QUANTITATIVE VISUAL METHODS FOR NATURAL STREAMS: EXAMPLES AND PERSPECTIVES

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ABSTRACT

In the recent years flow visualization, a valuable method in experimental studies, gained a new prospective for studies of flow structure in natural streams. Complimentary to conventional particle tracking (PTV) and image velocimetry (PIV), visual observation of flow domain in natural streams with artificial (seeded particles) or natural (aquatic plants, invertebrates) tracers has particularly important implications for environmental fluid mechanics and ecohydraulics. Though the visualization methods developed in experimental fluid mechanics are already greatly advanced, their application to natural streams is difficult or even impossible. Available reports on field studies provide little information on theoretical grounds of methodologies they used and often lack a direct comparison of obtained results with conventional point measuring techniques. The aim of this paper is to summarize experience gained from recent applications of visual techniques for studies of shallow mixing layers, flow over submerged aquatic plants, and to outline perspectives for further application in ecohydraulics and studies of transport processes in rivers. The methodological aspects of PTV application in natural environments are discussed and comparison with results of point velocity measurements is presented for semi-controlled field experiments. Synchronous video records of vegetation canopy and instantaneous flow velocity vectors are shown to provide valuable information on coherent structures of the flow and their interaction with canopies. Perspectives of coupling visual methods and techniques with point velocimetry for studies of complex flow-biota interactions are discussed on examples of resent investigations of invertebrates' entrainment into drift under action of waves.

Keywords: turbulence, macrophytes, mixing layers, invertebrates, bedforms

1 INTRODUCTION

Visualization techniques were obviously the first methods applied to study the structural properties of flow in natural streams. This can be conjectured from the ancient folios containing flow sketches of which most famous are drawings of Leonardo da Vinci and traditional motives of oriental arts (Nezu and Nakagawa, 1993). Although in the last century surface drifters and aerial photography were intensively applied to study mean flow structure especially in complex flow over submerged floodplains, relatively few studies used visualization techniques to study turbulent structures (Jackson, 1976). Rare application of visual methods at that time accounted for involved technical difficulties in both application of analogue cinematography and processing of records to obtain quantitative information.

Recent developments in flow visualization techniques as particle tracking velocimetry (PTV), particle image velocimetry (PIV), and automated processing of digital records greatly advanced laboratory investigations (Fujita et al., 1998; Zhang and Chu, 2003; Uijttewaal and Jirka, 2006) and inspired application of visualization techniques for studies of flow structure in field (Roy et al., 1999; Bradley et al., 2002; Muto et al., 2002; Sukhodolov et al., 2002), Figure 1.

Figure 1. Application of PTV for field studies in the Wesenitz River, Germany.

In natural environments with complex geometry of channel, moveable alluvium, and influence of biological processes, visual methods of investigation need to be expanded beyond conventional frames of particle velocimetry. These methods are particularly important for studies of complex interactions between biotic and abiotic components of fluvial ecosystems. Submerged vegetation in natural streams produces dense canopies which properties depend on the flow characteristics and also cause effect on the flow structure. Flexibility of plants cause adaptation of canopies to certain flow characteristics and can be studied by visual techniques (Statzner et al., 2006; Sukhodolov and Sukhodolova, 2006). Recent studies on bed form dynamics indicated effectiveness of visual methods for registering spatial distribution of riverbed elevations (Jerolmack and Mohrig, 2005).

Although the visual techniques have a valuable potential for studies in natural environments, many practical problems associated with these techniques and methods need to be clarified. Particularly, the choice of tracer particles for PTV and PIV, arrangement of field setup, calibration of images, and methods of their post-processing are the common problems for different field applications that presently have no standardized solutions. This paper is written with a goal to sort out recent developments toward standardization of field visual techniques and to outline further perspectives of their usage.

2 METHODOLOGY AND TECHNIQUES

Visual methods currently applied in field studies of river flow structure can be differentiated into two basic categories: surface and underwater methods. The difference in these methods naturally comes from organization of field setups, and calibration techniques whereas similarities are found in aspects such as post-processing technologies of obtained video records and photographs.

