Measurement and analysis methods of large scale horizontal coherent structures in a wide shallow channel

by

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ABSTRACT

Rivers can be characterized as wide, very shallow flows. Where contiguous flows of different velocity are present, shallow mixing layers develop. Examples are the mixing layer at the confluence of two rivers and the mixing layer between the flow in the main channel of the river and the slower flow over the flood plain. The lateral exchanges of momentum, sediments and pollutants through the mixing layers are important processes. A major contribution to these lateral exchanges stems from the large scale horizontal coherent structures present in shallow mixing layers.

Experimental investigation of the development of two kinds of shallow mixing layers was executed in very shallow flumes. One, the mixing layer at the confluence, was investigated in a flat glass-bottomed flume; second, the mixing layer between river and flood plain in a concrete compound channel. A main objective of this study was the detection and characterization of large scale horizontal structures. The investigation was executed with particle tracking velocimetry (PTV) and laser-Doppler velocimetry (LDV).

The experiments showed clearly the presence of the mixing layer and the large scale horizontal structures therein (see figure 1). The shallowness has a marked influence on the development of the mixing layer and on the large scale structures. PTV measurements were analysed in different ways in order to characterize the large scale structures. In particular ensemble averaged vorticity distributions and the enstrophy distribution appear useful for the evaluation of numerical modelling of shallow mixing layers.

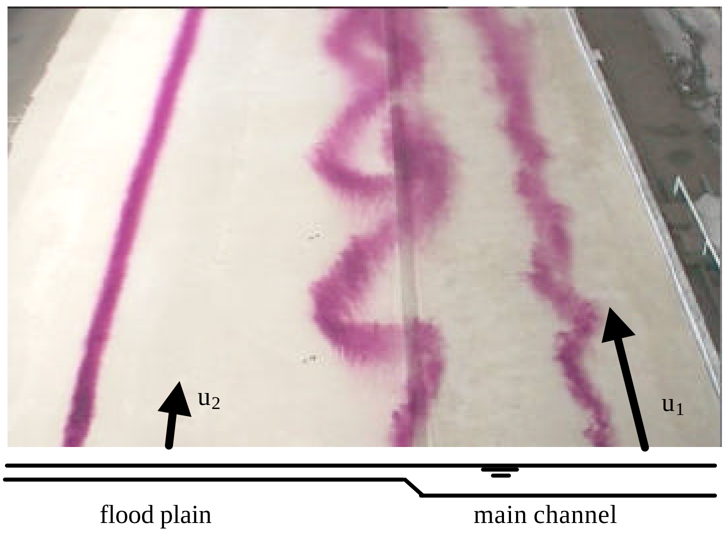

Figure 1: Top view of the compound channel experiment. The large coherent structures in the mixing layer are made visible by injecting dye.

1. INTRODUCTION

Rivers, in particular lowland rivers, can be characterized as wide, gently curved, shallow flows. Often the main channel is bordered by groyne fields to regulate the river flow and/or flood plains that allow for seasonal high flow rates. Not only the groyne fields and flood plains but also the deeper main channels are very shallow, with aspect ratios (depth/width) below 1 % or 2 % for the main channel generally and much lower even for the flood plains, see figure 2. At several places in shallow river flow shallow mixing layers, i.e. transverse shear layers between contiguous flows of different velocity, can arise. Examples are the mixing layer at the confluence of two rivers (Booij and Tukker, 2000), the mixing layer between the flow in the main channel and the slower flow between the groynes (Uijttewaal, 1999) or over the flood plain (Sellin, 1964) and the mixing layer in harbour entrances between the river flow and the harbour (Langendoen, 1992). The lateral exchanges of momentum and matter through this mixing layer are important, e.g. for the overall resistance of the river flow, for the sedimentation of the flood plains and for the longitudinal dispersion of pollutants.

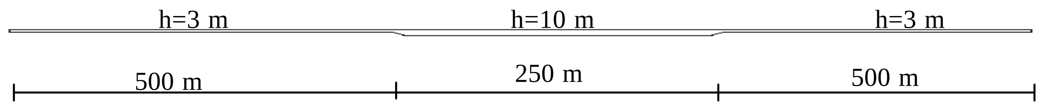

Figure 2: A cross-section of a lowland river.

