Flow Field Investigation in a Rectangular Shallow Reservoir using UVP, LSPIV and numerical model

SAMEH KANTOUSH, ERIK BOLLAERT, GIOVANNI DE CESARE,
JEAN-LOUIS BOILLAT and ANTON SCHLEISS
Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), CH - 1015 Lausanne, Switzerland,

Low velocity and shallow-depth flow fields often are a challenge to most velocity measuring instruments. In the framework of a research project on reservoir sedimentation, the influence of the geometry of the reservoir on sediment transport and deposition was studied. Inexpensive and accurate technique for Large Scale Particle Image Velocimetry (LSPIV) was developed to measure velocity field in 2D. An Ultrasonic Doppler Velocity Profiler (UVP) and numerical simulation were used for verification and validation for LSPIV technique. The velocities were measured by means of UVP, which allows an instantaneous measurement of the 1D velocity profile over the whole flow depth. The turbulence large scale structures and jet expansion in the basin have been developed from the 3D velocity measurements by UVP, LSPIV and numerical simulations. Vertical velocity distributions were developed to study the vertical velocity effect. UVP measurements confirms 2-D flow map in shallow reservoir. LSPIV has potential to measure low velocity. The comparison between LSPIV, UVP and numerical simulation give sufficient agreements.

Keywords: Shallow flow, Reservoir sedimentation, UVP, 3D-flow field, LSPIV, CCHE2D.

1 INTRODUCTION

1.1 Background

In the framework of a study on the influence of reservoir geometry on the process of sedimentation in shallow reservoirs by suspended load was studied [8]. Two measuring techniques were applied for velocities and instantaneous flow pattern visualization.

Several applications for 1D, 2D and 3D velocities measurements by using UVP have been carried out at Laboratory of Hydraulic Constructions (LCH). The influence of the ribs on the maximum scour depth at a curved channel flows by 3D time averaged flow field have been studied by [5]. Of course there are a lot of different applications by using UVP for velocities measurement (as example [2]).

PIV offers a simple method of measurement in areas with complicated geometry and flow conditions. Surface flow measurements with PIV are described for e.g. in [1]. In hydraulic engineering, however, this technique has so far mainly been applied for surface velocity measurements of water and ice flow in very uniform flow fields [3]; [4].

Numerical simulation of flows in shallow reservoirs has to be checked for its consistency in predicting real flow conditions and sedimentation patterns. Typical flow patterns may exhibit flow separation at the inlet, accompanied by several recirculation and stagnation regions all over the reservoir surface. In this paper, numerical simulations were carried out by CCHE2D [6].

1.2 Aim of the study

This study focuses on the sedimentation of shallow reservoirs by suspended sediments with the objective to gain insight into the physical process in shallow reservoirs. By investigation of 2D surface velocity fields and profiles of vertical velocity components, a better understanding of the mechanism governing the sediment exchange process between the jet entering the reservoir and the associated turbulence structures is attempted. The present paper focuses on:

1- The effect of the vertical velocity components on shallow reservoir sedimentation patterns.

2- A comparison between 2D-velocity obtained from two different techniques (UVP and LSPIV).

3- Validation of numerical model by use of LSPIV and UVP tests results.

3D velocity measurements are part of test series prepared to investigate the ideal reservoir geometry, minimizing the settlement of suspended sediments.

2 EXPERIMENTAL MEASURMENTS

2.1 Experiment facilities

The experiments were carried out in a specific test facility at the Laboratory of Hydraulic Constructions (LCH) of the Swiss Federal Institute of Technology (EPFL). A schematic view of the experimental setup is shown in Figure 1. The setup consists of a rectangular inlet channel 0.25 m wide and 1.0 m long made of PVC, a rectangular shallow basin with inner dimensions of 6.0 m length and 4.0 m width, an outlet rectangular channel 0.25 m wide and 1.0 m long, a flap gate 0.25 m wide and 0.30 m height at the end of the outlet (see Figure 1). A sediment supply tank is mounted above the mixing tank. The mixing tank is equipped with a propeller type mixer to create a homogenous sediment concentration. After filling the experimental reservoir with water, the water-sediment mixture will flow by gravity into the rectangular basin through a flexible pipe with 0.10 m diameter. On the basin side walls a 4.0 m long, movable aluminium frame is mounted which carries the measurement instruments can move in three directions.