2.1 PARTICLE TRACKING ON A FREE SURFACE

The general idea of the PTV method applied to a river free surface is simple and analogous to the traditional PTV used for laboratory measurements. After seeding the flow with floating particles, the movement of a group of particles is recorded by a camera. Depending on the amount of particles flow velocity is estimated by tracking positions of individual particles on successive frames (PTV), or determining velocity using statistical methods from a group of particles (PIV). Laboratory setups are usually designed to provide optimal conditions for PTV, or PIV measurements – cameras are located perpendicular to the measurements plane eliminating projective transformations. Appropriate contrast between background and particles is achieved by selecting contrasting colors schemes, the camera lens distortions are negligible because of relatively small fields of view (Uijttewaal and Jirka, 2006).

In the field it is mostly impossible to locate cameras directly overhead of the stream surface (Figure 1) and hence the most general scheme is to record images of the water surface from an oblique angle φ, Figure 2. An additional oblique angle θ appears because of non-central position of the camera mount, Figure 2. As result of these distortions of the images the coordinates of particles will require special transformations for converting them into physical system of co ordinates *x, y*. Coefficients of transformation matrix can be obtained using known physical coordinates of the spatial markers (Figure 2). Coordinates of the markers as well as the plane coordinates and elevation of the camera can be obtained performing measurements with geodetic instruments like total stations. Although theoretically four markers on the image provide sufficient information for derivation of transformation matrix, in practice is desirable to have marker sticks of known length at different distances from the camera.

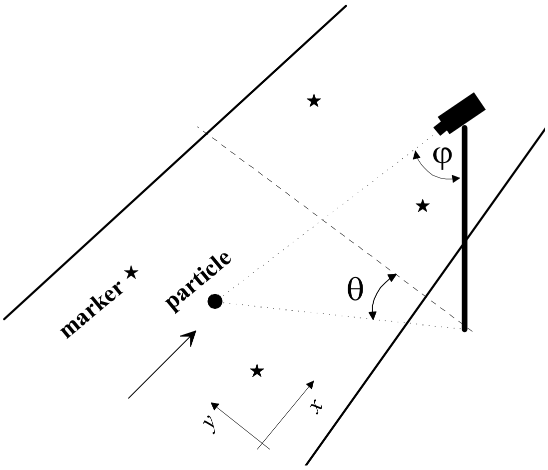

Figure 2. General scheme of field PTV or PIV on a free surface of a stream.

The choice of particles for tracing in field conditions is also different from laboratory experiments. In field the particles should be visible from relatively long distances and at the same time relatively small and providing enough contrast with the background. Different types of tracer particles have been applied – balloons filled with water and air (Figure 1), oranges and grapefruits. However, the best quality images were obtained using tea candles, Figure 3. These candles are 4 cm in diameter, inexpensive, and provide high quality images on video records obtained during night time. Performing PTV or PIV measurements at night time eliminates some additional problems like light reflection from the free surface, and effect of wind.

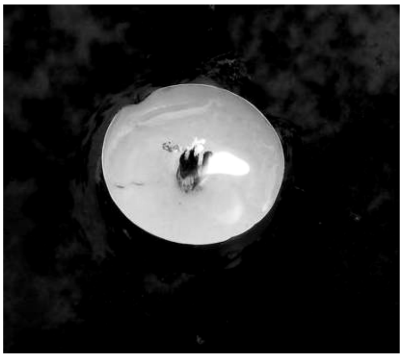

Figure 3. Tea candle as a tracer particle for free surface field PTV or PIV.

2.2 UNDERWATER TECHNIQUES

Studies employing underwater visual techniques report mainly on visualization of flow by injections of dye in combination with high frequency velocity measurements (Roy et al., 1999; Lacey and Roy, 2006) and studies of flow over submerged vegetation (Sukhodolov and Sukhodolova, 2006). In these studies video records are taken in the vertical plane over stream depth and hence normally limited to relatively small areas. Typical experimental setup for underwater visual studies is presented in Figure 4.