Experimental investigations of the mixing layer between co-flowing streams of equal depth showed the development of large scale horizontal coherent structures (Chu and Babarutsi, 1988, and Uijttewaal and Tukker, 1998).These structures contribute considerably to the lateral exchange through the mixing layer. The objective of this study is the detection and the characterization of such large scale structures and the determination of their influence on lateral exchanges. Knowledge of mixing layers concerns mostly two-dimensional or plane mixing layers without a spanwise confinement, which for the considered mixing layers would mean unlimited depth. In shallow flow both the limited depth and the bottom friction influence the development of the mixing layer. The limited depth restricts the large structures in the mixing layer to basically two-dimensional (2D) horizontal motions. Because of the shallowness the normal energy cascade from large to small eddies is interrupted. The bottom friction has a two-fold influence on the large scale structures. First, the bottom friction is responsible for dissipation of large scale energy which is transferred directly from the 2D large scale structures to 3D small-scale bed generated turbulence without interaction of intermediate scales. Second, the bottom friction has a stabilizing influence on the generation of large scale structures and thereby reduces the growth of the mixing layer (Uijttewaal and Booij, 2000).

An ultimate goal of this study is the improvement of the numerical modelling of shallow mixing layers and other shallow shear layers. Present models are not very successful. Modelling the interaction of 2D large scale structures and small scale 3D bed generated turbulence in a shallow mixing layer is difficult in classical Reynolds-average turbulence models (k-ε model, etc.) and the difference in length scales prevents the application of standard DNS (direct numerical simulation) and LES (large eddy simulation) models. The development of a quasi-2D LES model in which the large scale 2D structures are solved and the small scale 3D turbulence is modelled may prove necessary. To evaluate such a model experimental data describing the presence, scales and characteristics of large scale structures are required. To avoid the large amount of data in such an investigation an appropriate statistical analysis of the data is desired.

Two different experiments concerning shallow mixing layers are reported here:

- the development of a mixing layer downstream of the confluence of two flows of different velocity,
- the characteristics of a mixing layer between river and flood plain in a compound channel.

Particle tracking velocimetry (PTV) was used to obtain information about the presence, the dimensions and the structure of the large scale 2D structures. Single point velocity values giving detailed information on turbulence properties are obtained with laser Doppler velocimetry (LDV).

2. EXPERIMENTAL SETUP

2.1 The Confluence Experiment

The shallow mixing layer in this experiment was generated in a horizontal flume, 3 m wide and 20 m long, of the Laboratory for Fluid Mechanics at Delft University of Technology. The flume is positioned at 1.8 m above the floor and has a glass bottom to allow for laser-Doppler velocimetry from below (see figure 3) (Uijttewaal and Booij, 2000). The inlet section consists of two separate parts for high and low velocity flow respectively, divided by a splitter plate. Downstream of the splitter plate a mixing layer develops. The flow conditions at the end of the splitter plate are $u_{1,0}$ = 0.28 m/s and $u_{2,0}$ = 0.16 m/s for the velocity at the fast and slow flowing side respectively and the small water depth is h_0 = 67 mm , where the subscript $_0$ is used to denote the inflow conditions.

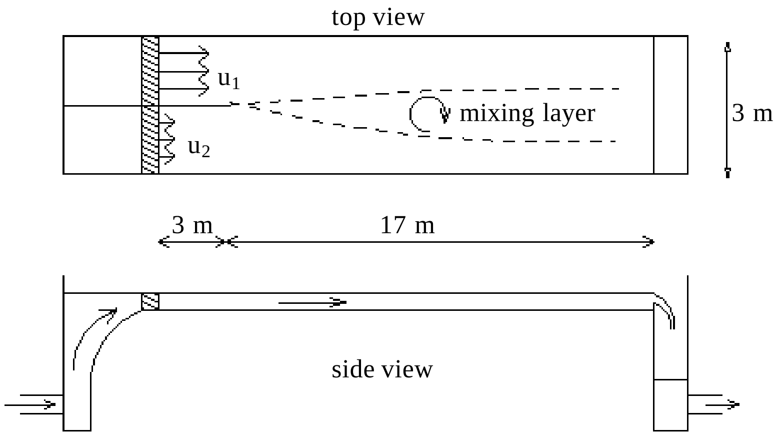

Figure 3: The top view and side view of the glass-bottom flume of Delft University of Technology. The inflow is on the left-hand-side and the outflow on the right-hand-side.