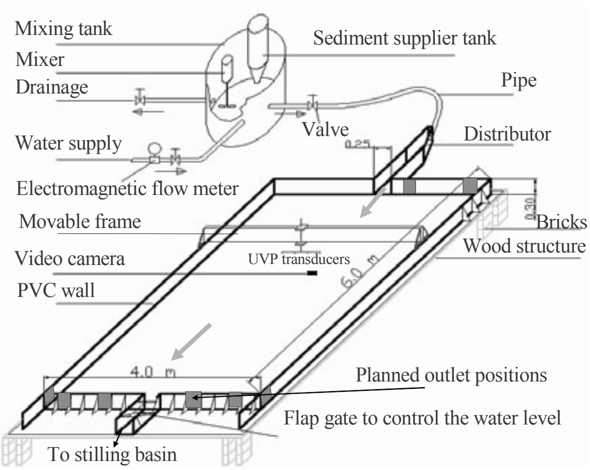


Figure 1: Schematic drawing of the experimental installation

2.2 Measurements and data acquisition system

Several parameters were measured during every test; namely: surface velocities, 3D flow velocity, water level and water temperature.

2.2.1 Ultrasonic Doppler Velocity Profiler (UVP)

The velocities were measured by means of an Ultrasonic Doppler Velocity Profiler (Metflow SA, UVP-DUO), which allows an instantaneous measurement of the 1D velocity profile over the whole flow depth [8]. The measurement probes were mounted on a support in groups of three, allowing the measurement of the 3D flow field (Figure 2). Since the number of measurement points was high, four PVC plates mounted on the measurements frame, allowing to record four groups of three 1D profiles (constituting one 3D profile) simultaneously to accelerate the data acquisition (see Figure 2). To cover the whole cross section of the basin, 4 positions were chosen along the cross section; each position has four groups of three probes (see Figure 2). All twelve probes were mounted on a frame which moves in the two horizontal directions. The probes were inclined at 20° to the vertical and had an emitting frequency of 2 MHz. A multiplexer shown in Figure 2 allowed switching between the different UVP-probes. Velocity profiles were recorded for all points on a 25* 50 cm grid in transversal and with flow direction respectively. In order to extract the 3D velocity field in twelve cross sections over the whole reservoir, the acquired binary velocity file needed some treatment. First the twelve 1D records were read from the raw data file. Then calculation of the velocity time-averaged measured components (average of 24 profiles). Then projection for these values and obtained velocity components cover the whole measurement depth. After rearrangement of the velocity profile, the data was exported to a text file for future automatic treatment with Matlab.

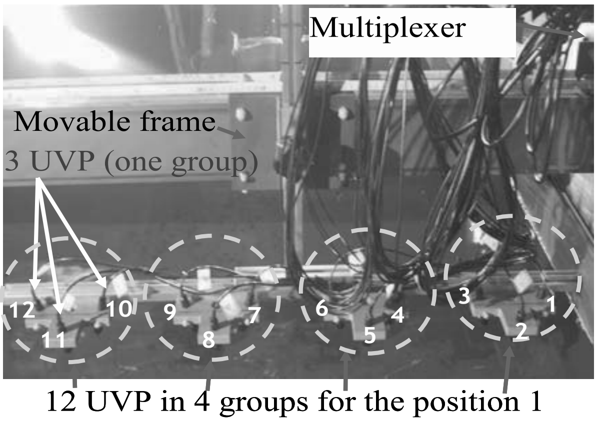


Figure 2: Above: Scheme of UVP installations and data acquisition, Below: Plane view and dimensions of UVP

2.2.2 Large-Scale Particle Velocimetr (LSPIV)

Large-scale particle image velocimetr (LSPIV) is an efficient and powerful technique for measuring river surface velocities. LSPIV is an extension of conventional PIV for velocity measurements in large-scale flows. While the image and data-processing algorithms are similar to those used in conventional PIV, adjustments are required for illumination, seeding, and pre-processing of the recorded images. A digital camera connected to a computer was used to record images, white plastic particles and reasonable lights as shown in Figure 3 were used for velocities measurements. Transformation of the images to remove perspective distortion from the objective lens using PTLens software and the image processing were conducted using FlowManeger software. The camera fixed perpendicular on the basin covering the plane basin area (the whole width 4.0 m and 5.0 from the length, missing 0.5m from upstream and downstream ends).

The flow is seeded with plastic particles (with average diameter 3.4 mm and specific weight 960 kg/m^3) which are then illuminated. The dispersed light allowed recording their positions at two successive instant by video (SMX-155, monochrome, 1.3 megapixel, CMOS camera with USB2.0 interface and frame rate up to 33 FPS). The plan view (measurement plan) is divided into several small sub-areas, known as interrogation areas, IA. In each IA the cross-correlation algorithm is applied in order to calculate the shift of the particles ΔX in the time between two images ΔT.

