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A field study of transport and mixing in a river using an Acoustic Doppler Velocity Profiler

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ABSTRACT: A 3-D Acoustic Doppler Velocity Profiler (ADVP) is used for measuring closely spaced profiles across the river Poisine (on a straight river reach with mean water depth ≈ 0.5 m, width ≈ 12 m, flat gravel bed with estimated $D_{50} \approx 6$ cm). The mean streamwise velocity profiles show logarithmic profiles all across the half section, decreasing towards the bank. Most of the three turbulence intensities profiles between the center ($B/y=0.5$) and $B/y=0.24$ agree relatively well with laboratory profiles. Closer to the bank ($B/y < 0.25$) strong deviations in the profile form indicate "side-wall" effects.

A cumulant discard method is applied and conditional statistics and conditional sampling are used to compare the experimental relative covariance contributions from the four quadrants in all three planes. In the center, all quadrant distributions correspond to those observed in laboratory open-channel flow. Near the bank, significant differences between the results for different depths occur in all planes. Thus, the flow near the bank cannot be considered two-dimensional.

1 INTRODUCTION

The physical-biological-chemical-geological interplay in rivers is strongly affected by transport and mixing processes. Effective resource management and river engineering require a good understanding of these processes. Unfortunately, at present, this is often still based on 1-D section averaged mean parameterization. This situation, however, is no longer satisfactory in order to assure water of high quality in view of conflicting interests:

- the impact of pollutants by ever more toxic substances
- the need for re-aeration due to the oxygen demand caused by waste discharge
- the variation of bed friction velocity and the re-naturalization of river systems
- the contaminant run-off from diffusive sources on the watershed
- the determination of realistic bed load transport rates for the control of river bed dynamics.

Only a limited number of field studies is reported in the literature and results often deviate from simple 1-D or 2-D assumptions widely used today. In particular, the dynamics of turbulence and coherent structures and their distribution across a river section

need to be addressed in order to understand why these deviations occur.

Coherent structures and secondary currents are transport processes. They act faster than small scale turbulent mixing and produce potentially harmful local maxima and minima in the distribution of pollutants and oxygen. They will influence the dynamics within the water column, the interaction with the bed and the exchange across the air-water interface. Therefore in order to progress in the understanding of river dynamics, field measurements must incorporate the whole spectrum of scales from large scale mean motion to small scale turbulence.

Here we report on a field study in a medium-sized, lowland river with the aim of investigating parameters which control transport and mixing in rivers. They will be interpreted in the framework of existing knowledge on open-channel hydrodynamics in order to determine to what extent rivers, where the Reynolds number is typically higher and where the idealized conditions of laboratory studies seldom exist, may be different from laboratory open-channels.

2 BACKGROUND

Nikora and Smart (1997) demonstrated the presence of a logarithmic longitudinal mean velocity profile and the inertial subrange in the turbulence domain in gravel bed rivers. In an artificial irrigation channel, Nikora and Goring (2000) took measurements in the center. They observed that the streamwise velocity is usually well represented by a logarithmic profile. They found coherent structures, dominated by ejections and sweeps, over the whole water depth for different discharge conditions. Ferguson et al. (1997) and Roy et al. (1997) describe flow over rough beds in rivers which have similar characteristics as those which we investigate. They verify the existence of coherent structures in rivers.

Smart (1999) points out that - different from laboratory channel studies - in gravel bed rivers the depth, the surface slope and the bed roughness vary across the channel. In such cases, local values of bed shear stress are important because the sum of transport rates across the section may be considerably different from the transport rate calculated with section averaged parameters. Powell et al. (1999) have shown that in coarse grained rivers on the average, transport rates in the center were about twice those recorded at the margins. These local differences in bedload transport are a direct indication of the local differences in bed-shear stress.