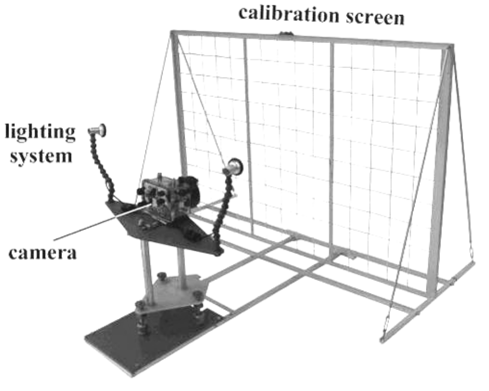

Figure 4. Underwater video recording setup.

Accurate positioning of cameras and markers in such studies is achieved with a help of special mounting platforms and wire screens. Quality of video records is generally limited there by the transparency of water in a river and light attenuation in the water column, but it can be substantially improved with the use of underwater lighting systems. Because of limitations in water transparency video or photo cameras have be positioned relatively close to the plane video recording and respectively enhancement of viewed area is achieved by using wide angel lenses. Respectively the important stage in data processing of underwater video records is transformation of distortions caused by lens.

2.3 POST PROCESSING AND EQUIPMENT

Post-processing of PTV or PIV of field data starts with projective transformations which aim is to eliminate the effect of oblique angles in setup. The transformations can be performed using a simple eight-parameter projective transformation algorithm (Bradley et al., 2002)

$$X = \frac{a_1 x + a_2 y + a_3}{a_7 x + a_8 y + 1} \tag{1}$$

$$Y = \frac{a_4 x + a_5 y + a_6}{a_7 x + a_8 y + 1} \tag{2}$$

where *x, y* are the coordinates of point in image system of coordinates, *X, Y* are coordinates in physical space, and a_i are transformation parameters. The approach assumes that the free surface is flat and horizontal. Transformation parameters should be determined using least squares method if the number of reference points is more than four (Bradley et al., 2002).

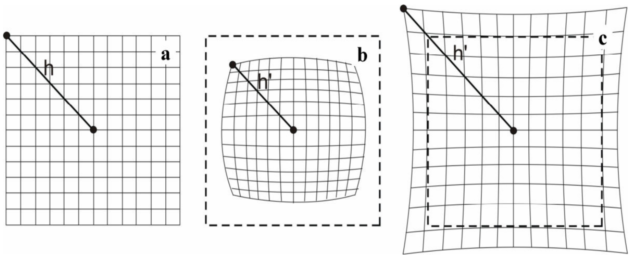

Figure 5. Images without (a), barrel $h' < h$ (b), and pincushion distortions $h' > h$ (c).

When special lenses (tele- or wide-angle) were applied the post-processing should also include procedures to compensate for distortions. The curvilinear distortion produces either barrel or pincushion effect, Figure 5. In optics relative distortion satisfies the relationship $\frac{h'-h}{h} = ah^2 + bh^4 + ch^6 + \dots$, where h is image size without distortion, and *a, b, c* are some coefficients. Therefore to compensate for distortion requires application of non-affine, higher order transformations. Correction procedure requires application of calibration grids as one illustrated in Figure 4. Presently there is ample specialized software available from commercial photography that provides automated compensation for distortion. Distortion is usually less important than projective transformations in PTV or PIV on free surface, but of high priority in underwater visual studies where optical properties of water itself produce similar effect of distortion even when distortion due to lenses is small.

The last step in visual methods is extraction of quantitative information from images. In PTV relatively simple methods are used to determine velocity from successive video frames, however the difficulty appear when there are many particles seeded and hard to determine where a particle from the first frame located on the second one. To solve this problem many algorithms have been proposed, for example; cross-correlation, relaxation methods, hybrid cross-correlation-relaxation methods, and velocity gradient tensor. Cross correlation method is the most often used algorithm for PTV. In this algorithm velocity of a particle *P* is obtained calculating a correlation coefficient between a sub-image (sub-matrix called interrogation windows) *A* centered on *P* in the first frame and a second sub-image *B* centered on a possible position of *P* in the second frame. The method of cross correlation is based on pure translation that means that the time interval between images must be short enough to describe only straight displacements. The algorithm thus looks for the repetition of a specific pattern in the second frame. However, even with short intervals between frames, the motion can be defined by high velocity gradients which produce an alteration in the distribution of particles. This problem is reduced by the use of relaxation methods which can recover most of the available vectors but with a high computational time. In order to decrease the computational time, increasing the number of correct vectors, a hybrid cross-correlation-relaxation method has been recently proposed (Brevis et al., 2007).

