Environmental Hydraulics: Turbulence and diffusion

Flow Patterns In Dead Zones of Rivers and their Effect On Exchange Processes

V. Weitbrecht & G. H. Jirka
Inst. for Hydromechanics, University of Karlsruhe, 76128 Karlsruhe, Germany
weitbrecht@ifh.uni-karlsruhe.de, jirka@uni-karlsruhe.de

Abstract: This paper presents experimental studies to examine the flow patterns in dead zones, formed by groyne fields in rivers and their effect on the mass exchange with the main stream, which has a controlling effect on the longitudinal dispersion. Particle-Image-Velocimetry Measurements at the water surface to quantify the influence of large coherent structures on the mass exchange are compared with depth averaged concentration measurements. Special focus is given to the influence of the inclination angle between main stream and groyne.

Introduction

Exchange processes between dead zones, as formed by groyne fields or side arms, and the main flow channel of a river system have a significant influence on the mass transport in rivers. The mass exchange with the dead zones increases longitudinal dispersion and leads to a reduction of the transport velocity in the river channel below its mean flow velocity. An accurate prediction of travel time, maximum concentration and spreading of a pollutant cloud requires an explicit consideration of the mechanism of these exchange processes. This needs to be included in existing one-dimensional models that are used online as "alarm models" for the management of accidental pollutant releases, as for example in the "River Rhine Alarm Model" (Spreafico & Mazijk 1993). This model was developed by the "International Commission for the Hydrology of the River Rhine" (CHR) and the "International Commission for the Protection of the Rhine" (ICPR), after the accidental Sandoz spill in (1986), where a large amount of toxic chemicals were released into the river Rhine. For this kind of predictive model, much effort and expenses must be spent on calibration by means of extensive tracer measurements. In case of the River Rhine Alarm Model which uses a one-dimensional analytical approximation for the travel times and the concentration curves, a dispersion coefficient and a lag coefficient have to be calibrated. The model works well for cases of similar hydrological situations. However, variations in discharge and thus changes in water surface level lead to increased errors if the same calibrated parameters are used for different hydrological characteristics.

The mass transport between dead zone and main stream is dominated by large coherent structures which are generated at the head of a groyne (Lehmann et al. 1999). These structures are advected within the mixing layer and transfer tracer mass from dead zone to main stream and vice versa (Fig. 1). Since the flow is very shallow, which means that the horizontal dimension of the flow is much larger than the vertical, these structures are mainly two-dimensional. Therefore it is possible to obtain quantitative information about the mass transport by simply analyzing...
surface velocities. From PIV (Particle-Image-Velocimetry) measurements, we get detailed information about the instantaneous velocity fields (Fig. 1), which can be used to analyze the flow characteristics with its large two-dimensional structures and, thus, the exchange processes. For an accurate interpretation of these results dye experiments are performed where the exchange process is analyzed by the depth integrated behavior of tracer mass in dead zones.

Experiments

In order to quantify the mass exchange between main stream and dead zone, laboratory experiments were conducted in a laboratory flume (20m x 1.8m). The bottom slope of the flume is adjustable so that nearly uniform flow conditions can be achieved. The water depth is 4.6 cm and the main stream mean flow velocity is 0.16 m/s, which leads to bulk Reynolds Number of about 7500. To simulate the flow in typical dead zones, a series of 15 groynes, made of perspex with a heavy core, are aligned on one side of the flume. These elements can be placed at various positions, so that the groyne aspect ratio (width/length) can be varied from 0.17 up to 3.33. In this paper experiments are presented, where the aspect ratio between width and length of a groyne field is 0.4 and the groyne inclination angle with respect to the main flow direction is changed from 90° to ±64° respectively. The shape of the groynes was chosen to be very simple, because earlier investigations suggest that there is no significant influence of the groynes shape on the exchange processes (Lehmann et al. 1999). Here the outline of a groyne is a rectangular box (0.5 m x 0.05 m x 0.05 m) with an attached half cylinder (diameter = 0.05 m).

