A discharge measurement system of WWTP inflow based on image processing

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ABSTRACT
Discharge measurement is a basic tool for process control and modelling in both natural and urbanized catchments. One of the limitations of measurement methods in use is the direct contact between the velocity measurement device and flowing liquid, resulting in maintenance difficulties. Thus, this paper deals with the design, laboratory testing and field verification of a nonintrusive discharge measurement method based on digital image processing of free-surface and particle tracking of floatable solids of natural origin.. Results demonstrate the ability of the LSPIV (Large-Scale Particle Image Velocimetry) method to estimate a free-surface velocity profile based on free-surface imaging and post-processing at a given cross section. The results of the project confirm the possibility of employing this technique for open-channel flow measurements in urban drainage systems using CCD cameras and image processing.

KEYWORDS
Combined sewer; discharge measurement; floatable solids; PIV; surface velocity;

INTRODUCTION
Discharge measurement methods generally used for open channel flow measurements and monitoring are based on an indirect discharge evaluation using information about other hydraulic quantities such as flow depth or velocity and known cross section area. The most often used method is the velocity-area method, with measurement of the specific velocity in cross section (maximal velocity or depth-averaged velocity) which is transformed to the cross section velocity based on an empirical formula. In the field of urban drainage, ultrasonic sensors with velocity evaluation based on a cross-correlation technique or Doppler principle are usually used. Those techniques require direct contact with the flowing medium and the sensors are usually placed on the channel bottom.

Discharge in open channels can also be estimated using information about the surface velocity obtained with optical methods. Particularly, Particle Ttracking Velocimetry (PTV) or Particle Image Velocimetry (PIV) are basic methods for velocity vector evaluations from particle motion in flowing liquids in general. The LSPIV method (Large Scale Particle Image Velocimetry), based on the PIV algorithm applied to surface velocity detection at macro scales, was introduced by Fujita *et al.* (1998). There are several field applications of this method in natural streams (Fujita *et al.*, 1998; Creutin *et al*., 2003; Bradley and Kruger, 2003). However, a crucial issue seems to be the necessity of a continuous and sufficient load of floatable solids of natural origin at the free surface. Significant concentrations of floatable solids in natural streams are mainly associated with flood flows. This can be used for reconstructing a flood-rating curve based on imaging of the free surface. However, the application of the LSPIV method for dry weather flows has to overcome the low seeding of natural floatable solids. The usability of the method in those cases can be increased using advanced techniques for tracking the movement of flow-coherent structures (boils, vortexes, waves etc.) (Weitbrecht *et al.*, 2007). Dosing of artificial solids usually used under laboratory conditions (Baud *et al.*, 2005; Weitbrecht *et al*, 2002) into a natural stream (Bradley and Kruger, 2003) is unrealistic in cases of standard discharge monitoring. However, combined sewer systems with a sufficient rate of floatable solids of natural origin seem to be an ideal field for the LSPIV methodology. Along these lines, Jeanbourquin *et al.* (2010) demonstrated a sewer monitoring system using long-term measurements.

This present study deals with the employment of optical methods for open flow measurements in urban drainage systems. In particular, image processing was used to estimate velocity vectors at a free surface under laboratory and field conditions to obtain a free surface velocity profile of longitudinal velocity vectors in a given cross section at a given time instant at WWTP inflow. Image analysis of the free surface provides the user information comparable to that obtained by acoustic methods. Further, the potential of this non-intrusive method increases under specific hydraulic conditions, e.g. intensive bed load transport.

METHODOLOGY OF DISCHARGE EVALUATION

Basic principles

A camera placed above the free surface of an open channel flow continuously images the appropriate area. We assume that the area of interest is homogenously seeded with a sufficient amount of floatable particles. Lighting of the free surface is ensured by a natural or artificial light source. Based on the cross-correlation technique and known time shift Δt between two images, a velocity profile at the free surface can be estimated (Figure 1). Based on theoretical considerations of a turbulent boundary layer and cross section geometry, total discharge can be evaluated.