Measurements of coherent structures in open channels and rivers have not been able to resolve the very near surface features of these structures because of the difficulty of tracking fine scales so close to a mobile interface. Pan and Banerjee (1995) have carried out a direct numerical simulation for this region. They found that surface boils are linked to coherent structures in the water column below. The impinging coherent structures and other vortices attach themselves to the free surface for a limited time creating "patches," below which lie greatly elevated vorticities. Moog and Jirka (1999) have studied the effect of surface boils on air-water gas exchange and have found that burst motions can transport turbulent energy to the free surface, creating active zones for gas transfer in which embedded small scale eddies may renew the surface many times, enhancing the gas transfer. Surface boils therefore provide for river reaeration and affect water quality management concepts in the context of river recovery from biochemical oxygen demand created by waste discharge.

3 FIELD STUDY

We have carried out several field studies in small turbulent rivers under fluvial conditions on the lower Swiss plateau. The results from the river Poisine (on a straight river reach with mean water depth ≈ 0.6 m, width ≈ 12 m, gravel bed with estimated $D_{50} \approx 6$ cm) which are presented here are typical for our findings in other rivers. The study reach has been "corrected" and resembles closely a wide laboratory channel. The shorelines are straight and the bottom is flat with very subdued bed topography. The roughness height is small compared to the water depth and with a minimum of scour holes. In such sections, form drag is commonly assumed to be minimal (Prestegard, 1983).

In this study, we have used the Acoustic Doppler Velocity Profiler (ADVP) which we have developed and which is capable of taking instantaneous velocity profiles of all three velocity components with a resolution of turbulence scales. The parameters we have investigated are the cross section distributions of: a) the mean values of the three velocity components, b) the velocity variances, c) the shear stresses and d) the dynamics of coherent structures and their relation to bottom shear stress.

Measurements were carried out at a large number of verticals across the cross-section with the ADVP system suspended from a portable bridge placed above the water surface. The distance of the ADVP from a shore reference point is marked and repeated measurements with the same setting were made. At each point, the ADVP is first optimized for the particular conditions and 3-D instantaneous profile measurements are then carried out for about 5 min. at each point. The instrument can detect the river bottom and the instantaneous water depth is therefore known at all times.

Here, we briefly resume the characteristics of the focalized 3-D acoustic Doppler velocity profiler. Details are documented in the literature (Roland & Lemmin, 1998; Hurther & Lemmin, 1998). The instrument works at an acoustic frequency of 1 MHz. Profiles are obtained by subdividing the water depth into a number of consecutive equal-sized range bins. The bin location is determined by the time of flight with respect to the acoustic transducer. The instrument is capable of resolving the 3-D velocity vector at up to 256 points in each profile simultaneously with a time resolution of normally 15 Hz, but at least 5 Hz. The actual resolution depends to some extent on the river flow conditions. However, the resolution we can obtain is always satisfactory for the study of turbulence under the conditions specified by Nezu and Nakagawa (1993; eq. 3.1). Coherent structures

and secondary currents occur at a much lower frequency and are therefore well resolved.

