A Random Walk Approach for Investigating Near- and Far-Field Transport Phenomena in Rivers with Groin Fields

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ABSTRACT Dead-water-zones in rivers formed by groin fields strongly influence the dispersive mass transport of dissolved pollutants. The cause for this influence is the exchange process between groin fields and main stream. With the help of laboratory experiments the most important parameters, such as storage time, velocity distribution and distribution of the diffusivity have been investigated. A transport model using a Lagrangian-Particle-Tracking-Method (LPTM) has been developed, to transfer the locally obtained experimental results for a single dead-water-zone into the global parameters of a one-dimensional far field model that comprises the action of many dead water zones. It is shown that in the presence of large dead water zones at the river banks, an equilibrium between longitudinal dispersion and transverse diffusion can be reached if the morphologic conditions do not change. The simulations result in a cross sectional averaged concentration distribution that converges asymptotically to a Gaussian distribution over the longitudinal coordinate. Due to the presence of dead water zones the distribution of tracer material becomes inhomogeneous in transverse direction.

1 INTRODUCTION

Predicting the transport of dissolved pollutants in rivers is difficult, because of the various effects of the morphological conditions. In rivers with strong morphological heterogeneities, like extensive dead-water-zones, the prediction of transport velocities, maximum concentration and skewness contains strong uncertainties that need to be reduced. The River-Rhine-Alarm-Model (Spreafico and van Mazijk 1993) has been developed by the "International Commission for the Hydrology of the River Rhine" (CHR) and the "International Commission for the Protection of the Rhine" (ICPR). For this kind of predictive models, much effort and money is spent on calibration by means of extensive in-situ tracer measurements (van Mazijk 2002). In the case of the River Rhine Alarm Model, which uses a one-dimensional analytical approximation for the travel time and concentration curve, 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 levels, lead to increased errors if the same calibrated parameters are used for different hydrological situations. Insufficient knowledge about the relation between river morphology and transport processes are the reason for these uncertainties. Hence, predictive methods that are appropriate for variable flows and changing morphological conditions are needed.

With the present work we focus on the influence of dead water zones, such as groin fields, on the dispersive mass transport in the far field of pollutant releases. Longitudinal dispersion in rivers that can be treated as shallow flows is controlled by two processes. First, the longitudinal stretching due to the horizontal shear, and second, transverse homogenization by turbulent diffusion (Fischer et al. 1979). Detailed velocity and concentration measurements have been performed in the laboratory in order to determine typical flow patterns and local mass transport phenomena. Direct measurements of dispersion coefficients are problematic because the dispersive character of a transport phenomena reaches its final behavior only after a very long travel time (Fischer et al. 1979), which is determined by the width of the flow and the intensity of the transverse turbulent diffusion. In most cases laboratory flumes are far too short, to examine longitudinal dispersion in the far field. To address this problem, laboratory and numerical experiments have been combined in such a way that the ef-
fect of local phenomena that have been measured, are translated into the behavior of tracer clouds in the far field with the help of Lagrangian-Particle-Tracking-Method (LPTM).

2 EXPERIMENTS
In the present study the experiments have been performed in a laboratory flume of 20m length and 1.8m width, which has an adjustable bottom slope. In all the experiments only half of the channel width has been modelled, which means that only on one side of the flume groins have been placed. The shape of the groins was chosen to be very simple due to the fact that earlier investigations suggest that there is no significant effect of the groin shape on the exchange processes (Lehmann 1999). Using a simple geometry leads to a small number of parameters, which allows clear understanding of the basic relations between geometry and flow or transport phenomena, respectively.

The flume bottom consists of a plastic laminate with small roughness elements < 0.2 mm. Level changes in x- and y-direction (Fig. 1) of the flume bottom are smaller than 0.2 mm. The flume is connected to a system of a water storage tank and a constant head tank, which is supplied by three different pumps, enabling discharges up to 100 ℓ/s. The discharge is controlled by an inductive-flow-meter together with an PC controlled gate valve. In the present case, only very small discharges of up to 10 ℓ/s are needed. Therefore, the gate valve is equipped with a pentagonal regulating orifice, which leads to constant discharges (changes smaller than 0.5%), even if the valve is opened only 5%.

