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Flow field investigation in a rectangular shallow reservoir using UVP, LSPIV and numerical modelling

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Abstract

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 reservoir geometry on sediment transport and deposition was studied. An inexpensive and accurate technique for Large-Scale Particle Image Velocimetry (LSPIV) was developed to measure the surface velocity field in 2D. An Ultrasonic Doppler Velocity Profiler (UVP) and LSPIV techniques were used for verification and validation of the numerical simulations. The velocities measured by means of UVP allowed 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 determined based on UVP, LSPIV and numerical simulations. Vertical velocity distributions were defined to study the vertical velocity effect. UVP measurements confirm 2D flow map in shallow reservoir. LSPIV has potential to measure low velocities. The comparison between LSPIV, UVP and numerical simulation gives good agreements.

Keywords: Shallow flow; Reservoir sedimentation; UVP; 3D flow field; LSPIV; CCHE2D; Particle image velocimetry; Experiments; Measurements

1. Introduction

1.1. Background

In the framework of a study on the influence of reservoir geometry on the process of sedimentation, suspension in a shallow reservoir has been investigated [1]. Two measuring techniques were applied to define velocities and time-averaged flow pattern visualization.

Several applications for 1D, 2D and 3D velocity measurements by using UVP have been carried out at the Laboratory of Hydraulic Constructions (LCH) [2]. For example, the influence of ribs on the maximum scour depth along a curved channel has been described in [3].

PIV offers a straightforward method of flow measurement in areas with complicated geometry and flow conditions [4]. In hydraulic engineering, however, this technique has so far mainly been applied for surface velocity measurements of water and ice flow in uniform flow fields in the laboratory as well as in field experiments in river channels with groins [5–8]. LSPIV has been applied for flows in large shallow reservoir under various configurations [9].

Numerical simulation of flow 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. The numerical simulations presented in this paper were carried out by CCHE2D [10].

1.2. Aim of the study

This study focuses on the sedimentation of shallow reservoirs by suspended load with the objective to gain insight into the governing physical processes. 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.

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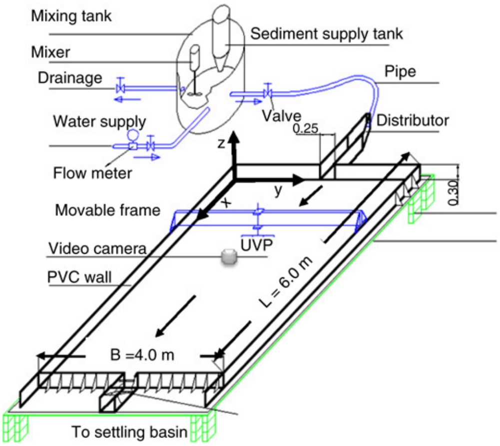

Fig. 1. Schematic view of the experimental installation of the shallow reservoir.

The present paper focuses on the effect of the vertical velocity components on shallow reservoir sedimentation patterns. Furthermore, comparisons of the 2D velocity fields obtained by two different techniques (UVP and LSPIV) are given. The UVP and LSPIV tests results are then used for the validation of numerical model. Finally 3D velocity measurements are presented being part of the test series prepared to investigate the ideal reservoir geometry with the purpose of minimizing the settlement of suspended sediments.

2. Experimental measurements

2.1. Experimental facility

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). The setup shown in Fig. 1 consists of a rectangular inlet channel, 0.25 m wide and 1.0 m long, 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 Fig. 1). A sediment supply tank is mounted above the mixing tank. The mixing tank is equipped with a propeller type mixer to create a homogeneous sediment concentration. To model the suspended sediment currents in the laboratory model, crushed walnut shells with a median grain size $d_{50} = 50$ μm, density 1500 kg/m^3 are used in the test. These are non-cohesive and light grains. The sediments are added to the mixing tank during the test with concentration 3.0 g/l. 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. A 4.0 m long, movable aluminium frame is mounted over the basin, which carries the measurement instruments and moves in three directions.