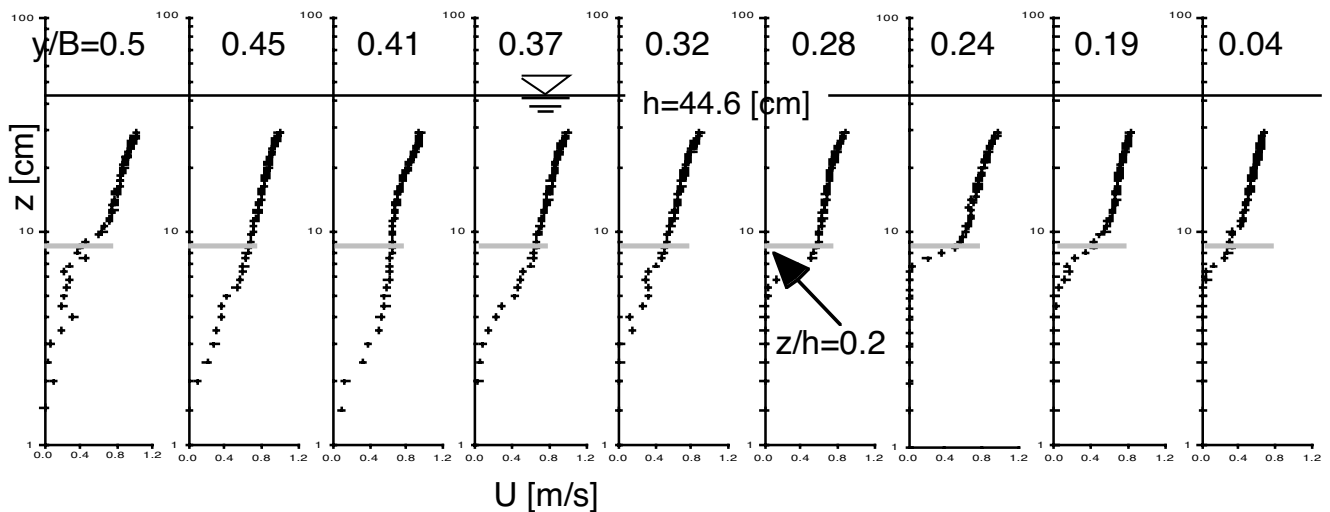


Figure 1. Cross-section distribution of the mean streamwise velocity profiles in the river Poisine.

The instantaneous profiling capability of the ADVP is an important feature in river studies. A great number of vertical profiles across the river section are needed for sufficient resolution. With single point instruments this can never be realized within a reasonable time (one day). Measurement campaigns which need longer time periods are logistically impractical and risk significant variations in river discharge.

4 DATA ANALYSIS

The data analysis addresses the objectives indicated above. The basis for the analysis is a set of computer programs which we have developed over the years for the treatment of ADVP data and in particular for the measurements in rivers. They allow us to test for all profile laws in mean, turbulence and shear stress distributions related to the logarithmic velocity profile.

For the analysis of coherent structures we use the technique which Nakagawa and Nezu (1977) developed. The equations for the relative covariance term $u'w'$ are conditionally sampled over the four quadrants of the $(u'w')$ plane. Events in quadrant one to four are identified as outward interaction, ejection, inward interaction and sweep respectively. A third-order Gram-Charlier distribution was found sufficient to quantify the quadrant covariance fraction and time fraction over most of the water column under laboratory conditions (Hurther & Lemmin, 2000). Experimental results of fractional contribution to the corresponding

shear from each quadrant will be compared to results from a cumulant discard Gram-Charlier distribution applied to the $u'w'$ term.

This analysis is designed to determine whether and in what way rivers may deviate from laboratory open-channels and the importance of coherent structures.

5 RESULTS

5.1 Mean profiles

Above 0.2 h, the mean streamwise velocity profiles (Fig. 1) show a structure which is not far from a logarithmic profile all across the half section. In this layer the mean velocity decreases continuously from the center towards the bank. Below 0.2 h there are local deviations which are sometimes important, particularly in the near bank zone. From our observations of the bed roughness, they most likely result from form roughness elements. In the near bank zone, however, the deviation to almost no flow in this lower layer is more systematic and seems to indicate that the flow in this zone is not two-dimensional.

The mean profiles of the three relative turbulence intensities are compared to the profiles seen in the center of a uniform, laboratory open-channel flow (Fig. 2). In most of the profiles between the center ($B/y=0.5$) and $B/y=0.24$ the intensities agree relatively well with those from the laboratory study, particularly for the transversal component. The streamwise component is slightly larger, while the vertical component is always larger. Stronger deviations are seen below 0.2h where often no clear

profile form can be established. Nevertheless, one can assume that in this part of the cross-section the