Velocity vector evaluation

Individual images are fragmented into interrogation windows with size of 2Px2P pixels. The vector of displacement is calculated by a cross-correlation function of the signal (image) between two related interrogation windows of image A (I_1) and image B (I_2). The cross-correlation function provides the cross-correlation plane ϕ_{fg} with maximum intensity at position (i,j) (Figure 2). The displacement of a peak in the cross-correlation plane provides the shift between the windows in pixels. While the value of displacement is not an integer, the real displacement is found by interpolation. The number of computed vectors is given by the product of a number of interrogation windows in vertical and horizontal directions. An appropriate velocity scale can be estimated based on geometrical similarity and the frame rate.

Scale and image transformation

To obtain the absolute value of velocity, the geometrical relation between the image and physical plane has to be known. If the camera is placed perpendicular to the free surface of water and the lens does not cause significant image distortion (Wolf, 1983), the transformation is a linear function of distance between the camera and the free surface of water only.

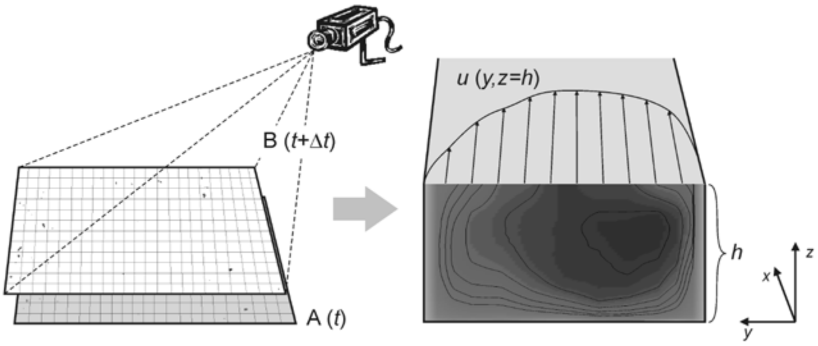

Figure 1. Basic principle of flow measurement using the LSPIV method.

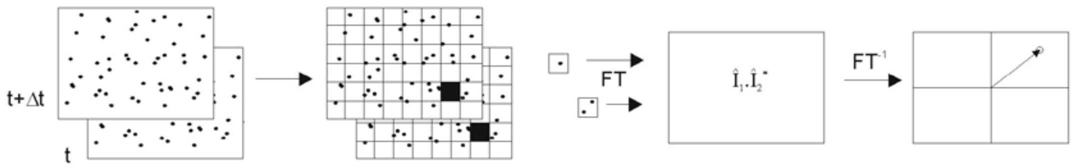

Figure 2. Analysis of a double frame exposure: the digital cross correlation method (after Raffael *et al*, 2007).

However, in the field the camera often is or has to be placed under a given skew angle with respect to the water free surface. In this case a coordinate transformation between the image and physical reality using calibration is needed. The relation between the image (x_b,y_b) and the free surface plane (X_a,Y_a) can generally be described using optical characteristics such as focal length, camera angle etc. However, this approach introduces a high number of parameters and increases the uncertainty of transformation.

Therefore, the transformation of images was described using 2D homography as follows:

$$Pb' = H.Pa \tag{1}$$

where H is a 3 by 3 homography matrix, *Pa* and *Pb* are the coordinates of selected calibrating points in the image and in the water surface plane.

$$Pa = \begin{bmatrix} X_a \\ Y_b \\ 1 \end{bmatrix} \qquad Pb' = \begin{bmatrix} w'x_b \\ w'y_b \\ w' \end{bmatrix} \qquad H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \tag{2}$$

The absolute coordinates can be calculated as follows:

$$Pb = \frac{Pb'}{w'} = \begin{bmatrix} x_b \\ y_b \\ 1 \end{bmatrix} \tag{3}$$

Figure 3 shows an original and transformed image of an open channel at WWTP inflow. As the flow depths in the channel varied only slightly compared to the camera distance, no depth-adapting algorithm was used. In streams with a wide range of flow depths, however, the depth-adapting algorithm should be considered (Jeanbourquin *et al*., 2010).