In our studies we use a digital camera Olympus C-5060 with a wide lens converter WCON-07. For underwater video recording the camera is mounted in an underwater housing IKELITE and supplied with an underwater lighting system Werner Videolight 100. The mounting system of the underwater camera together with calibrating screen and lighting comprises customary developed underwater video system UVS-RAY, Figure 4. The mesh of wire screen is 10 cm, the screen is 1.5 long and 1 m high. The same camera is used for free surface PTV or PIV. An advantage of using this camera in comparison with digital camcorders is that the camera has better optical characteristics and permits recording of a wide area even without a wide lens converter.

3 EXAMPLES AND DISCUSSION OF THE RESULTS

Quantitative visual methods were employed in our studies to expand capabilities of standard for river flow point measurements completed with acoustic Doppler velocimeters (ADV). Here we would like to illustrate the results on the example of mixing layers developing in shallow flow of two parallel streams (section 3.1), and analogous mixing layers evolving over a patch of submerged vegetation (section 3.2). First example illustrates application of free surface PTV, and the second one reports on underwater video recording and determination of vegetation characteristics from video records.

3.1 SHALLOW MIXING LAYERS

Shallow mixing layers belong to a fundamental class of free turbulent flows and are ubiquitous in fluvial environments. Until recently detailed investigations of mixing layers were traditionally accomplished experimentally in laboratory facilities (Uijttewaal and Booij, 2000). Recently we have performed first experimental field study on the Spree River in Germany. A field scale model of a confluence of two parallel streams was obtained by constructing a thin vertical splitting wall (30 m long) in the centerline of a straight river reach (20 m wide, 1 m deep). A weir with vertical piles was installed in the upstream section of the splitter to control the velocity difference at the confluence in the downstream section. Three experimental runs (velocity differences 45, 30, 15 cm/s) were completed on the 80 m long experimental section of the river. Each run consisted of velocity measurements at 5 cross-sections of the mixing layer in 8 vertical profiles consisting of 6-7 point measurements. Velocities were recorded with 4 acoustic Doppler velocimeters (NDV, Nortek AS,

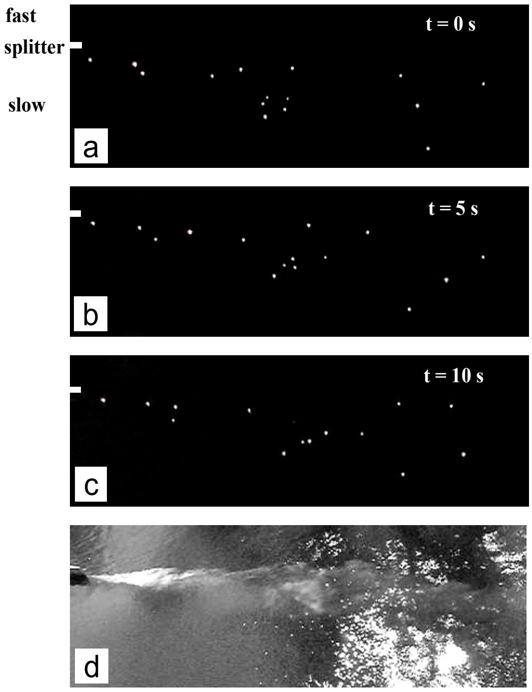

Figure 6. Examples of video records for flow visualization with tea candles (a-c) and visualization using solution of uranin (d), note the light reflection.