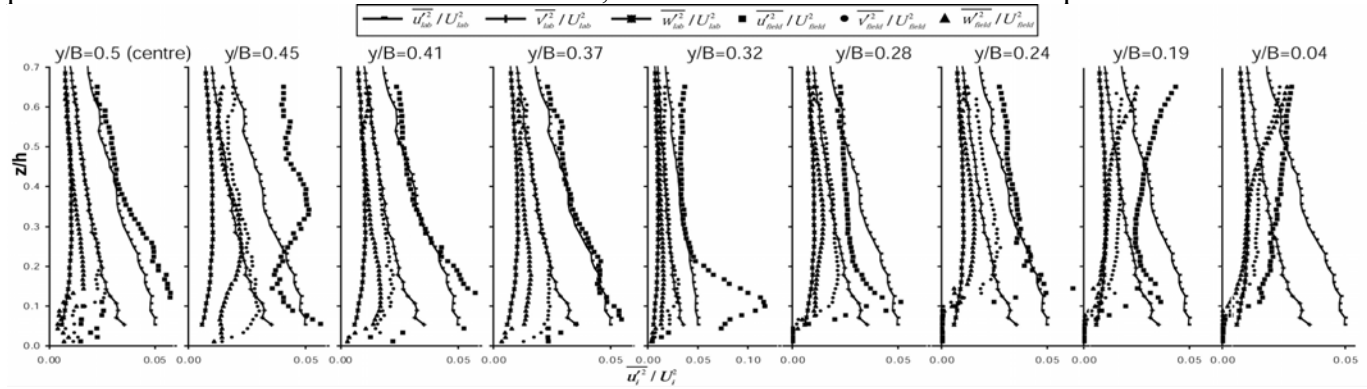


Figure 2. Cross-section distribution of the relative turbulence intensity profiles in the river Poisine.

flow is not very far from two-dimensional. At the moment, we cannot explain local deviations (such as at $B/h=0.45$). More detailed measurements are needed there to determine the transition into this profile or the effect of localized form drag. For the part of the cross-section closer to the bank ($B/h < 0.25$) we observe strong deviations from the laboratory profile form indicating a “side-wall” effect. At the point closest to the bank ($y/B=0.04$) the measured profiles decrease over the whole water depth. These measurements indicate that about 30% of the cross-section is affected by this effect.

Mean profiles of the Reynolds stresses and the turbulence intensities are shown in figure 3. A behaviour similar to that of the turbulence intensities is seen in that above $0.2h$ and for $y/B > 0.25$ the values obtained from the river follow the curves from the laboratory but the intensities are often slightly higher, particularly for the turbulent kinetic energy. The strongest deviations are once more observed below $0.2h$. In the near bank zone we find again greater deviations over the whole water column. In this zone, the shear stress term $u'v'$ becomes quite large and positive above $0.2h$.

5.2 Coherent structures

Similar to our laboratory studies, a cumulant discard method is applied to describe the statistical properties of the covariance term $u'w'$ along the mean flow relative to their time means. Conditional statistics and conditional sampling are used to compare the experimental relative covariance contributions from the four quadrants in the streamwise plane. Results for the vertical at $B/h=0.5$ in the center of the river are compared to those at $B/h=0.05$ close to the bank in figure 4. At each vertical, results for the same three relative depth at mid-depth are presented. The change from the center to the bank is striking.

In the center, the quadrant distribution corresponds to the one observed in the laboratory open-channel

flow (Hurther & Lemmin, 2000) with quadrants two and four clearly dominating along the mean flow $u'w'$. Thus, ejections (quadrant two) and sweeps (quadrant four) are the dominant structures. There is only a slight difference between the curves from the different depths. However, the sweep curves fall off faster than in the laboratory channel with respect to the threshold level H . Increasing the level of H allows to select progressively stronger fractional covariance events. Contributions are already nearly negligible for values of $H=10$. This level is reached in the laboratory study for $H=20$. The opposite trend is seen for the ejections. In the laboratory study values had fallen to less than 0.05 for $H=20$ while they remain at about 0.1 or above in the river. As was observed in the laboratory, there is no preferential quadrant orientation in the cross flow direction $v'w'$ (not shown here). As in the laboratory study, values taper off to below 0.1 only for very high values of H around 90. This means that coherent structures are aligned in the streamwise direction.

Near the bank, sweeps (quadrant four) show an intensity and a distribution which is very similar to that in the center of the river. This means that downward oriented structures behave similarly all across the river. Significant differences are seen for the ejections (quadrant two) where the distribution is strongly modified from that observed in the center. In quadrant two and also mirrored but at smaller amplitude in quadrant three, curves do not taper off with increasing selection criterion H . Instead, they remain constant over a wide range of H . Thus, there is no balance between the ejections and the sweeps in the near bank zone. Furthermore, the behaviour at the three selected depths is quite different. The distribution between the quadrants remains balanced for the $v'w'$ plane (not shown).