2.2. Measurements and data acquisition system

Several parameters were measured during every test; namely: surface velocities, deposited sediment layer thickness, suspended sediment concentration at the outlet, 3D flow velocity, water level and water temperature. Table 1 provides an overview of the measurements and instrumentations used during the tests.

Table 1
Model parameters and instrumentations

Measured parameters	Dimension	Instrument
Water level	[m]	Ultrasonic probe
Sediment thickness	[m]	MiniEchoSounder (UWS)
Discharge	[m^3/s]	Flow meter
Surface velocity	[m/s]	LSPIV technique
3D flow velocity	[m/s]	Ultrasonic Velocity Profiler (UVP)
Sediment concentration	[g/l]	Turbidity meter
Temperature	[C°]	Thermistors

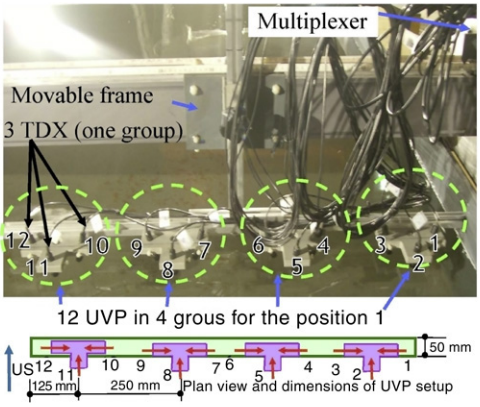

Fig. 2. Above: Scheme of UVP installations and data acquisition, Below: Plane view and dimensions of UVP.

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 [11]. The measurement probes were mounted on a support in groups of three, allowing the measurement of the 3D flow field (Fig. 2). Since the number of measurement points was high, four PVC plates were mounted on the measurement frame, allowing to record four groups of three 1D profiles (constituting one 3D profile) to accelerate the data acquisition process (see Fig. 2). Measurements are carried out at different time instants. To cover the whole cross-section of the basin, 4 positions were chosen along the cross-section; each position containing four groups of three probes (see Fig. 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 allowed switching between the different transducers (Fig. 2). Velocity profiles were recorded for all points on a 25 cm × 50 cm grid in transversal and in flow direction respectively.

Several preliminary tests have been carried out for the optimization of UVP parameters specifications. Due to low velocity and shallow flow injection for tracer has to be used. Hydrogen bubbles can be used as fluid tracers for providing echo, i.e., ultrasound reflector. In the performed

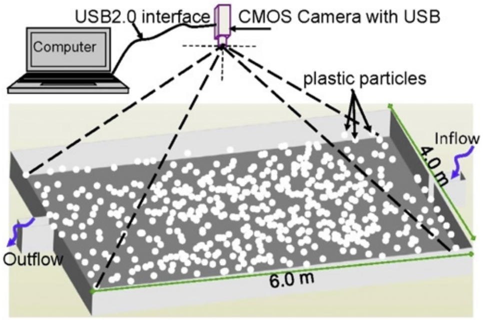

Fig. 3. Scheme of LSPIV installations and data acquisition.

tests, the bubbles are generating using an array of horizontal stainless steel wires with a diameter of 100 μm with a vertical spacing of 1 cm. With hydrogen bubble the local obtained echo was sufficient near the transducer but due to the low velocity the bubble did not distribute quickly to the other transducers. Moreover the bubbles did not generate in the transducers directions; consequently a fine suspended sediment particle (Walnut crushed shells) has been used to generate US echoes. These are non-cohesive, light weight and homogeneous particles with very low settling velocity to guarantee a completely mixing state in the entire volume. Particle settling velocity is less than 0.001 m/s. Vertical velocities are approximately 25 times higher than the particles settling velocities. The fine particles with low specific gravity have negligible influence on the vertical velocity measurements.

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, followed by the calculation of the velocity time-averaged measured components (average of 24 profiles). Then projections of these values to obtain perpendicular velocity components (U, V, W) covering the whole measurement depth. After the rearrangement of the velocity profile, the data was exported to a text file for future automatic treatment with Matlab.