Norway) synchronously sampling at 25Hz for 180s at each measurement point. A set of visual measurements with tea candles and injections of uranin solution complemented point velocity measurements. Video records were performed from operational platform elevated about 10 m above the water surface. Records about 30 minutes long were taken at recording speed of 25 frames per second. A characteristic sequence of frames for visualizations with tea candles in experimental run 1 (velocity difference 45 cm/s) is shown in Figure 6a-c. Figure 6d illustrates flow visualization with uranin solution. Visualizations with tea candles were performed in the night time and one can mark sufficient contrast between background and tracer particles. Figure 6d illustrates two typical factors affecting quality of PTV or PIV measurements in field: reflection of sunlight from the free surface of the river and effect of wind. Both records with candles and solutions of uranin are effective in visualizations of turbulent structures. One can easy perceive motion of large scale coherent vortices with vertical axes of rotation which are prominent features of mixing layers. Those vortices are depicted by clusters of candles that reproduce two principal types of motions in the structures – stretching and rotations. This valuable information about the structure of turbulence can be further extracted using analysis of particles ensemble motions, and in point measurements such information is unavailable.

Some results of post-processed data for field experiments (run 1, velocity difference 45 cm/s) and comparison with conventional point measurements with ADV are shown in Figure 7. Figure 7a shows distribution of depth averaged mean velocity vectors over the area of mixing layer (margins of the layer are depicted by dashed lines), and distribution of depth averaged kinetic energy of turbulence is depicted in Figure 7b. Trajectories of individual tea candles released near the splitter plate are shown in Figure 7c. These trajectories were used to obtain instantaneous distribution of flow velocities at the free surface which were later interpolated to the nodes of a regular grid, Figure 7d. Despite the obvious bias in the lateral velocity component due to the inhomogeneous particle distribution, a reasonable agreement was found for velocity data obtained by those two different methods. At the same time the distributions of velocity over the flow depth have revealed general reliability of data obtained by visual methods for representation of the kinematic features of the flow.

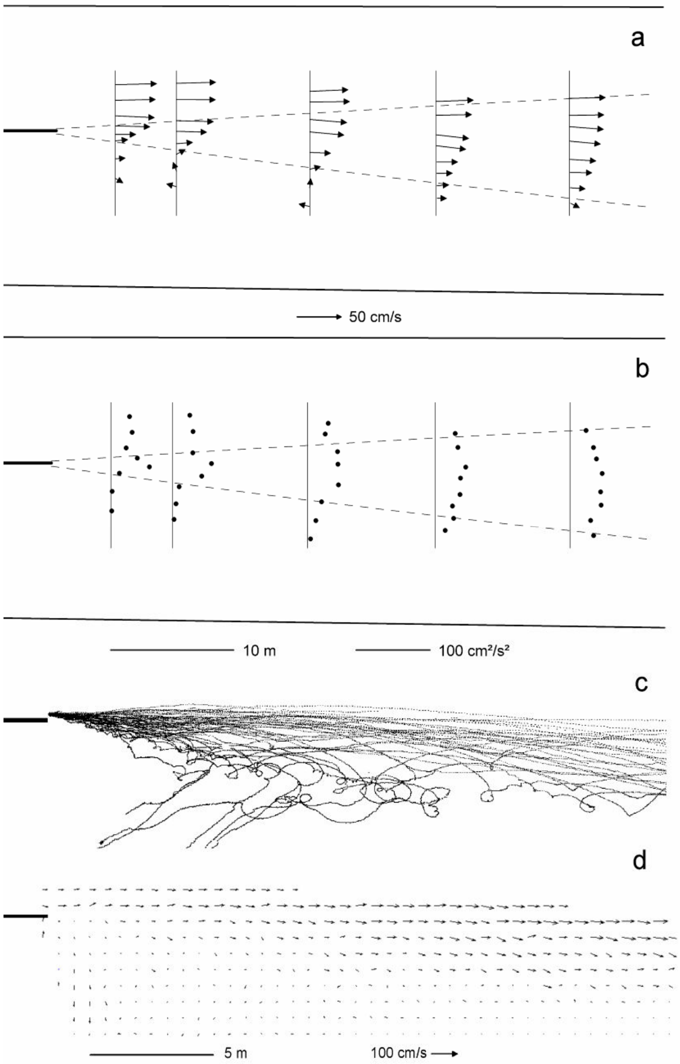

Figure 7. Comparison of results for point-measured mean velocity vectors (a) and velocity vectors obtained with PTV (d), turbulent kinetic energy (b), and trajectories of particles in the mixing layer region (c), experimental run 1.