Thus, as was already seen for the mean profiles of turbulence and Reynolds stress above, it is obvious that the flow near the bank cannot be considered

two-dimensional. This is further supported by the

decrease in strength for the terms in the $u\text{-}w$ plane.

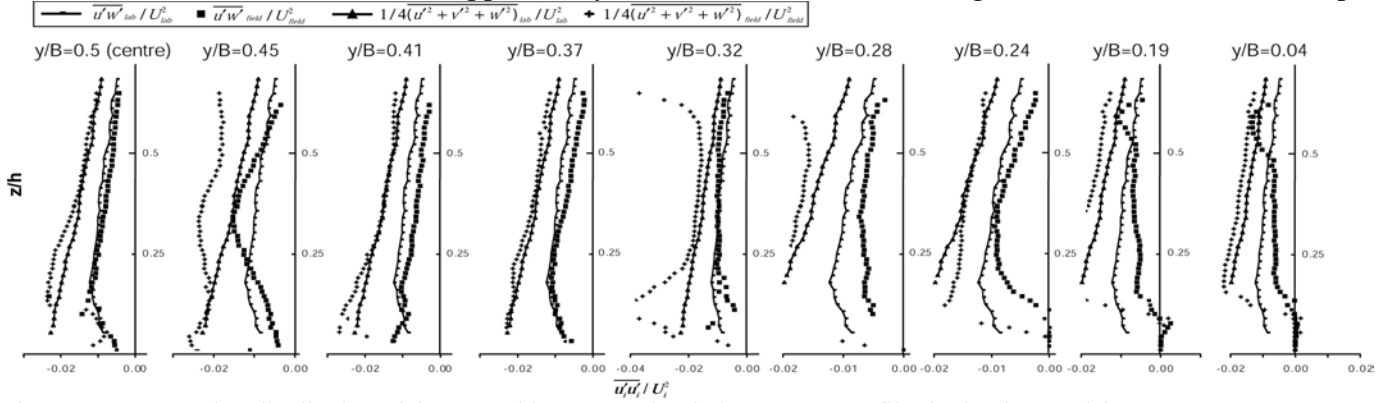


Figure 3. Cross-section distribution of the Reynolds stress and turbulent energy profiles in the river Poisine.

They approach the same level as those in the $u'w'$ plane indicating that this shear term becomes important in the near bank area.

6 SUMMARY AND CONCLUSIONS

The overall objective of this study was to provide a first insight into transport and mixing dynamics in medium scale rivers, where at present little is known due to the difficulty in measuring the relevant parameters with sufficient resolution and precision. In order to attain this objective we have carried out field measurements in rivers using our Acoustic Doppler Velocity Profiler. By measuring instantaneous three-dimensional profiles at a large number of verticals across river sections, we have investigated the mean field and the fluctuating field of all three velocity components.

Our still limited set of river field studies either indicates or suggests that compared to open channel laboratory studies:

- vertical mean value distributions of stream-wise velocity are similar in both cases.
- the vertical distribution of the turbulence parameters changes strongly across a section.
- the distribution of parameters such as bed friction velocity may vary across a section.
- coherent structures are present in rivers and may affect mixing and transport processes.

At the same time these measurements indicate that different from laboratory flow:

- the mean profile structure across a river section does not support the concept of 2-D flow.
- the dynamics of coherent structures change across the cross-section.

There are still questions which need to be addressed in order to understand the dynamics of river flow:

- Can the deviations be explained by a change in bottom roughness alone?
- What is the effect of secondary currents; are they locally or globally important enough to rule out the application of 2-D concepts?

From the high scatter of all data below $0.2h$ it is obvious that it will be rather difficult to obtain reliable bottom shear velocity information by classical methods of profile extension. This is not surprising because most laboratory studies for which this concept was developed were carried out with rather uniform roughness throughout the channel. The bottom roughness in rivers varies over a rather wide range. We have recently used our ADVP measurements in laboratory open channel flow to show the universality of the concept of wall similarity (Hurther & Lemmin, 2000). We will also test it for the river condition because it may provide a new way to determine the effective bottom roughness from the TKE balance in midwater depth.