In order to simulate flow patterns under the influence of dead-water zones, respectively groin fields, a series of 15 schematized groins made of PVC with a heavy core were built, so that these elements could be placed at variable positions. The outline of a single groin was chosen to be a combination of a rectangular box (0.45m x 0.05m x 0.05m) with an attached half cylinder (diameter = 0.05m). In the present study experiments have been performed with varying groin field aspect ratio \( W/L \) (0.17 - 3.5) and different inclination angles of the groins (Fig. 2).

The velocity measurements were performed using Particle-Image-Velocimetry at the water surface, using the PIV package DaVis from LaVision (Weitbrecht et al. 2002). With the help of a particle dispenser the water surface is seeded with black Polypropylene particles, such that homogeneous particle distribution on the water surface is achieved. The flow field in the main stream and in the groin field is then recorded with a digital camera at a temporal resolution of 7 Hz. The vector fields are obtained by using a cross-correlation technique, leading to spatial resolution of 2 cm x 2 cm.

In Fig. 3 the measured mean velocity profiles are plotted for the different aspect ratios in the case of the standard groins.

The comparison in Fig. 3 shows that, the aspect ra-
tio of the groin field has limited influence on the mean flow properties in the main stream. Above the groin field boundary no significant differences between the normalized velocity profiles can be observed. The velocity profile in Fig. 3 in the main stream part of the flow has the typical shape of a mixing layer velocity profile and can be approximated using a hyperbolic tangent function of the form

\[ \frac{u(y)}{U_s} = a \tanh \left( \frac{y}{h_s} b \right) + c \]  

(1)

where \( a, b \) and \( c \) are constants that have to be adapted. In the present case the profile for the reference case \( W/L = 0.4 \) leads to the following values: \( a = 0.82, b = 0.24 \) and \( c = 0.17 \). \( h_s \) is the water depth in the main stream. This equation represents the velocity profile that is responsible for the stretching mechanism of a tracer cloud in the main stream.

In Fig. 4 the normalized rms-velocities of the transverse component \( v'/u_s \) measured with the PIV system are plotted. These values indicate the strength of the transverse turbulent mixing, which is the second important parameter influencing longitudinal dispersion.

![Figure 4: Comparison of the normalized strength of the velocity fluctuations \( v'/u_s \) for the different aspect ratios \( W/L \)](image)

Additional concentration measurements have been performed to measure the mean residence time \( T_D \) of tracer material in the dead-water-zones (Kurzke et al. 2002) using a depth averaged adsorptive technique. With the help of a multi-port injection-device tracer has been injected instantaneously into one groin field. The evolution of concentration distribution has been recorded with a CCD-camera. Gray scale analysis, which takes into account inhomogeneous illumination and changing background intensities, finally leads to an exponential decay function for every groin field setup

\[ C(t) = C_o e^{-\frac{t}{T_D}} \]  

(2)

where \( C \) is the spatial averaged concentration in the dead zone, \( C_o \) the initial concentration. The residence time \( T_D \) is used in the LPTM transport model to parameterize the influence of dead-water zones on the mass transport in the river.

\( T_D \) can be normalized with the width of the groin field \( W \) and the main stream velocity \( U \) to give a dimensionless exchange coefficient \( k \)

\[ k = \frac{W}{T_DU} \]  

(3)

The resulting exchange coefficients \( k \) for the different groin field setups are shown in Fig. 5.