3.2 MIXING LAYER ANALOGY OVER SUBMERGED VEGETATION

The main purpose of the field experimental program on investigation of mixing layers developing over submerged vegetation was to obtain the spatial patterns of flow characteristics over a patch of submersible plants. The experiment was controlled by choosing the properties of the vegetation patch – its composition, location, and the density of the canopy. Measurements of instantaneous velocities were taken on the verticals distributed along the longitudinal axis of the patch. Experimental run typically consisted of ten vertical profiles and a stationary point. After completion of each particular experimental run the canopy density was progressively reduced by factor of four preserving uniformity and the pattern of plants distribution and a next run was commenced. The patch of rectangular shape 4×8 m in dimension was created artificially in the central part of the river reach. It was composed of uniformly distributed submerged macrophytes *Sagittaria sagittifolia.* Plants of approximately the same dimensions (leaves length 1.6 m, number of leaves 12, and the diameter near the root of 20 mm) were gathered over the river reach and manually implanted.

Instantaneous 3-D velocities were measured at seven points uniformly distributed over each vertical profile. Records were taken at 25Hz sampling rate and over 300 s sampling periods for each point. Video recording of the underwater canopy was performed for each experimental run after velocity measurements. Video records were taken over 50 second for each of five frames juxtaposed longitudinally on the right hand side of the experimental vegetative patch (Figure 8a). Video records were converted into a sequence of digital images in the JPEG format. JPEG images were imported into GRAPHER 6 software and the boundaries between free flow and macrophytes were digitalized. The physical coordinates of the boundaries were computed using calibration screen marks (Figure 8b) and averaged over the sequence of the frames to obtain double time-spatial averages of variable canopy boundaries. Obtained from video records contours of vegetation canopies were then used in the analysis of complex flow-vegetation interactions (Sukhodolov and Sukhodolova, 2006). An example of flow pattern over vegetation canopy for run 1 is shown in Figure 8c.

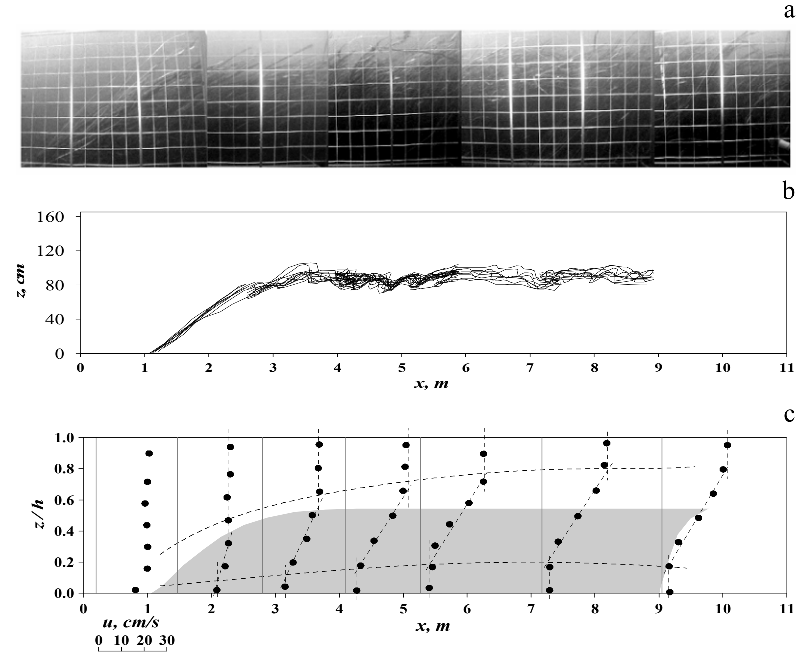

Figure 8. Examples of underwater records for submerged vegetation canopy (a), instantaneous coordinates for upper boundary of the canopy (b), and distribution of mean velocities in the mixing layer developing over the canopy (c).

