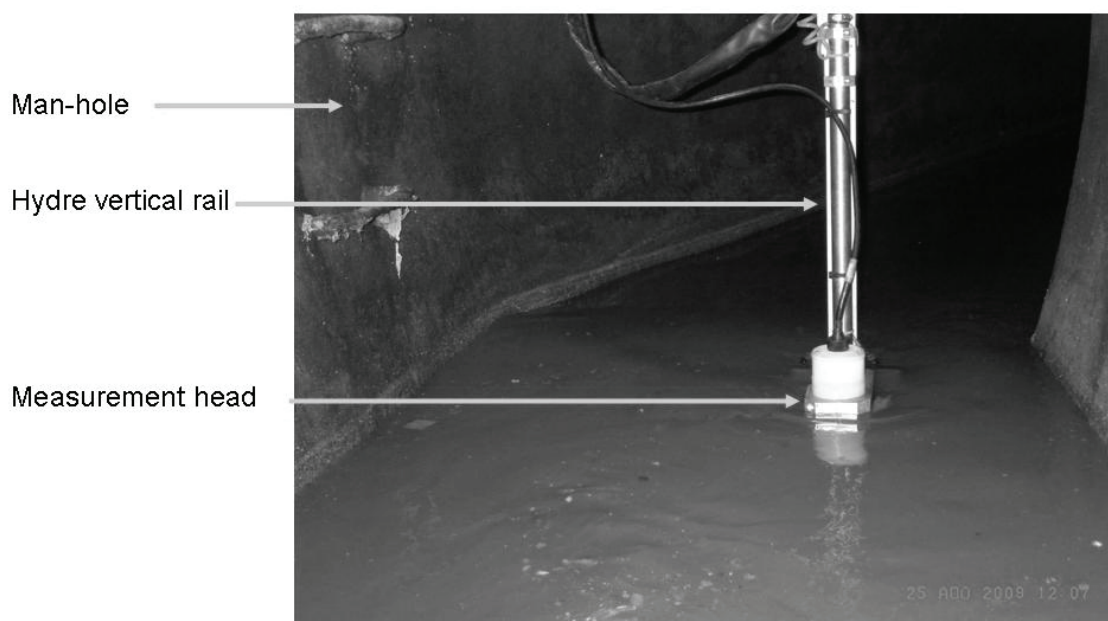


Figure 4. : . PC-ADP on Hydre sampler within the combined sewer, looking at downstream.

4 RESULTS

Velocity and suspended measurements were made on April 24th of 2008, during a rainy day. The profiles are presented as usual in sewer topics, with $z = 0$ located at the channel bottom. Figure 5 shows a very good agreement between the profiles on 60 % of the vertical distribution. The velocity profile measured with Hydre presents its maximum below the free surface. This is the characteristic of a dip phenomenon due to secondary currents of Prandtl secondary kind. They are generated by the three dimensional pattern of the flow in this narrow channel. This phenomenon can not be seen on the profile obtained with the profiler, because the blank zone gives no access to this area of the flow. The profile obtained with the PC-ADP shows a sharp change at the bottom level. This is related to the ultrasonic beam encountering the bottom of the sewer. Thanks to this behaviour but with an uncertainty of one cell height due to secondary acoustic lobes, the velocity can be measured in the inner layer of the flow boundary with a method much more faster than most of the traditional ones like Hydre and with a sensor that does not disturb this area. This is not currently being investigated much due to many technical difficulties, but it is of great interest for sewer managements because the sediments that settle have a lot of implications (reduction of the useful cross section, pollutant that can be eroded and poured into the receiving waters, etc ..). Moreover, thanks to its position at the surface, the profiler is less sensitive to be clogged than Hydre.