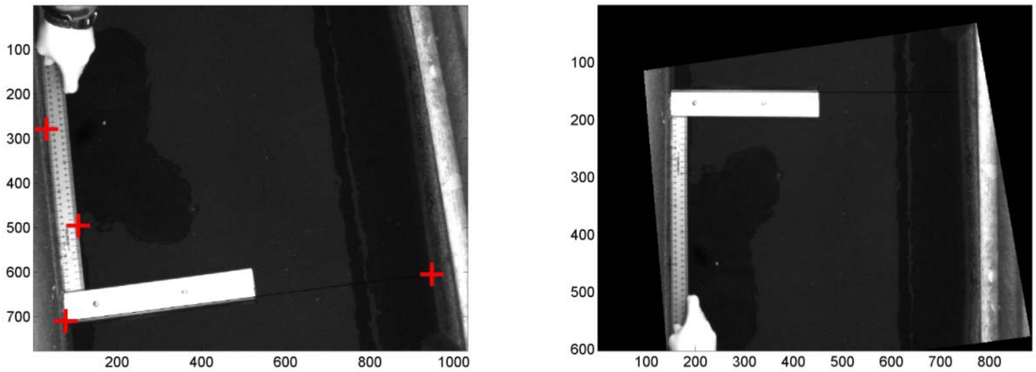

Figure 3. Original and transformed images with calibrating points in an open channel at the WWTP inflow.

Time-averaged surface velocity profiles

This method provides instantaneous profiling with a frequency of 30 Hz. Time-averaged surface velocity profiles are based on specific application. In this present study, 1000 frames were evaluated for each experiment. In field experiments 150 frames over 5 seconds were logged every 30 seconds.

Discharge estimation

A crucial factor for calculating discharge is the relationship between the surface velocity profile and the average cross section velocity. The simplest approach is based on a constant empirical coefficient between the point surface velocity u_s and the depth-averaged velocity u_p at all verticals across the channel width. Creutin *et al*. (2003) used the reduction factor $RF = u_p/u_s = 0.85$, but alternatively the parabolic (Buchanan, 1969), logarithmic or power law (Fujita *et al.*, 1998) velocity distribution models can be employed. These approaches can be used in streams were secondary circulation is negligible, i.e. the flow is two-dimensional. As a boundary condition, the ratio between the channel width B and average flow depth in the cross section h can be used. Graf (1998) evaluated the boundary as $B/h = 3.5$. Therefore, in channels with a lower ratio of B/h,a, the variable velocity reduction factor RF over the channel width B should rather be considered.

EXPERIMENTAL SETUP

Hardware and software

Regarding the physical dimensions of monitored areas and expected velocity range, standard CCD cameras with an appropriate sampling frequency can be used. Here, we used a monochromatic CCD camera BASLER Scout scA-1000-30fm with progressive scanning technology and maximal sampling frequency of 30 fps for full resolution of 1034 x 779 pixels. The sampling frequency was kept at a level of 30 fps for all experiments. Numerical sub-sampling was used for testing lower sampling frequencies. The camera was extended with the lens FUJINON HFHA-1B (HFHB-1B) of different focal lengths selected based on area dimensions. The camera has a FireWire-b (IEEE1394) interface with a baud rate of 800 Mbits/s. Image grabbing was performed using StreamPix 4.16.0 (Norpix) software and external commands. Image processing and velocity vector evaluations were performed in the Matlab/Simulink environment.

Tracking particles

In contrast to the standard PIV method, it is necessary to use particles with a density lower than the density of fluid. Further, the particles should have sufficient contrast with respect to the background (flowing liquid, channel walls and bottom). For laboratory experiments, LDPE Bralen VA 20-60 particles with density of 0,914 g/cm^3 and diameter of 3.5 mm were used. All types of particles showed a high potential to agglomerate at the free surface into clouds, which results in an inhomogeneous particle distribution over the area of interest. It is not possible to estimate the velocity vector in some regions where no particles are found. Therefore, special attention was paid to particle selection and treating their surface with a black mat lacquer. At the WWTP inflow, no artificial particles were seeded, and only floatable particles of natural origin were used to detect the velocity vector.