The PTV measurements were carried out with a camera at 2 m above the flume looking vertically downward. The PTV measuring equipment consists of a digital 8 bit black/white video camera (Kodak ES1.0) with a resolution of $1K^2$, a maximum frequency of 30 Hz and a storage capacity of 10,000 frames. Areas of 1.65m x 1.65m and 0.83m x 0.83m were measured (see figure 4). PE-granulate with a diameter of 4 mm was used as particles. These particles remain for about 90% below the water surface and are therefore not sensitive to clustering together. For the PTV measurements white foil is fixed to the glass bottom from below to give a good contrasting background for the black particles. The software for the PTV converting the digital images to vector velocity fields was developed at the Eindhoven University of Technology. Details about the PTV software procedures are described in Van der Plas and Bastiaans (1998).

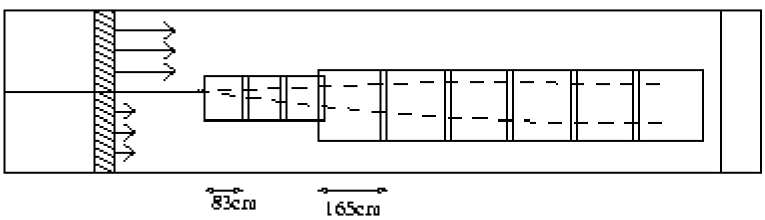

Figure 4: The mixing layer is covered by three small and six larger measurement areas. Due to the expected lateral shift of the mixing layer the areas are also shifted.

Due to the large width of the flume, combined with the small water depth and the free water surface the only feasible way of executing LDV measurements was through the bottom. To this end the flume was provided with a glass bottom. Velocities in the horizontal plane were measured by means of a DANTEC fibre-optic backscatter LDV system.

The properties of the ambient flows outside the mixing layer, which determine the circumstances for the development of the mixing layer, can be described as follows. The ambient streams on both sides of the mixing layer are wide shallow flows. They are of equal depth, but different velocity, and hence encounter different bottom shear stress. This can be shown (Booij and Tukker, 2000) to result in a increase of the velocity at the low velocity side and a decrease of the velocity at the fast flowing side. Hence the velocity difference between both ambient streams (u_1 - u_2) decreases downstream, which leads to a diminishing growth rate of the mixing layer. Moreover, preservation of mass then leads to a gradual displacement of the mixing layer to the low velocity side and the bottom shear stress leads to a slight downstream decrease of the water level.

2.2 The Compound Flow Experiment

Most experiments in compound flow are executed in uncharacteristically deep flumes, where the effects sought for play a minor role. The experiments in this investigation are performed in a large concrete basin of 11.5m width and 28.5m length. The main channel is 3m wide with a water depth of 0.12m, the flood plain is 8.5m wide with a water depth of 0.04m. Typical flow velocities are 0.27m/s in the main channel and 0.16m/s in the flood plain. These dimensions were chosen to ensure a wide, shallow compound flow in which the developing mixing layer stays far from the side walls of the flume. In this way the side walls have no effect on the large horizontal structures generated in the mixing layer. The great length of the basin allows for a proper development of the mixing layer flow. Dye visualisations in figure 1 show the presence of large coherent structures in the mixing layer and illustrate the sufficient width of the flume.

The PTV measurements were carried out in the same way as in the confluence flow experiment. However the larger measures of the flume necessitated a larger measuring area (3m x 3m) and therewith a larger distance of the camera (about 6m). Because of the lower resolution of the camera at this distance larger particles were required. Wooden beads of 8mm diameter floating on the water proved useful.

The concrete bottom prevented the use of a normal LDV system. To obtain detailed information on single point velocity values and turbulence properties an immersible LDV system made by Delft Hydraulics was used. This LDV yields velocity components in main flow direction and vertical direction.

In this case, by a careful setup of the inflow conditions, it is possible to obtain nearly uniform ambient flows and a mixing layer that does not displace to the low velocity side. To realize this the bottom shear stress of the faster flow in the deeper main channel has to be equal to the bottom shear stress of the slower flow in the shallower flood plain. The step in the bottom below the mixing layer leads to a slightly more complicated exchange process.