![Figure 5: Dimensionless exchange coefficient \( k \) against the aspect ratio \( W/L \)](image)

Figure 5 shows that \( k \) reduces with increasing \( W/L \), which means that the residence time \( T_D \) is longer in the very narrow cases of groin fields. Another result is the increased mass exchange for backward inclined groins compared to downward inclined or regular groins. For short groins Fig. 5 shows also the tendency towards smaller exchange values with increasing \( W/L \). However, the \( k \)-values for short groins are noticeably smaller for the same aspect ratio \( W/L \) than in the standard case. This shows, that the groin field volume has to be taken into account for the prediction of \( k \).

A slight modification of the scaling factor \( W/L \) into \( WL/(W + L) \), which can be interpreted as a kind of hydraulic radius \( R_D \) of the dead-water-zone, leads to a better normalization shown in Fig. 6. Why the exchange coefficients should scale with the hydraulic radius \( R_D \) can be explained by the following: In the case of very long groin fields with \( L \rightarrow \infty \) the expression \( WL/(W + L) \) tends to \( W \). Therefore, in the case of very long groin fields the recirculating flow is only determined by the width \( W \) of the groin field. In the other extreme case for \( W \rightarrow \infty \) the hydraulic radius \( R_D \) tends to \( L \), which means that the mass exchange in this case is only determined by the length of the mixing layer.
The method has been verified with the aid of the analytical solution presented for the Advection-Diffusion-Equation for a Couette-Flow problem (Fischer et al. 1979) and turbulent unbounded vertical shear flow given by Elder (1959). Dispersion coefficients obtained from these solutions are compared with the transport characteristics using the LPTM (Weitbrecht et al. 2003).

In the next step the transport model is used to predict the transport parameters for the flow conditions, taken from the experiments. Mean flow quantities and turbulence intensities are determined in pure channel flow and are adapted to the LPTM. Finally the influence of dead-zones (groin fields) is implemented.

A random walk simulation can be understood as the tracking of discrete particles, under the influence of the governing flow processes. Typically, the particle displacement $dX_i$ is described by a deterministic and a stochastic part, leading to the so called Langevin equation (Gardiner 1985)

$$dX_i = f(X_i, t) dt + Z(t) g(X_i, t) dt$$

(4)

where $X_i$ is the position $x, y$ and $z$. $f(X_i, t)$ represents the advective or drift component, which can be interpreted as the mean flow velocity field. The expression $g(x_i, t)$ describes the diffusive or noise component of the particle movement that describes the strength of the turbulent diffusion in space. The stochastic part is represented by the Langevin force $Z$, which is a Gaussian distributed variate with a mean value of zero and a variance equal to one.

In the present case the governing processes are advection in x-direction and diffusion in transverse direction (Fig. 7), which implies that we can neglect the drift component in y-direction and the noise component in x-direction in Eq. 4. An important part of such a model is the link between the diffusive step size and the length of the time step. Here we use the approach given by Taylor (1921) who stated that the spreading of a particle ensemble measured with the standard
deviation under the influence of turbulent diffusion can be treated as a Fickian type of diffusion, where \( \sigma \sim \sqrt{2D_t} \). The diffusive step size for a single particle at a certain time step in y-direction is therefore given with

\[
v'\Delta t = \sqrt{2D_y \Delta t}
\]

(5)

where \( D_y \) is the turbulent diffusion coefficient in y-direction. Using these assumptions, the position of the particles in every time step \( \Delta t \) can be described by a simplified two-dimensional version of Eq. 4.

\[
x_{\text{new}} = x_{\text{old}} + (\Delta t \cdot w(y))_{\text{deterministic}}
\]

(6)

\[
y_{\text{new}} = y_{\text{old}} + Z\sqrt{2D_y \Delta t}_{\text{stochastic}}
\]

(7)

where \( x_{\text{old}}, y_{\text{old}} \) and \( x_{\text{new}}, y_{\text{new}} \) are the spatial locations at times \( t \) and \( t + \Delta t \) respectively, and \( D_y \) is the transverse component of the turbulent diffusion coefficient. The function \( u(y) \) denotes the mean flow velocity in relation to the position in transverse direction. Consequently, in every time step, a particle moves convectively in x-direction depending on the velocity profile and does a positive or negative diffusive step in transverse y-direction.