2.2.2. *Large-scale particle velocimetry (LSPIV)*

Large-scale particle image velocimetry (LSPIV) is an efficient and a powerful technique for measuring surface flow velocities. LSPIV is an extension of the 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 is used to record images. White plastic particles and light sources, shown in Fig. 3, were used for velocity measurements. Transformation of the images to remove perspective distortion from the objective lens using PTLens software and the image processing are conducted using FlowManager software. The camera is fixed perpendicularly above the basin, covering almost the whole basin area (the whole width 4.0 m and 5.0 m of the length, 0.5 m missing of the upstream and downstream ends).

The flow is seeded with plastic particles (with 3.4 mm average diameter and 960 kg/m^3 specific weight) which are illuminated. The dispersed light allows recording their positions at two successive instants 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.

2.2.3. *Numerical simulations*

Numerical simulations have been performed by using the CCHE2D software with the purpose to compare them with the laboratory experiments. CCHE2D is a 2D hydrodynamic and sediment transport model for unsteady open channel flows over mobile bed [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, 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 discharge of 7.0 l/s, a flow depth of 0.20 m and a bed roughness of $n = 0.01$ have been used as boundary and initial conditions. The turbulence closure scheme is a parabolic eddy viscosity model.

Governing equations

The depth-integrated 2D equations that are solved in the model are:

Continuity equation:

$$\frac{\partial z}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0. \tag{1}$$

Momentum equations

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial z}{\partial x} + \frac{1}{h}\left[\frac{\partial (h\tau_{xx})}{\partial x} + \frac{\partial (h\tau_{xy})}{\partial y}\right] - \frac{\tau_{bx}}{\rho h} + f_{\text{cor}} v \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial z}{\partial y} + \frac{1}{h}\left[\frac{\partial (h\tau_{yx})}{\partial x} + \frac{\partial (h\tau_{yy})}{\partial y}\right] - \frac{\tau_{by}}{\rho h} - f_{\text{cor}} u \tag{3}$$

where u and v are the depth-integrated velocity components in x and y directions, respectively; t is the time; g is the gravitational acceleration; z is the water surface elevation; ρ is the density of water; h is the local water depth; f_{cor} is the Coriolis parameter; τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are depth-integrated Reynolds stresses; and τ_{bx} and τ_{by} are shear stresses on the bed surface.

3. Results

3.1. *Velocity distribution by UVP*

The distribution of the vertical velocity in an alluvial river is particularly important to know the transport of suspended

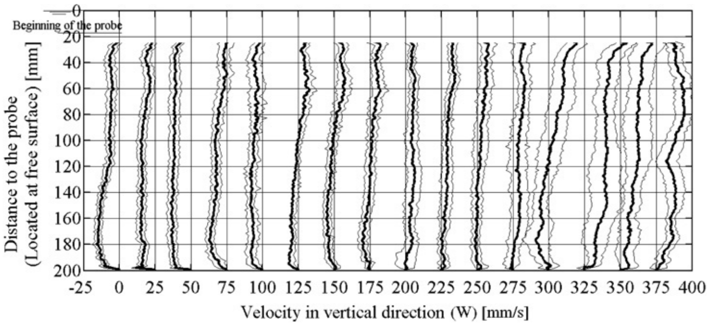

Fig. 4. Vertical velocity profiles and standard deviation measured by UVP (CS11).

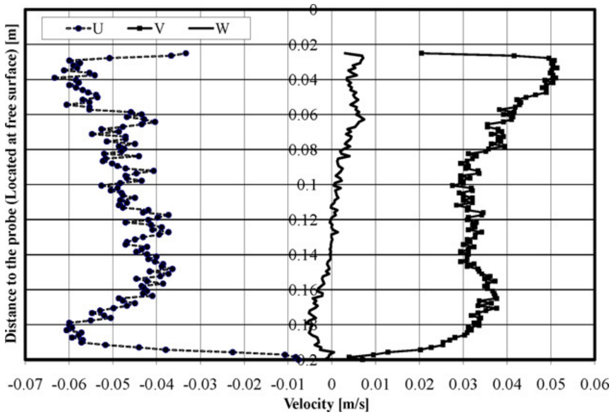

Fig. 5. Quasi-instantaneous velocity profiles in three directions longitudinal (U), lateral (V) and vertical (W) at x-distance 1875 mm from the left bank of cross-section 11.