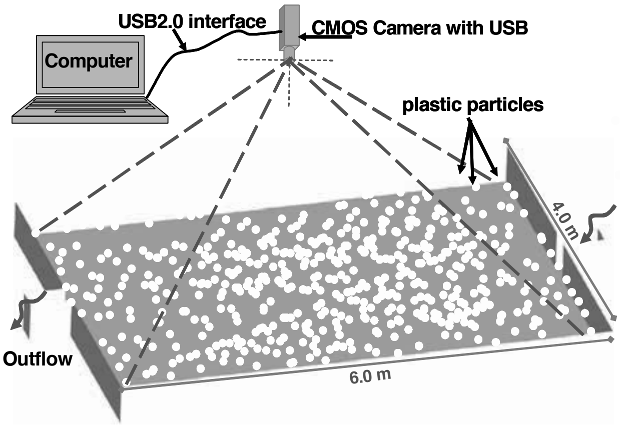


Figure 3: Scheme of LSPIV installations and data acquisition

2.2.3 Numerical simulations

Numerical simulations have been performed by using the CCHE2D software with the objective of comparing with the laboratory experiments. CCHE2D is two-dimensional hydrodynamic and sediment transport model for unsteady open channel flows over loose bed. Further details can be found in [6] & [7]. CCHE2D is a depth-integrated 2D hydrodynamic and sediment transport model based on a variant of the finite element method. Simple reservoir geometry has been simulated in order to study whether the relevant processes can be reproduced mathematically, and what features are controlling the phenomena. The model has been represented by a simple rectangular grid spacing of about 0.10 m in the flow direction and 0.05 m in the transverse direction. A total discharges of 7.0 l/s, a flow depth of 0.20 m and a bed roughness n = 0.01 have been used as boundary and initial conditions. For detailed study of the boundary conditions and the results about these simulations see [7].

3 RESULTS

3.1 Velocity distribution by UVP

Distribution of vertical velocity for alluvial river is particularly important to know the transport of suspended sediment. For the analysis of the 3D velocities measured by UVP one cross section (CS11) near the downstream end of the basin (x=5.5 m) have been chosen. Due to the following reasons the first data point of the velocity profile is located at 18 mm from the free water surface (Figure 4). After 1.50 hour experiment time, regular and uniform velocity profile in vertical depth and friction near zero along the cross section are observed in the downstream cross section shown in Figure 4.

Velocity distributions in stream wise, transversal and vertical directions (U, V, W respectively) at cross section11 (CS11), located at x-distance 1875 mm; are shown in Figure 5. Vertical velocity are rather small comparing with the other two which it could be negligible and consider the reservoir as a shallow 2D. Moreover, the vertical eddies can be seen clearly from both Figures 4 and 6. So in the same time with horizontal circulations there is a vertical circulation is interaction with the horizontal one. The measurements showed that the velocity has a uniform distribution in vertical direction which confirms that the shallowness of the flow and vertical velocity is so low and uniform comparing with the other directions.

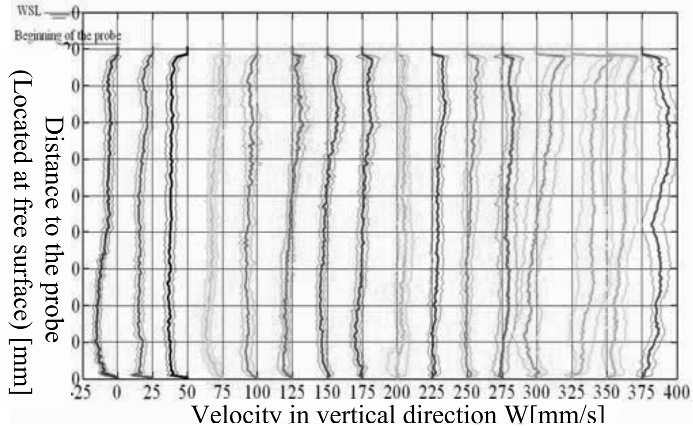


Figure 4: Velocity profiles and standard deviation measured by UVP (CS11)