4 PERSPECTIVES

In this section we would like to discuss some perspectives of using visualization techniques in ecohydraulics. As a first example a briefly outline will be given of the preliminary research program recently completed on entrainment of invertebrates into drift under action of ship-induced waves. The visual techniques which we plan to implement for field studies as the next phase of this research will serve two aims: observation of organisms involved into drift, and determination of main parameters of ship-induced waves from a pair of stereo-video records. Another perspective application of underwater visual techniques is determination of spatial and dynamical characteristics of riverbed relief with the stereo-video records.

Stereo particle tracking velocimetry (SPTV) employs two (or even more) cameras to record in a synchronized way the movement of a group of particles. Cameras can be used in different stereo configurations - parallel or angular. The first one allows the determination of the velocity field with an almost constant matrix of magnification and the complete image in focus. In the angular setup an image is normally appear out of focus requiring further the use of a Scheimpflug adaptor (Prasad, 2000). However, the angular configuration maximizes the intersected (working) area the camera pair (or triplet) and therefore is more widely used.

To project the image displacement into the displacement in physical space a calibration is needed. The calibration methods are mainly classified on geometrical (camera models) or calibration based reconstructions. In case of complex optical effects (lens distortion, refraction by optical windows, fluid interfaces) the use of calibration based methods is easily implemented compare to geometrical reconstruction. However, in field measurements the use of a calibration based method is not always simple, because it necessitates placing of a calibration grid in the measurements area. In geometrical reconstruction the intrinsic parameters (camera geometric and optical characteristics) and extrinsic parameters (camera orientation relative to the physical coordinate system) are determined. Most of the geometrical reconstruction models are based on the method proposed by Tsai (1987), in which in addition to the incorporation of the radial lens distortion into the pinhole camera, a two-stage technique for the geometrical reconstruction is proposed, i.e. the determination of the camera external position and orientation relative to the object reference coordinate system as well as the effective focal length and image scanning parameters.

4.1 INVERTEBRATE COMMUNITIES IN WAVE WASH ZONES

The combination of visual methods with conventional point velocity measurements also became a practical tool in ecohydraulics applications. Recently some research conducted in the IGB was focussed on the quantification of the effects of waves induced by navigation in waterways on invertebrate communities colonizing wash zones. The research approach has been successfully tested in a laboratory wave flume. The experimental setup included two video cameras registering the central flow area where some invertebrates of different species were placed on a substrate that was varied during experimental program. Shear stresses exerted by flow on the substrate and hence experienced by organisms were registered with ADV. The stresses were varied between experimental runs to investigate critical conditions sustainable for these invertebrates.