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) has been chosen. The first valid data point of the velocity profile is located at 25 mm from the free water surface (Fig. 4). After 1.50 hour of experiment, regular and uniform velocity profiles along the vertical are observed in the downstream cross-section, shown in Fig. 4.

Velocity distributions in streamwise, transversal and vertical directions (U, V, W respectively) at cross-section (CS11), located at x-distance 1875 mm, are shown in Fig. 5. Vertical velocities are rather small compared to the horizontal ones, confirming the shallow 2D character of the reservoir. Moreover, the eddies with horizontal axis are clearly visible at Figs. 4 and 6. So, together with horizontal circulations, there is a vertical circulation.

Fig. 6 shows the vertical velocity contours W, distributed across the reservoir for twelve cross-sections of every 0.5 m. It can be seen that the higher velocity is shifted to the right-hand side and the maximum velocity occurs near the wall; gyres and eddies are clearly shown in Fig. 6.

3.2. *Velocity vector map*

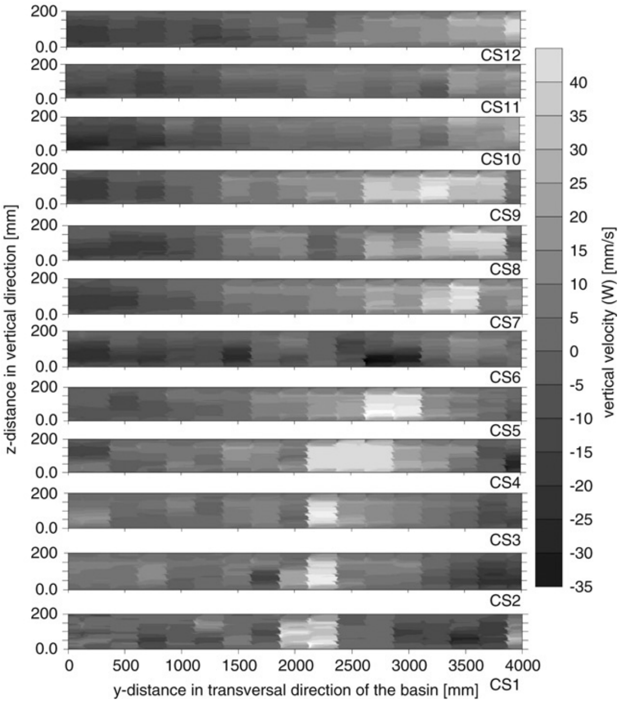

Fig. 6. Vertical velocity contours at different cross-sections (every 500 mm distance).

The time-averaged flow fields, obtained by using UVP and LSPIV techniques and by CCHE2D numerical software are depicted in Fig. 7(a), (b) and (c) respectively. Fig. 7 shows that the flow enters as a plane jet issuing from the narrow approach channel to the wide basin. After the jet issuance, the main flow tends towards the right-hand side, generating a large and stable main gyre, rotating anticlockwise, and two small 'triangular' shape 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.