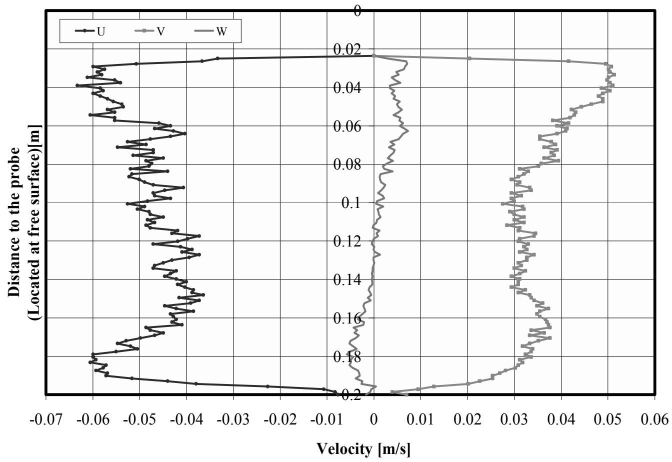


Figure 5: Velocity profiles in three directions U, V & W at x-distance 1875 mm from the left bank of cross section 11

Figure 6 shows the vertical velocity W contours distributed across the reservoir section (twelve cross sections every 0.5 m). The measurements shows that the higher velocity is shifted to the right hand side and the maximum velocity occurs near the wall; gyres and eddies are shown clearly in Figure 6. The maximum velocity is around the centerline and increases towards the walls which indicate that there is no friction in the bed.

3.2 Velocity vector map

Averaged flow fields have been obtained by using

UVP, LSPIV and CCHE2D software; are depicted in Figure 7(a), (b) & (c) respectively. Figure 7 shows that the flow enters as a plane jet issuing from the narrow leading channel to the wide basin. After jet issuance, the main flow tends towards the right hand side, generating a large and stable main gyre rotating anticlockwise and two small ‘triangular’ gyres rotating clockwise in the two upstream corners of the basin. The jet appears to be attracted to one of the side-walls. Its preference for the right side is weak since a stable mirror image of the flow pattern can easily be established by slightly adapting the initial conditions.

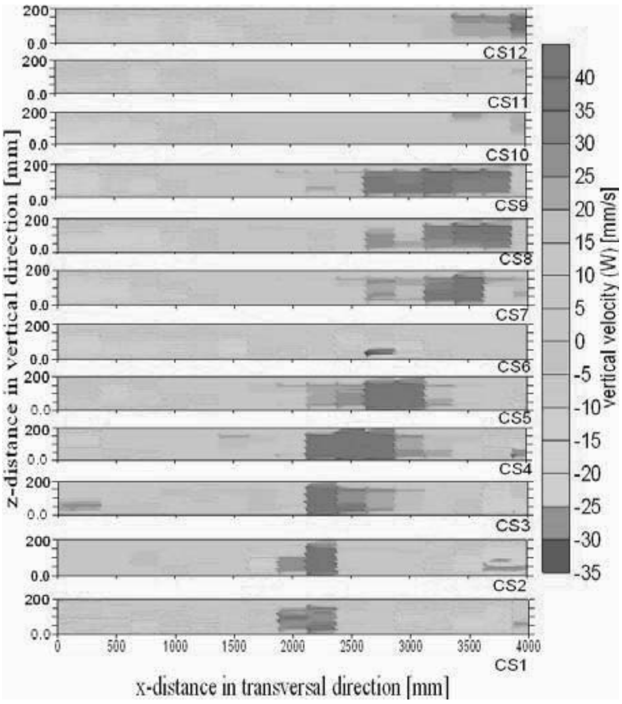
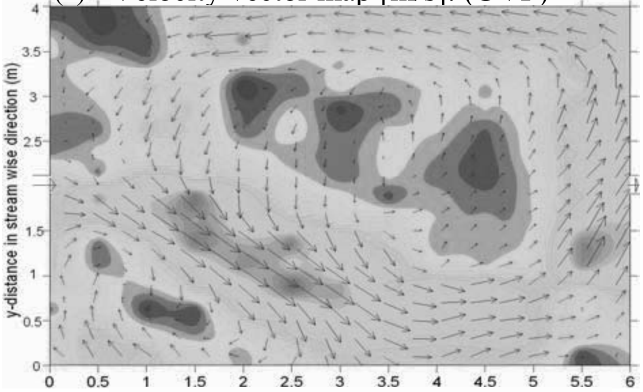