The measurement technique used in this study is based on a PIV-System (LaVision), which has been adapted so that a flow field of 1.2 m x 1.4 m could be observed with a high spatial resolution leading to a 46 x 78 vector matrix. Because the dynamic range of the velocities in the region of interest is very high a simple PIV algorithm would fail. In this case an adaptive multipass processing tool is used, where the PIV algorithm starts with a large area of interest (AOI) and uses the obtained velocity as reference velocity for the next smaller AOI. The time resolution of 7 Hz is provided by a PCO-Sensicam camera (12 Bit, 1024 x 1280 pixels). A NIKON lens (f-mount) with a focal length of 15 mm is used for an undistorted high quality
image. Black polypropylene particles are used as particles for the PIV-measurements. With the help of a particle dispenser the water surface is seeded with a high density of particle so that a detailed analysis of the flow field is possible. For further detail see Weitbrecht & Jirka (2001).

Dye experiments to verify the results of the velocity measurements were done under the same flow conditions. The idea of the concentration measurements was to observe the dilution of tracer mass in one single groyne field after an instantaneous planar tracer injection. The problem in this case is how to generate an instantaneous volume source without disturbing the flow field. In older investigations the dead zone was separated by a gate from the main stream to inject the tracer and mix it up before observing the exchange process (Westrich 1977). In this case the early stage of the experiment is strongly disturbed by the undeveloped flow conditions in the mixing zone and in the groyne field. In the case of the experimental setup that is described by Lehmann et al. 1999, the tracer was spilled by hand into a groyne field without any separation between main stream and groyne field. In this case the flow is almost undisturbed so that the processes in the mixing zone represent a real situation. The problem with this experimental setup is the difficulty to reach a well mixed situation as initial condition for the experiment.

In our case a special injection device (Fig. 2) was developed, which leads to a homogeneous mixed situation in the groyne field as initial condition. The idea of this device is to inject tracer from above into the dead zone with a large number of injection points so that the tracer is uniformly distributed over the entire area. The main part of the injection device consists of a rectangular box (1.4m x 0.6m x 0.02m) that is connected to a moving frame mounted upon the channels walls. The bottom side of the box consists of a 3cm x 3cm array of thin needles, where the tracer can be injected into the flow without penetrating the water body. The device is controlled by a vacuum-pressure-system (Fig. 2), from which we can pump the dissolved tracer from the different reservoirs into the injection tank and into the high pressure reservoir. From the high pressure tank an exact amount of tracer can be injected into the water body. When the tracer is injected into the water body the injection tank is pushed to the other side of the channel so that the CCD-camera can observe the flow field. The frame rate is 4 Hz and 2500 pictures are captured. For every setup the experiment is repeated three times. To evaluate the depth integrated concentrations, the local gray scale intensities (Fig. 1) in the region of the groyne field are analyzed. To get exact results, the gray values are calibrated with different known dye concentrations and the change of background illumination during the experiment is taken into account.
Analysis

Valentine & Wood (1979) states that the one dimensional dispersion model that was initiated by Taylor (1954) for pipe flow, and which has been adapted by Elder (1959) for wide open channels, and by Fischer (1979) for natural channels, does not describe always the transport mechanisms in rivers adequately. They showed that the dead zone model where the one-dimensional convection diffusion equation is linked with a second equation (eq. 1) describing the concentration in the dead zone represents more precisely the behavior of a pollution cloud in the presence of dead zones.

\[
\frac{\partial C_b}{\partial t} = -D_b (C_s - C_b)
\]  

(1)

\(C_b\) is the concentration in the dead zone, \(C_s\) the concentration in the main stream and \(D_b\) the ratio between the exchanged volume per time \(Q_e\) and the dead zone volume \(V_b\).

\[
D_b = \frac{Q_e}{V_b} = \frac{L h E}{L B h} = \frac{E}{W}
\]  

(2)

where \(W\), \(L\), \(h\), \(B\) and the exchange velocity \(E\) are defined in Fig. 3 and Fig. 4. \(D_b\) is the reciprocal of a typical time scale which corresponds to the overturn time of the gyre inside the groyne field. Normalization of \(D_b\) with the mean velocity in the main stream \(U_s\) and the width of the groyne field \(W\) gives a dimensionless exchange coefficient \(k\) which has been defined by Valentine & Wood (1977) which expresses the ratio between the exchange velocity \(E\) and the main stream velocity \(U_s\). Typical values of \(k\) are on the order of 0.015 - 0.04 (Valentine & Wood 1979, Booij 1989, Wallast 1999, Weitbrecht 2001).