RESULTS

Laboratory flume

Preliminary experiments were done in a laboratory flume with rectangular cross section and channel width of B = 500 mm under steady flow conditions. The cross section velocity varied within the range of U = 0.13 - 0.35 m.s^{-1}, and the ratio between channel width and flow depth in the range B/h = 2.7 - 7.3. Different boundary conditions (particle concentration, size of interrogation area or sampling frequency) were tested in this flume. Velocity distribution in the cross section was obtained based on calibration experiments using the Ultrasonic Velocity Profiling method (Takeda, 1999). The results (Table 1) show sufficient agreement with reference measurements obtained by the MID flowmeter. The relative error varies around 2% for experiments with high B/h ratio values, while run 3 introduces an error of 10%. This is caused by a strong wall effect on velocity distribution for low B/h ratio values ($\approx$ 2.7). This indicates that for flows with significant secondary currents it is necessary to employ the width-varying reduction factor *RF*.

Non-prismatic channel under laboratory conditions

Subsequent experiments were conducted in a channel with a non-prismatic cross section under laboratory conditions. Two sets of experiments were performed. First, the CCD camera was placed perpendicularly to the water surface (Table 2, Figure 4). Then, 2D homography was employed for image transformation. Both geometrical configurations describe the free surface velocity distribution with high precision. This experimental setup allows changing the boundary conditions on channel inflow (Figure 4).

Table 1. The results of experiments in a laboratory flume for flowrate Q = 13.45 l.s^{-1}.

run	Q	h	B/h	S	U	Up_piv	RF	U_piv	Q_piv	rel. error	fps	res xy
	[l/s]	[cm]	[-]	[m2]	[m/s]	[m/s]	[-]	[m/s]	[l/s]	[%]		[pix*pix]
1	13.93	11.15	4.7	0.059	0.238	0.251	0.925	0.232	13.58	-2%	30 fps	64 x 64
2	13.45	8.65	6.1	0.045	0.296	0.313	0.925	0.290	13.14	-2%	30 fps	64 x 64
3	13.45	19.2	2.7	0.101	0.133	0.130	0.925	0.120	12.12	-10%	30 fps	64 x 64
4	13.45	8.65	6.1	0.045	0.296	0.322	0.925	0.298	13.54	1%	30 fps	64 x 64
5	13.45	7.3	7.2	0.038	0.351	0.385	0.925	0.356	13.64	1%	30 fps	64 x 64
6	13.45	19.2	2.7	0.101	0.133	0.133	0.925	0.123	12.40	-8%	15 fps	64 x 64
7	13.45	19.2	2.7	0.101	0.133	0.133	0.925	0.123	12.40	-8%	10 fps	64 x 64
8	13.45	19.2	2.7	0.101	0.133	0.137	0.925	0.126	12.73	-5%	30 fps	128 x 64
9	13.45	19.2	2.7	0.101	0.133	0.139	0.925	0.128	12.91	-4%	30 fps	256 x 64

Table 2. The results of experiments in non-prismatic channel – CCD camera perpendicular to free surface.

run	Qth [l/s]	h [mm]	B [mm]	B/h [-]	Up_piv [m/s]	RF [-]	Qpiv [l/s]	rel.error [%]	fps [fps]	res xy [pix*pix]
1	2.27	21	498	23.7	0.264	0.870	2.25	1%	30	64 x 64
2	2.27	21	498	23.7	0.262	0.870	2.23	2%	30	64 x 64
3	2.27	21	498	23.7	0.261	0.870	2.21	3%	30	64 x 64
4	4.24	43.4	612	14.1	0.201	0.870	4.07	4%	30	64 x 64
5	4.24	48	635	13.2	0.183	0.870	4.17	2%	30	64 x 64
6	4.24	54.2	667	12.3	0.160	0.870	4.19	1%	30	64 x 64