By following the floating particles, it can be noticed that, in the first meter downstream from the entrance, they enter in the axis of the approach channel and in the following two meters, they deflect to the right until arriving at the stagnation point near the middle of the right wall (2.65 m from the entrance). The particles which do not leave the basin through the outlet channel circulate with the main gyre and arrive near the separation zone at the farthest left side wall. There, a small gyre is formed at the left corner of the basin with a triangular shape 1.2 m × 1.2 m. The circulation pattern sustains itself because of the inertia of the main gyre, which pushes the incoming jet aside. More

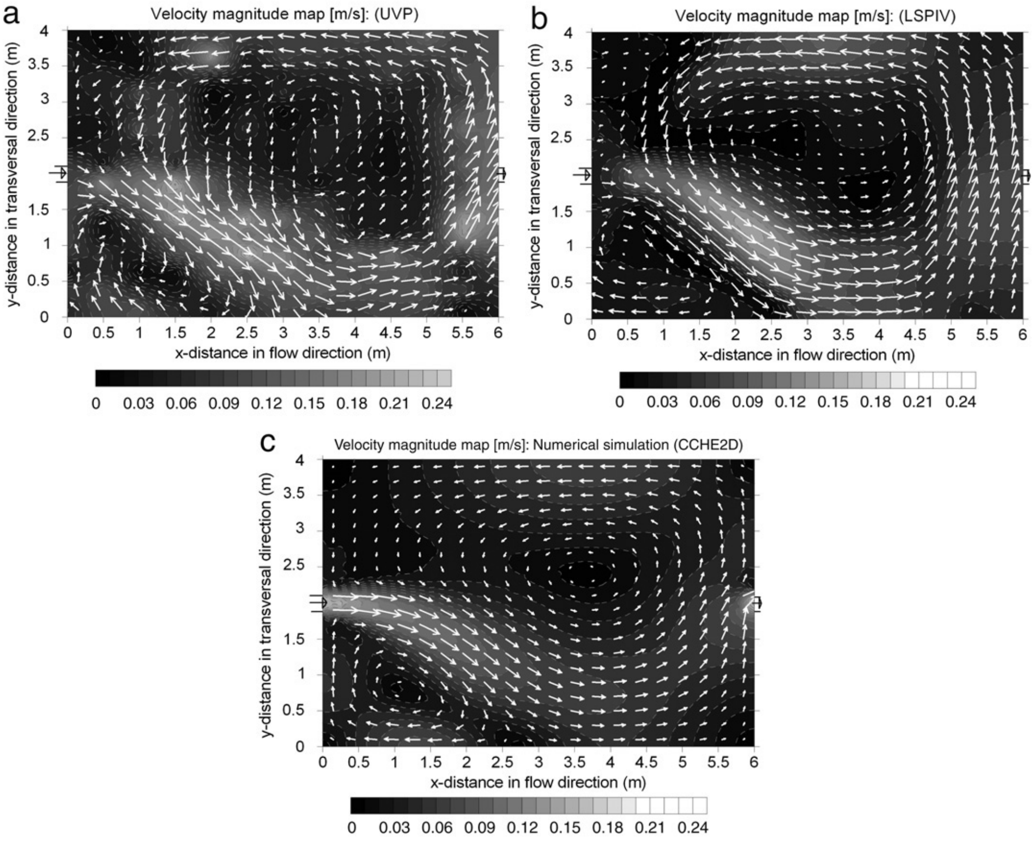

Fig. 7. Stationary flow field from three different techniques (a) UVP (b) LSPIV and (c) CCHE2D.

details about asymmetric flow behaviour in the reservoir have been studied by Kantoush [12].

By comparing the three techniques, similar gyre patterns are obtained. The flow structures measured by UVP and LSPIV in Fig. 7(a) and (b) respectively are similar in magnitude and share the same position for the gyre centres. Numerical simulation for that kind of complex flow structures is rather difficult. In spite of that, good agreement for both velocity vectors and magnitude are obtained with CCHE2D as shown in Fig. 7(c).

Fig. 8 compares the simulated (computed by CCHE2D) and measured (measured by UVP and LSPIV) velocity vectors over the entire basin. The measured vectors are generally in very good agreement. Small differences (see Fig. 8) exist at the middle part of the reservoir, due to the low number of UVP measurement points and the low circulation velocity. There exists a small discrepancy between numerical and experimental results in particular, water flows from the upper wall (at $x = 4$ m) toward the inlet jet are less than the measured values. Fig. 8 shows that the velocity vectors computed by CCHE2D are acceptable and generally in good agreement with the measurement techniques. For a better approximation of turbulent eddies and jets formation, it is recommended to use a more detailed model for horizontal turbulence. For instance techniques such as horizontal large eddy simulation or even fully 3D approaches may be considered.