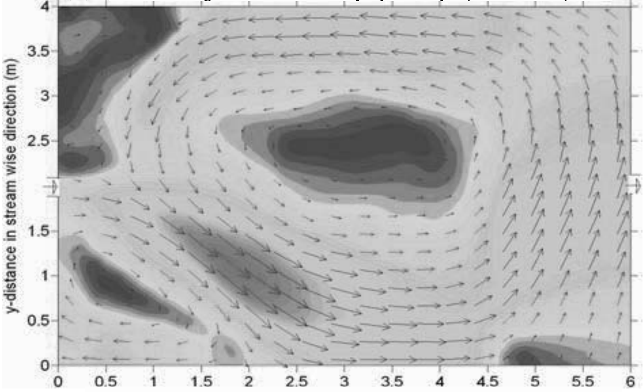
Figure 6: Vertical velocity contours at different cross sections (every 500 mm distance)

By following floating particles, it is noticed that in the first meter from the entrance the particle is straightly entering and, in the next two meters, it deflects to the right until it arrives at the stagnation points near the right wall at the middle (3m from the entrance). The particles that do not leave the basin through the outlet channel circulate with the main gyre to arrive near the separation zone at the farthest left side wall. There, a small gyre has formed at the left corner of the basin with a triangular shape 1.2mx1.2m. The circulation pattern sustains itself because the inertia of the main gyre pushes the in coming jet aside. By comparing the three techniques similar gyre patterns are obtained even with different measuring techniques and calculating program. It’s clear that the flows structures by UVP and LSPIV in Figures 7(a) & (b) respectively are similar in magnitude and sharing the same position for the gyres centers. Numerical simulation for that kind of complex flow structure is rather difficult. In spit of that a good agreement velocity vectors and magnitude are obtained with CCHE2D as shown in Figure 7(c). Figure 8 compare the simulated (computed by CCHE2D) and measured (measured by UVP and LSPIV) velocity vectors overall the basin. The measured vectors by UVP and LSPIV are in excellent agreement. By comparing the two method small difference (see Figure 8) exist at the middle part of the reservoir due to low number of the measured points by UVP and low velocity in the large circulation. Figure 8 shows that the velocity vectors by CCHE2D are acceptable and generally in a good agreement with the two other techniques. It could be explained by the complexity of that type of flow and the possibility that the turbulence model is too diffusive and may be the related to the inadequacy of the eddy viscosity models.

(a) Velocity vector map [m/s]: (UVP)



(b) Velocity vector map [m/s]: (LSPIV)



(c) Velocity vector map [m/s]: (CCHE2D)

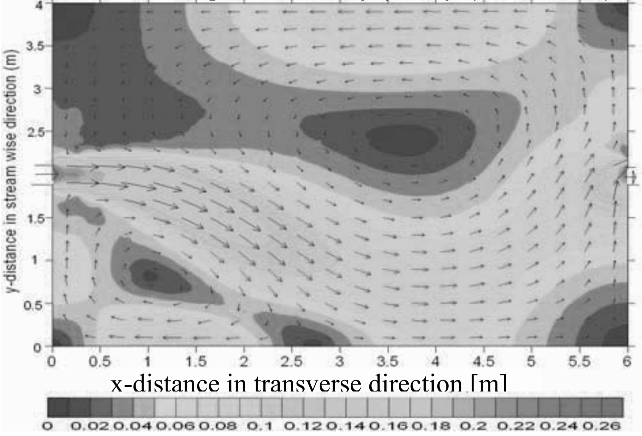


Figure 7: Stationary flow field from three different techniques a) UVP b) LSPIV c) CCHE2D

Figure 9 compares the computed and measured axial velocity magnitude at the basin centerline. Velocity distributions for UVP and LSPIV are approximately the same in the inlet channel. At the interface between inlet channel and basin, a sudden velocity increase may be observed, followed by a gradual decrease throughout the whole basin length. The sudden increase in velocity might be due to the sudden influence of the recirculation eddy that produces significant shear between the jet and the stagnant water, influencing so the horizontal velocity distribution of the jet, before jet diffusion becomes more important.

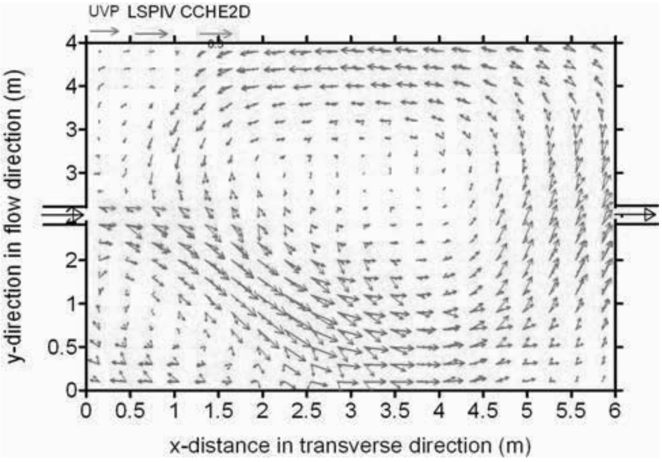


Figure 8: Comparison of velocity magnitude vectors from UVP, LSPIV, and CCHE2D program.