3. EXPERIMENTAL RESULTS

LDV measurements through the bottom of the glass-bottom flume confirmed the large influence of the shallowness of the flow on the development of the mixing layer. In a plane turbulent mixing layer, corresponding to a deep flow situation, the width δ of the mixing layer is proportional to the downstream distance to the origin of the mixing layer, i.e. the end of the splitter. The velocity profiles across the mixing layer are self-similar and can be well described with an error function. If the mixing layer width is defined as the maximum slope thickness (see also figure 5)

$$d = \frac{u_1 - u_2}{\left(\partial u / \partial y\right)_{\max}}$$

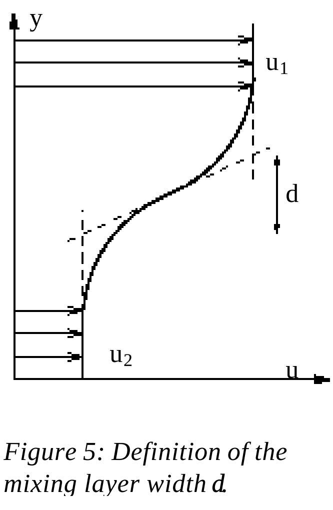

Figure 5: Definition of the mixing layer width d.

then the growth rate of the plane mixing layer is

$$\frac{dd}{dx} = a_{dw} \frac{u_1 - u_2}{\frac{1}{2}(u_1 + u_2)}$$

The constant of proportionality α_{dw}, where the subscript $_{dw}$ denotes deep water, has an empirically determined value of about 0.09.

For a shallow mixing layer the influence of the bottom shear stress on the velocity difference and on the stability of the large scale structures leads to a decreasing growth of the mixing layer width, although the velocity profile hardly deviates from the self-similar profile of the plane mixing layer (see figure 6).

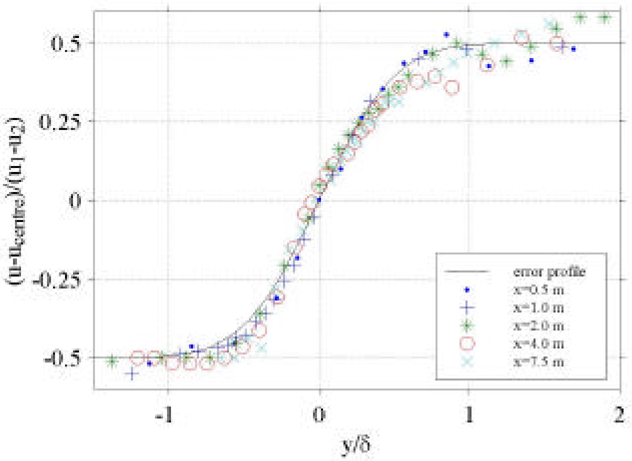

Figure 6: Mean streamwise velocities vs lateral distance. Lateral distances are scaled with the mixing layer width d.

PTV was used to obtain information on the large scale 2D structures. Although The PTV technique is in particular suited for instantaneous measurements, time-averaged characteristics can also be derived if a sufficiently large period is observed. A period of 5 minutes was used to determine proper mean values and standard deviations of the velocities. In this way it was possible to determine e.g. the development of the mixing layer width (see figure 7) and the development of the transverse shear stress τ, obtained from the turbulent velocity components u' and v' (see figure 8), with much less measuring effort than LDV measurements would require. It should be realized that the PTV measurements concern the flow velocities and large scale structures at the water surface.

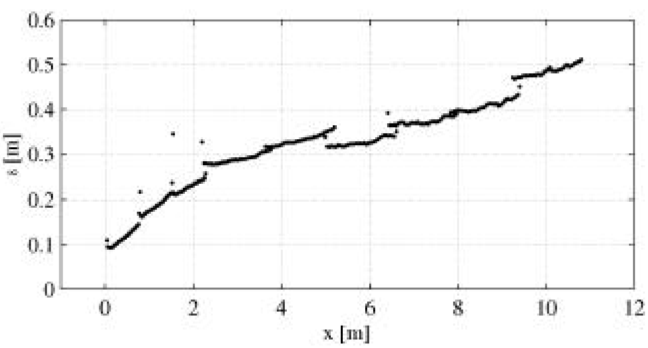

Figure 7: Mixing layer width d vs downstream distance.

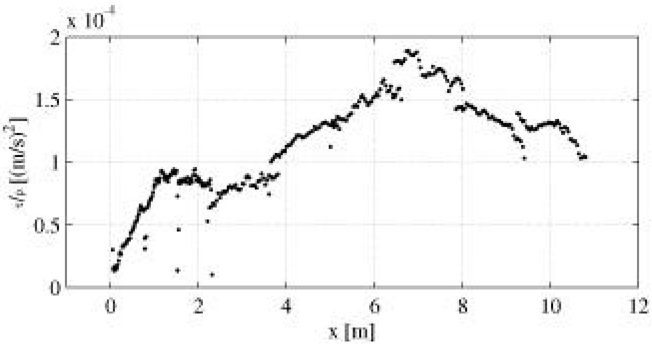

Figure 8: Maximum transverse Reynolds stress t/r vs downstream distance.