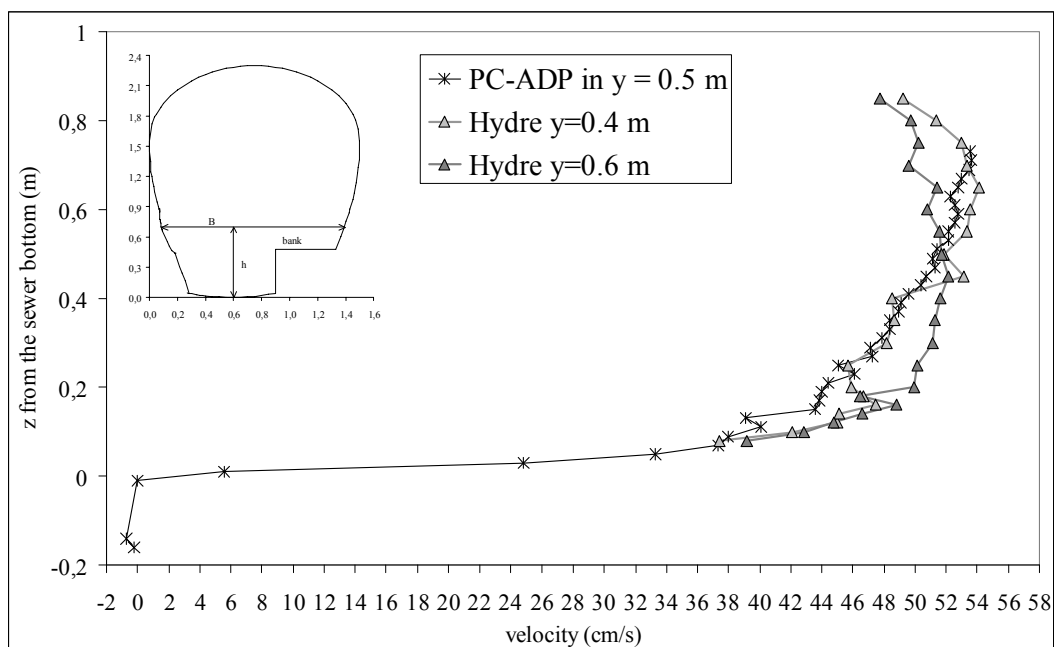


Figure 5 Comparison of Hydre and PC-ADP velocity profiles (24/08/2008)

Figure 6 shows a study of the mean value of the backscattered intensity for 2 different experimental days. They have the same general shape with a systematic decay of 3.5 dB and an intensity decreasing from the surface to about 0.1 m over the bottom before a sudden increase. On the other hand, it can be seen from figure 6 that the total suspended solids (TSS) concentrations, obtained following the ISO EN NF 872 standard, show variations but not any gradient. Moreover, the organic compounds and percentage of fine particles remained the same in spite of TSS concentrations in November is 70% higher than in February. During the same period, the water temperature decreased from 17 to 12°C. Those results show that the relation between backscattered intensity and TSS requires further investigations.

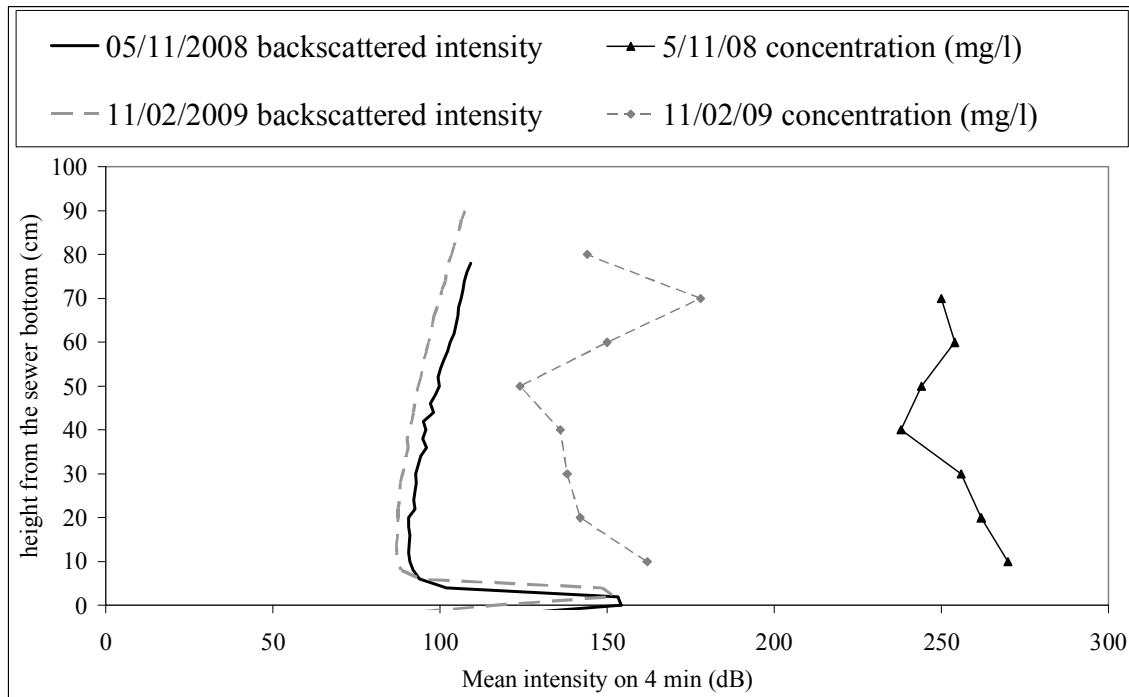


Figure 6 : Attenuation and TSS concentration profiles

5 CONCLUSION

Currently, it has been proven that it is difficult to spatially investigate velocity or total suspended solids field into sewers and almost impossible to do it simultaneously. This paper presents an experimental study aimed at testing the potential of acoustic Doppler profiler to measure the pollutant fluxes within sewers. After theoretical studies, a presentation of the devices was made and the results discussed.

The profiler is an interesting device that gives velocity profiles which are very close to those obtained with a more traditional method but in a much effective way as a whole profile can be obtained in less than a minute. The analysis of the backscattered intensity shows some good potential but the conversion between intensity and TSS proves to require more investigations.

The profilers, in their current form, remain more research oriented than common management devices because they are rather expensive and the analyses of the experimental data are far from routine. An important next step should be a collaboration between sensor makers and experimental research teams in order to make profiler easier to handle and investigate the influence of particles characteristics on the relation between TSS and backscattered intensity.

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