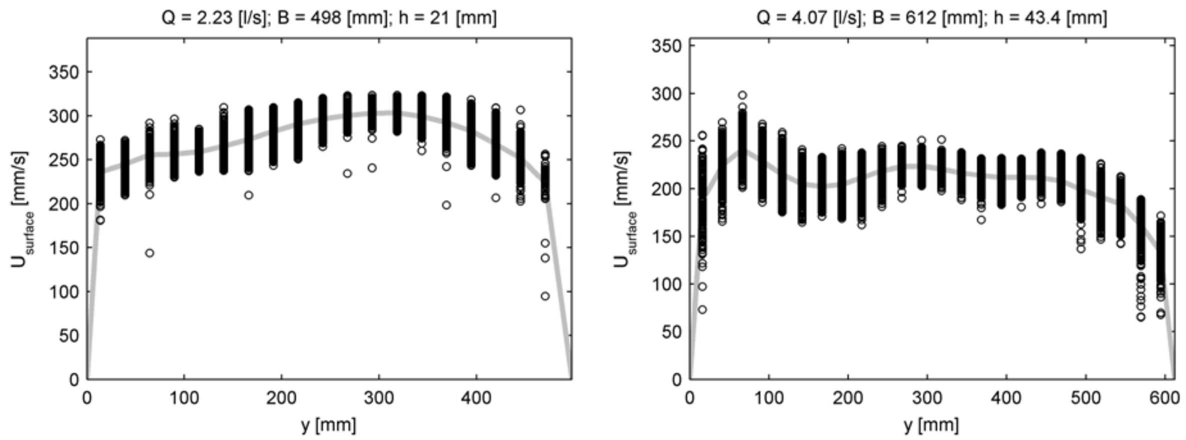

Figure 4. Open channel flow velocity distribution at the free surface of a non-prismatic channel under laboratory conditions (instantaneous values and time-averaged velocity profile). **Left** – flow distribution is almost uniform over the channel width. The deviation to the right side is caused by curvature in the channel course. **Right** –an artificial stream jet on the left side of the channel is visible.

Therefore, the maximal velocity is achieved at different location in the cross section (Figure 4). These results confirm the possibility of using this method also in channels with varying cross section e.g. CSO, flow splitters etc. With respect to the ratio *B*/*h,* a constant *RF* factor was used for all verticals over the channel width.

WWTP inflow

In-situ experiments were conducted in the flume of rectangular cross section at the WWTP inflow. This measuring profile was placed next to the calibrated measuring flume in front of the inflow to the primary sedimentation tank. Based on laboratory experiments and due to the low *B/h* ratio ($B/h \approx 3.0$), the velocity distribution in the cross section was calibrated prior to the experiments using the velocity gauging probe. The estimated results confirmed the potential of applying the method under field conditions. Figure 5 shows the measured time-averaged velocity profiles at the waste water surface. Comparison with the reference measurement by the calibrated Venturi flume, showing excellent agreement, is given in Figure 6.