The influence of the shallowness of the flow on the development is obvious from the non-linear relation between mixing layer width and downstream distance. The detailed behaviour of the measured development and the Reynolds stress is not completely understood yet.

The main object of the PTV measurements was to obtain information about the presence, the dimensions and the structure of large scale horizontal coherent structures. In figure 9 the instantaneous flow field measured with PTV shows coherent vortex motions. To clarify the structure the mean advection velocity in the mixing layer was subtracted.

The identification of large structures from a flow field in this way is somewhat subjective, because of the large differences of main flow velocities over the PTV area. An often used identification procedure is based on the vorticity, in this case the vertical vorticity component, defined by:

$$w = -\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

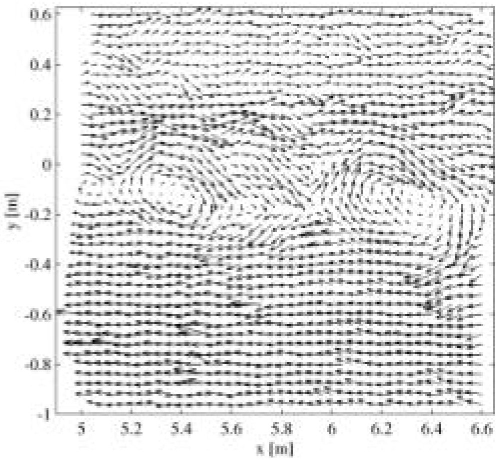

Figure 9: Instanteneous velocity field with subtracted advection velocity.

In figure 10 a series of contour plots of the vorticity shows the downward propagation of large 2D structures in the mixing layer.
For the evaluation of numerical models the use of individual vorticity plots is not very useful. This disadvantage can be removed by using the ensemble (and conditional) average of a series of structures.

For this the following procedure is used
- the centre of the individual structures, i.e. the place of maximum vorticity, is determined
- the moment at which this centre passes the desired cross-section is determined,
- the transverse (y) location of this passage is determined and used to shift the concerned structure in transverse direction until its centre coincides with the middle of the mixing layer,
- the individual shifted vorticity fields around the considered cross-sections are averaged.

Figure 11 shows an example of the ensemble averaged vorticity contour plots obtained in this way. The obtained ensemble averaged vorticity contour plots can be used to evaluate a LES computation. To this end the computation should be subjected to the same procedure.

In the vorticity plot obtained in this way no distinction is made between the vorticity of the structure and the mean vorticity of the mixing layer itself. To distinguish the vorticity in the structure the enstrophy (the ensemble- or time- average of the square of the turbulent variation of the vorticity) should be used. Figure 12 shows a contour plot of the enstrophy around a certain cross-section.

Generally large 2D horizontal structures in compound flow and their consequences, e.g. for sedimentation of flood plains, are not taken into account or are not even assumed to exist. The experiments in the compound channel with dye (see figure 1) and PTV shows clearly the existence of those large structures in the mixing layer over the transition between main channel and flood plain. Of practical importance is the increased sedimentation of the flood plains. Sediment can be entrained to the flood plains by the large horizontal structures, and deposited there because of the locally smaller mean flow velocity. This process takes place even in case of a flow that is directed slightly away from the flood plain into the main channel.

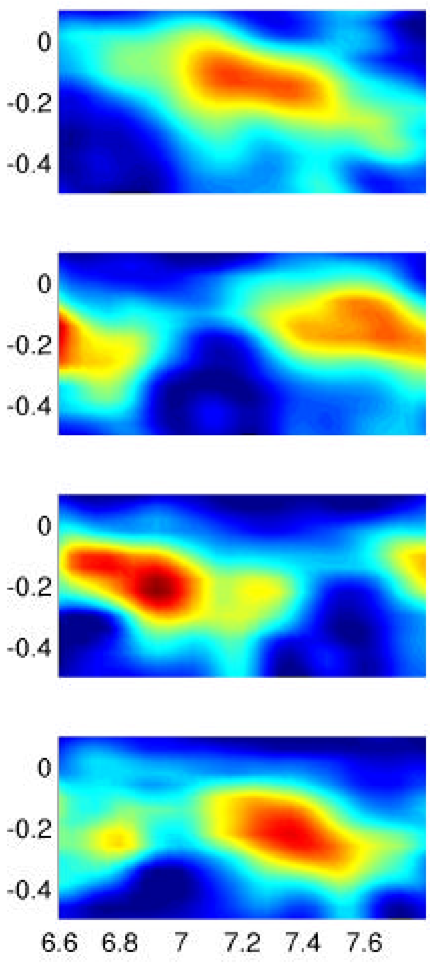

Figure 10: Propagation of large 2D structures (from left to right) as observed from vorticity contour plots with intervals of 2 s; position in m from the origin of the mixing layer .