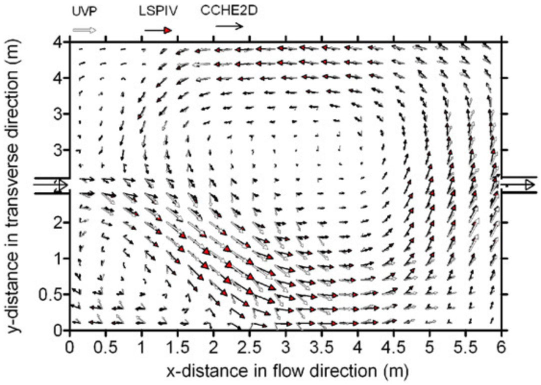

Fig. 8. Comparison of velocity magnitude vectors obtained from UVP and LSPIV measurement, and CCHE2D simulation.

Fig. 9 compares the computed and measured values of axial velocity at the centreline of the basin. Velocity distributions for UVP and LSPIV are approximately the same in the approach channel. At the interface between the approach channel and the basin, a sudden velocity increase is observed, followed by a gradual decrease throughout the whole basin length. The sudden velocity increase might be related to the sudden influence of the recirculation eddy which produces significant shear between the jet and the stagnant water, therefore the horizontal velocity distribution of the jet is influenced, before the jet diffusion becomes more important.

4. Conclusions

Analysis of these first-hand experiments allowed the following observations:

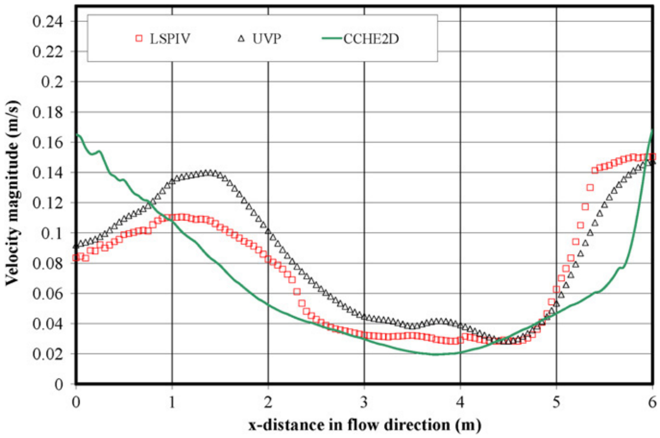

Fig. 9. Comparison of longitudinal velocity magnitude along the basin centreline from UVP, LSPIV and numerical model (CCHE2D).

Selected results of velocity measurements of a research searching the influence of the geometry of a shallow reservoir on suspended sediment transport and deposition have been presented. The flow is quite sensitive to the boundary and initial conditions. The flow structures and velocity distributions in shallow reservoirs have been successfully measured using the two techniques LSPIV and UVP. Also, strong asymmetric flow patterns developed during the experiment. These patterns could be simulated numerically by using a parabolic eddy viscosity model. The following points could be confirmed:

(1) The flow pattern in a shallow reservoir can be reconstructed by combining three measurement data sets of UVP.
(2) LSPIV efficiency as a surface velocity measurement tool reveals capable in low velocity shallow water that presents numerous difficulties and challenges to the existing instruments.
(3) The measured flow patterns could be reproduced by a 2D depth-averaged flow and sediment transport model (CCHE2D). The numerical simulation indicates that the flow pattern can easily switch to different directions, depending on small changes of the boundary and initial conditions.

The comparison with UVP measurements allow us 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 the verification of a numerical model. Regarding the continuation of this research project, the major goal is to find out which reservoir geometry leads to minimum sediment deposition on the long term. This requires experiments of long duration combined with 3D numerical modelling techniques that include the main processes related to water and sediment flow.

Acknowledgments

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