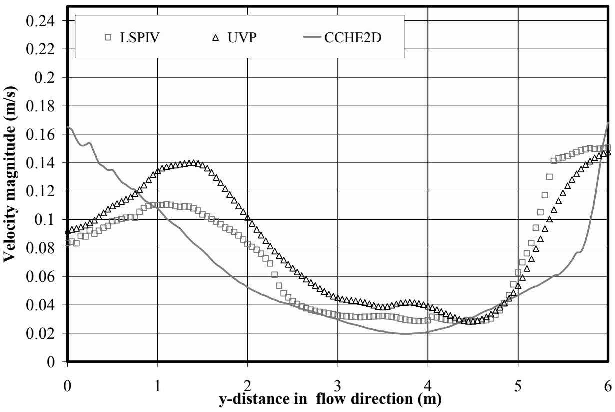


Figure 9: Comparison of longitudinal velocity magnitude along the basin centerline from UVP, LSPIV and numerical model (CCHE2D).

6 SUMMARY AND CONCLUSIONS

The first results of ongoing research on the influence of the geometry of a shallow reservoir on suspended sediment transport and deposition have been presented. It was found that the flow is quite sensitive to the boundary and initial conditions. The flow structures for shallow reservoir have been successfully measured using two different techniques LSPIV and UVP. Moreover; low and near zero velocities successfully measured by LSPIV were validated with UVP measurements and numerical simulations by CCHE2D. The following points could be confirmed:

(1) The two-dimensional velocity vector field in shallow reservoir can be reconstructed by combining three measurement data sets of UVP.

(2) The LSPIV efficiency as a surface velocity measurement tool reveals efficient in low velocity shallow water that present numerous difficulties and challenges to existing instruments.

(3) This particular behavior could also be reproduced by a two-dimensional depth-averaged flow and sediment transport model (CCHE2D). The numerical simulation indicates that the flow pattern can easily switch to different directions, depending on the boundary and initial conditions.

The comparison with UVP measurements allow to conclude that LSPIV has potential for measuring low velocities and is believed to be applicable in field tests as well. Moreover; it could be used for verification of the numerical model. Regarding the continuation of this research project the major goal is to find out which reservoir geometry leads to minimum sediment deposition. This requires experiments of long duration combined with numerical modeling techniques that include all the processes related to water and sediment.

ACKNOWLEDGMENTS

Authors thanks for Metflow SA, Lausanne, Switzerland for support and providing UVP probes.

REFERENCES

[1] Adrian, R. J. Particle-imaging techniques for experimental fluid mechanics. Annu. Re. Fluid Mech. 23, 261-304 (1991).

[2] De Cesare G. Use of UVP monitor in applied hydraulics, Proc. XVI. Symposium on Anemometry, (1999).

[3] Emttea R., Fujita I., Muste M., Krufer A. Particle Image Velocimetry for whole field measurement of ice velocities. Cold Regions Science and Technology Vol. 26, 97-112 (1997).

[4] Fujita I., Muste M., Kruger A. Large scale Particle Image Velocimetry for flow analysis in hydraulic engineering ap-plications, Journal of hydraulic Research, Vol. 36, No 3, 397-414 (1998).

[5] Hersberger, D.S. Measurement of 3D flow field in a 90° bend with ultrasonic Doppler velocity profiler. Third International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering. PSI Proceedings 02 -01, ISSN 1019 – 6447: 59 – 66. (EPFL), (2002).

[6] Jia, Y., and Wang, S. S. Y., 1999. Numerical model for channel flow and morphological change studies. J. Hydraulic. Eng. Vol. 125(9), 924-933.

[7] Kantoush, S. A., Bollaert, E. F. R., Boillat, J.-L., Schleiss, A. J. Suspended load transport in shallow reservoirs. Final Proc. XXXI IAHR Congress. Korea Water Resources Association, Seoul, South Korea, 1787-1799 (2005).

[8] Metflow. UVP Monitor – Model UVP-DIO. Users guide, Metflow SA, Lausanne, Switzerland, (2002).