Classical concepts of transport and mixing reach their limits, when as is often the case today, the fine-scale dynamics are required. This is particularly true in the bottom boundary layer of the river where pollutants and waste material come in contact with sediment. They risk affecting the oxygen budget in the near bottom layer. This is the zone in which biological activities are predominant and which may suffer severe damage as a consequence. The dominant time and length scales of the turbulent flow and the residence time of the pollutant in that layer need to be determined. This problem also relates to sediment resuspension and sediment transport. We have recently shown that using an extension of the ADVP instrument, the particle flux can be determined by measuring particle concentration at the same time. These measurements can give new insight into particle transport (Hurther & Lemmin, 2001).

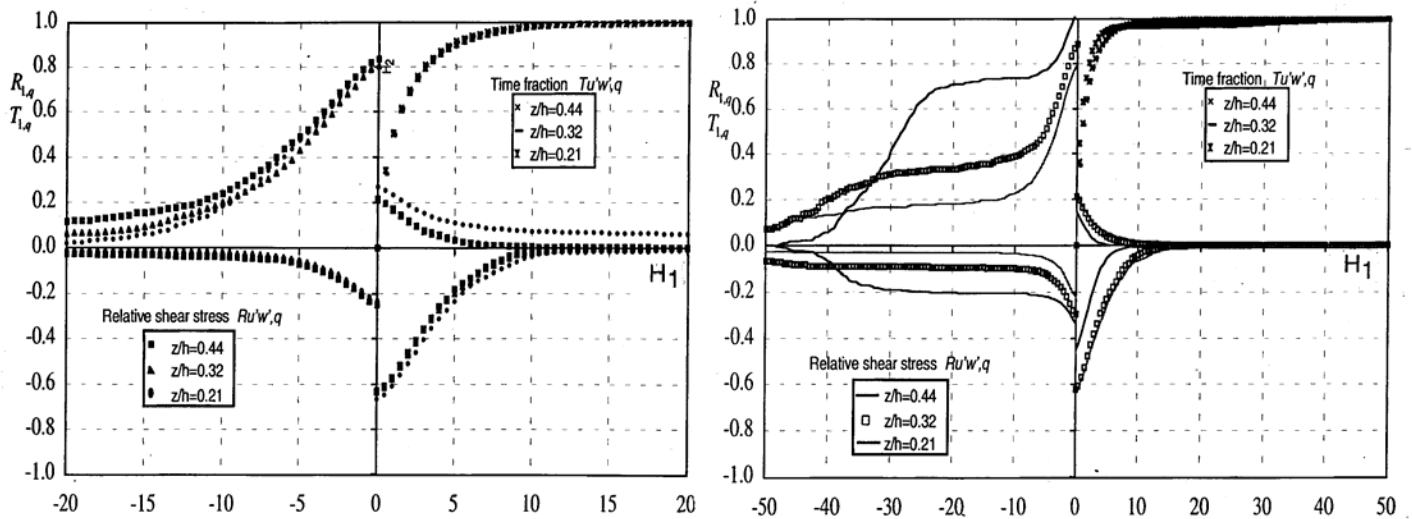


Figure 4. Quadrant distribution of shear stresses at the center (left) and the bank (right; $y/B = 0.05$) of the river Poisine. The horizontal axis is the selection criterion H .

It is expected that the information which will be obtained from detailed measurements in rivers will contribute to the improvement of numerical predictive models of pollutant mixing, which in turn will improve effective water resource management. We will continue these measurements and their analysis and extend them into other rivers in order to give more statistical significance to the first results we have provided here.

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NOMENCLATURE:

B = river width
 H = threshold level
 h = water depth
 u = streamwise velocity component
 v = transversal velocity component
 w = vertical velocity component
 x = streamwise direction
 y = transversal direction
 z = vertical direction
superscript ' = fluctuating velocity component

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