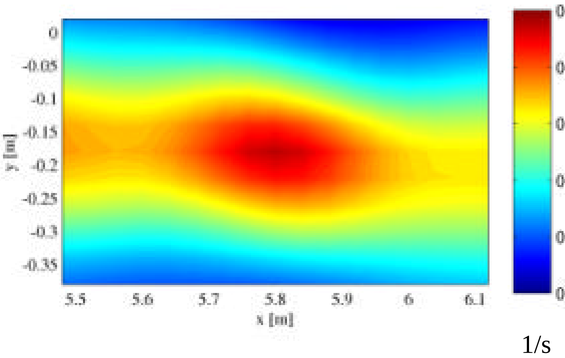

Figure 11: A contourplot of the ensemble averaged vorticity 5.8 m downstream of the splitter plate

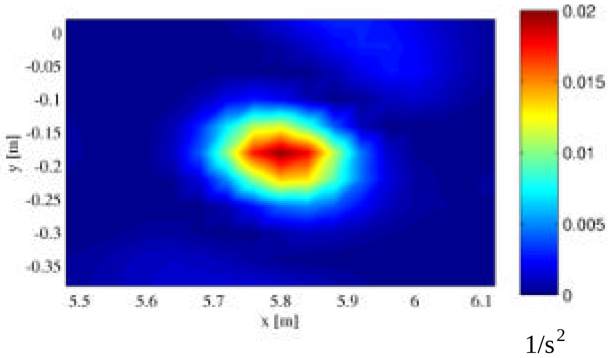

Figure 12: A contourplot of the ensemble averaged enstrophy 5.8 m downstream of the splitter plate

On theoretical grounds a difference between the behaviour of large scale structures of mixing layers in shallow flow and in deep flow was expected. Where in deep flow the large structures dissipate their energy through a normal turbulence energy cascade, in shallow flow this road would be largely blocked by the insufficient presence of intermediate turbulence scales due to the small depth. The spectra in figure 13 obtained in the compound channel from very long (8 hours) LDV measurements confirm this view. The spectrum of horizontal velocity fluctuations shows a clear low-frequency peak on top of the 3-dimensional turbulence spectrum, which is absent outside the mixing layer in the main channel. The vertical velocity fluctuations do not show this peak.

4. CONCLUSIONS

- In shallow flow the development of mixing layers deviates strongly from that in deep flow.
- Quasi-2D large scale horizontal structures play an important role in shallow mixing layers.
- PTV is a very useful measuring method to determine presence and characteristics of large scale horizontal structures.
- Large structures can be characterized by their vorticity and enstrophy distributions.
- Ensemble (and conditional) averaged vorticity distributions and enstrophy distributions can be used to evaluate appropriate turbulence models.

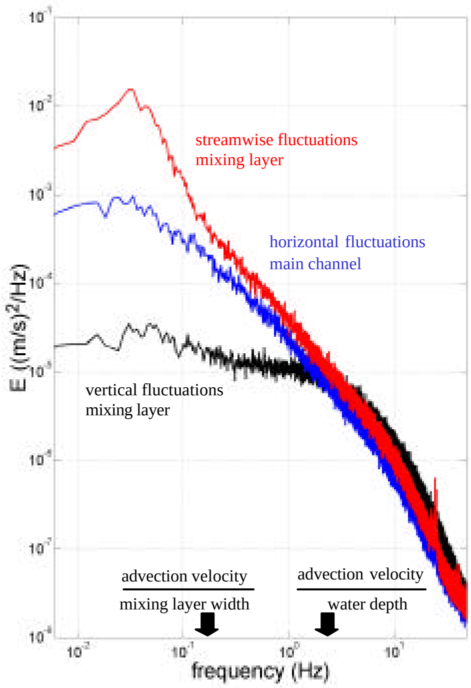

Figure 13: Power density spectra of the streamwise and vertical velocity in the mixing layer and the streamwise velocity outside the mixing layer measured in the compound channel.

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