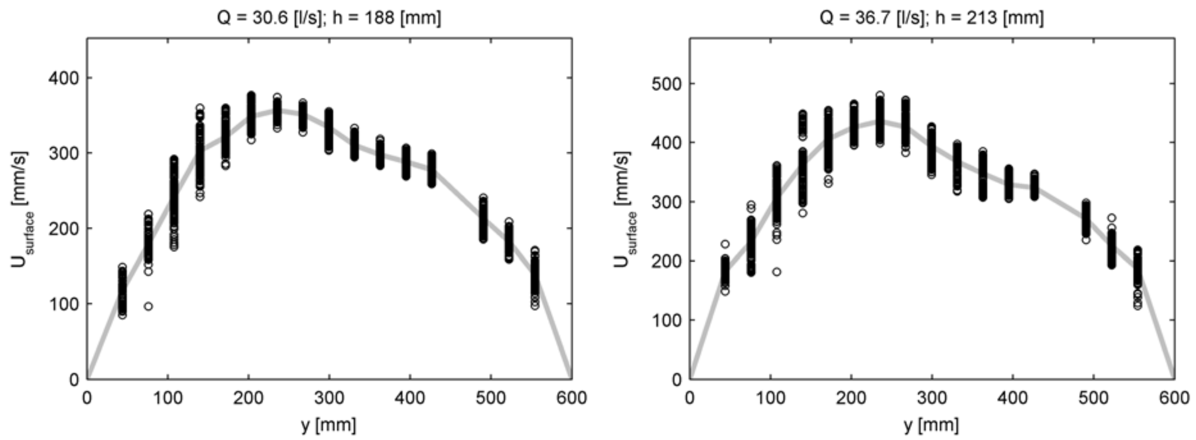

Figure 5. Open channel flow velocity distribution at the free surface of the rectangular channel at the WWTP inflow (instantaneous and time-averaged velocity).

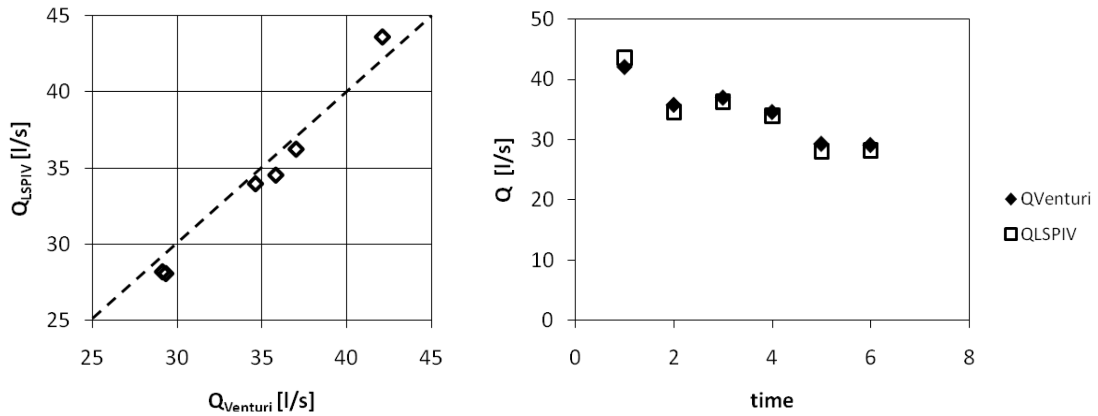

Figure 6. Correlation between the discharge estimated using the LSPIV method and a calibrated Venturi flume at the WWTP inflow.

CONCLUSIONS

These results demonstrate the applicability of the method based on image processing for discharge measurement in open channel flow under different boundary conditions. The main outputs can be summarized as follows:

- the method is applicable to urban drainage systems
- raw waste water has a sufficient concentration of floatable solids for the correct detection of velocity vectors using the correlation technique. Full instantaneous and time-averaged surface velocity distribution can be monitored using the LSPIV technique
- the flowrate evaluation strongly depends on the method used to transform the surface velocity distribution to average velocity in the cross section. This transformation strongly depends on dimensionality of the flow and the presence of secondary currents in the cross section. Therefore, the width-varying *RF* between depth-average velocity and surface velocity is generally recommended
- in flows with a high *B/h* ratio, e.g natural streams, the depth-averaged velocity can be rationally estimated based on the theoretically established *RF* factor

- our experiments show the possibility of monitoring the flow rate of waste water continuously in time and with high precision.

Based on the experiments performed, it can be concluded that the numerical modeling of open channel flow with the inverse modeling approach can successfully be used to evaluate flow rate for different channel geometry and flow conditions. Such an approach could significantly decrease the uncertainty of the method originating from the transformation of surface velocity distribution to average velocity in the cross section.

AKNOWLEDGEMENT

This work was supported by the Czech Science Foundation; project No. 103/07/P269 and by the project of the Czech Ministry of Education, Youth and Sport No. MSM6840770002. Special thanks for technical support go to M. Urban (Eyedea Ltd.) and Prague Water Supply and Sewerage System Company (PVK).

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