Within this investigation the exchange parameter \(k\) is determined with two different approaches. In the first case the exchange is determined with velocity measurements and in the second case with concentration measurements. First, the exchange parameter \(k\) is determined with the results of the planar velocity measurements. The norm of the transverse component of the velocity vectors \(E_i\) between groyne tip and groyne tip (Fig. 4) is averaged over the groyne field area, resulting in the total specific volume flux through the exchange interface. Division by 2 yields the total specific out flux \(\overline{E}\) into the main stream

\[
\overline{E} = \frac{1}{2 n} \sum_{i=1}^{n} |E_i|
\]  

(3)

By dividing the time average of the specific out flux with the groyne field width \(W\), \(D_b\) can be determined. If \(D_b\) is known, the exchange parameter \(k\) can be calculated. Account should be taken to the fact, that the velocities are measured at the water surface and do not represent the depth averaged velocity. This is one reason why we have to verify these results by dye experiments.
To verify the determined $k$ with the surface velocities we use a direct approach to evaluate the concentration fields. Eq. 1 yields the solution $C_b = C_o \exp (-D_b * t)$ if we assume the concentration in the main stream to be zero. In order to determine $D_b$ this function is fitted to the measured time dependent mean concentration in the groyne field. Normalization with $U_s$ and $W$ finally yields the dimensionless exchange parameter $k$.

**Results:**

Three different cases with variation of the inclination angle of the groyne against the main stream direction have been evaluated (Fig. 5) and are summarized in Table 1.

<table>
<thead>
<tr>
<th>inclination angle</th>
<th>$k$ evaluated from velocity measurement</th>
<th>$k$ evaluated from dye experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 1: 90°</td>
<td>0.034</td>
<td>0.029</td>
</tr>
<tr>
<td>case 2: -64°</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>case 3: +64°</td>
<td>0.026</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: dimensionless $k$-values for the various experimental conditions

For case 1, the values for $k$ are determined with the velocity fields and with the concentration measurements. Compared to $k$ obtained with the velocity data the exchange is reduced when $k$ is evaluated from concentration measurements. This tendency represents the effect of the higher surface velocity than the mean flow velocity.

If we look at the influence of the inclination angle it is found that for groynes which are inclined with respect to the main flow direction (case 2 and 3) the exchange parameter is significantly altered compared to the right-angled case 1. The reason why the exchange is stronger when the groynes are inclined against the main flow direction can be found by comparing the turbulent characteristics in the mixing zone of the three different cases. The maximum rms value of the transverse velocities in the mixing zone for case 2 is about 0.020 m/s whereas for case 3 it is only 0.015 m/s. A second effect which decreases the exchange is the size of the secondary eddy in the upstream corner of the groyne field (Fig. 5). Since this part of the dead zone is exchanging mass with the primary gyre much slower (Lehmann et al. 1999) than the primary gyre with the main stream, the size of the secondary gyre represents an additional sheltering effect. In case 3 the secondary eddy covers the largest volume fraction of the dead zone, which leads to a smaller $k$. 

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*Fig. 5: Comparison of the averaged flow field of three different groyne fields with the same aspect ratio (width/length (W/L) = 0.4)*
This result shows that \( k \) is not only dependent on the W/L aspect ratio, but is also influenced by the inclination angle of the groynes.

**Conclusions**

With the aid of dye experiments, the exchange processes between dead zones and main stream can be determined if the tracer is well mixed in the initial stage of the experiment. The results of these experiments serve as a justification of the results which are obtained with velocity measurements at the water surface. This is necessary because velocity measurements are much easier to perform and so future setups with different geometries can be analyzed only with velocity measurements as long as the groynes are not submerged.

Groynes which are inclined against the flow direction lead to higher exchange values than the opposite inclination angle. In the second case a much larger secondary eddy is generated in the upstream corner of the groyne field which also leads to smaller exchange values. Further dye experiments with different geometric conditions, such as variation in the aspect ratio, will be conducted in the near future.

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**References**

Elder, J. (1959), The dispersion of marked fluid in turbulent shear flow. J. Fluid Mech. 5
Wallast, I., Uijtewaal, W., Mazijk, A. van, (1999), Exchange processes between groyne field and main stream. Proceedings 28th IAHR Congress, Graz
Westrich, B. (1977), Massenaustausch in Strömungen mit Totwasserzonen unter stationären Fließbedingungen, SFB 80, Institute for Hydromechanics, University of Karlsruhe