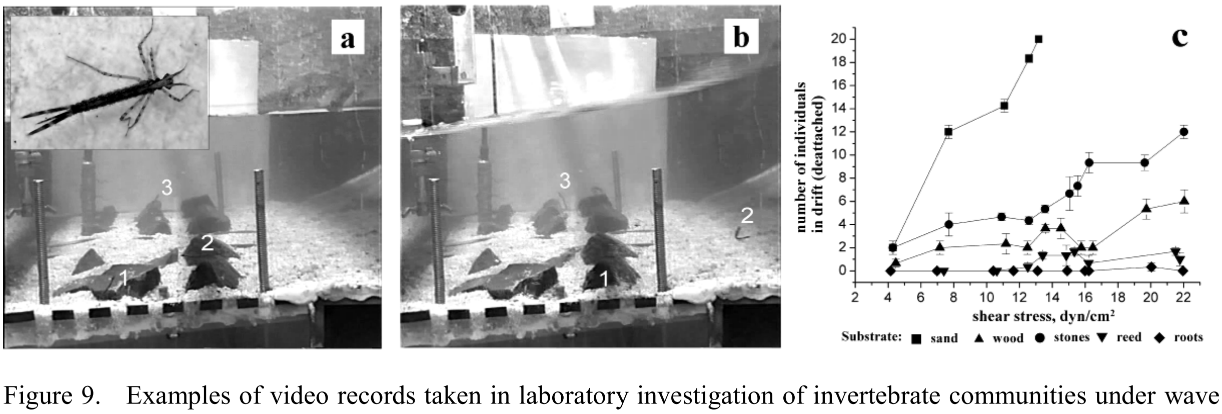

Figure 9. Examples of video records taken in laboratory investigation of invertebrate communities under wave action. A dragonfly larva (*Calopteryx splendens*) is shown in the inserted bar of the frame recorded before (a, numbers mark positions of organisms), and after displacement (b). Relationship between number of organisms entrained by waves and shear stress applied for different types of substrate (c).

Results showed a significant positive relationship between the number of detached individuals and increasing wave-induced shear stress for five investigated species and five different habitats. The detachments of individuals decreased with increasing degrees of habitat structural complexity. Consequently, a gradient was observed from sand (where 20 individuals, as a mean of all species were detached at the maximum) to roots (only 1 individual reattached) with intermediate detachment rates in coarse woody debris, stones and reed-habitats (8-10 detached individuals) was observed. In a next stage experimental investigation are planned in field where SPTV methods on a free surface and underwater will provide information on velocity fields in wave dominated environments, invertebrates entrainment and in drift.

4.2 DYNAMICS OF BEDFORMS IN RIVERS

Traditionally fluvial morphodynamics studies conventionally employ sonar techniques to determine riverbed elevations. Some recent studies reveal that image registration methods can be effective and accurate as the conventional methods (Jerolmack and Mohrig, 2005). In our experimental investigations of shallow mixing layers we have performed underwater documentation of the riverbed relief. A typical image obtained in the fast stream of the mixing layers is shown in Figure 10. The quality of the image and the resolution even allows for the determination of individual sediment grains and their entrainment into motion. Underwater video recordings and observations indicated the possibility for documenting appearance of distinctive motions, called sweeps, that produced significant local mobilization of sand particles. We hope that with employment of field scale experimentation, underwater and conventional velocimetry significant progress in sediment transport studies can be achieved.

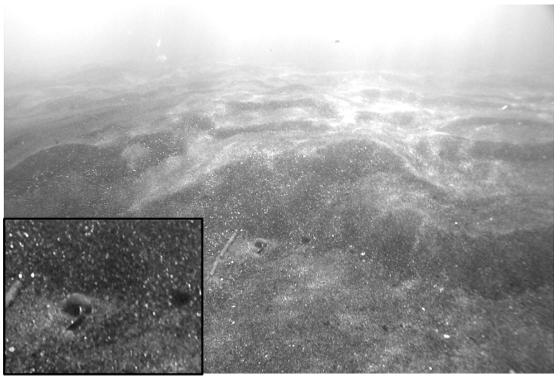

Figure 10. Example of underwater images of sand waves developing in the fast stream of the mixing layer.

5 CONCLUSIONS

The present paper illustrates the effectiveness of modern flow visualization techniques coupled with conventional point measurements for analysis of flow in field conditions. The fields of mean horizontal components of velocity vector can be determined accurately over relatively large areas with fine spatial resolution thus expanding data sets obtained with conventional point measurements. Moreover, the Lagrangian approach for examination of turbulent flow structure provided by records of drifting particles reveals subtle information on the behavior of individual turbulent vortices – the rates of stretching and rotation that is unavailable, or only extracted with crude assumptions from conventional point measurements. Quantitative analysis of visual records for biological components of fluvial systems, like submerged vegetation, registered simultaneously with point velocity measurements is valuable tool for development of advanced models of flow accounting for reconfiguration of aquatic plants (Statzner et al., 2006). Stereo-pair visual techniques are viewed as promising methods with a wide area of application in ecohydraulics and morphodynamics.

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