The reason why there is no diffusive step in the x-direction needed (Eq. 6), can be explained by the fact, that turbulent diffusion in x-direction and longitudinal dispersion are additive processes (Aris 1959), which means that the final dispersion coefficient can be adjusted by adding the turbulent diffusion coefficient. Fischer et al. (1979) showed that in natural rivers the coefficient of longitudinal dispersion \( D_L \) lies in the range of \( 30 < D_L/(u_s h) < 3000 \), while the longitudinal turbulent diffusion coefficient \( D_x \) is considerably smaller. A typical approximation of the turbulent diffusion coefficient is given by \( D_x \approx (0.6 u_s h) \), which means that in this approach turbulent diffusion in longitudinal direction can be neglected in comparison to longitudinal dispersion. An advantage of this simplification is a shorter computing time.

Flows with inhomogeneous turbulent diffusion coefficients are treated here, which means that \( D_y \) is a function of \( y \). A problem in performing LPTM-simulations is given by the fact that particles segregate into regions of low diffusivity (Hunter et al. 1993). In the stochastic model particles move independently from regions with high diffusivity into regions with low diffusivity. As a consequence the probability of a particle to move from a region of high diffusivity into a region of low diffusivity is higher than vice versa. In order to satisfy continuity an extra advection term in y-direction has to be included, to achieve consistency with the governing Advection-Diffusion-Equation. This extra term is called the noise-induced drift component. By matching the resulting stochastic transport equations with the Advection-Diffusion-Equation Dunsbergen (1994) showed, that in this case, the noise-induced drift component \( \Delta y_n \) can be formulated as follows

\[
\Delta y_n = \frac{\partial D_y}{\partial y} \Delta t
\]

(8)

If Eq. 7 is extended with the given expression for the noise-induced drift component (Eq. 8), the transport problem with varying diffusivity is described consistently with the Advection-Diffusion-Equation.

\[
y_{\text{new}} = y_{\text{old}} + Z\sqrt{2D_y(y)\Delta t} + \frac{\partial D_y}{\partial y} \Delta t
\]

(9)

Also the boundaries of the calculation domain and their effect on the particles are important. The inflow and outflow boundaries do not affect the particles as in our case the domain has an infinite length. In case of horizontal shear the boundaries representing the channel bank and channel centre line act as reflective walls. Particles which would cross the left or right boundary at a certain time step are reflected into the calculation domain. Consequently, a particle with a calculated y-position outside the calculation domain \( y < 0 \) is re-introduced as follows

\[
y_{\text{new}} = -y_{\text{calc}}
\]

(10)

where \( y_{\text{calc}} \) is the calculated y-position at a certain time step.

With the given equations and boundary conditions transport in open channel flow can be simulated with a depth-averaged velocity profile in transverse direction and a certain distribution of the diffusivity. The next step is to include the influence of dead-water zones (Fig. 8) into the LPTM.

The mean residence time of tracer material in the dead-water zone is the most important parameter to describe the behavior of a dead-water zone. Therefore, it should be possible to model the influence of the mass transport by including this parameter into the LPTM. A possibility is to include the residence time into the boundary condition, such that this boundary simulates the behavior of mass trapping and mass release. Thus, the interface between main channel and dead-water zone has to act as a transient-adhesion boundary, which means that particles that reach such a boundary are fixed to that position until \( T_D \) has passed. This mimics to the real dead-zone behavior. A particle that enters a dead-water zone because of turbulent motion in the mixing layer, does not move.
on average in x-direction, assuming that the longitudinal extension of the dead-water zone is small compared to the length of the modeled river section. The particle remains in the dead-water zone on average for time period given by the mean residence time \( T_D \), where \( T_D \) is the mean residence time.

The outcome of a LPTM simulation are \( x \) and \( y \)-positions of every single particle at every time step. By analyzing the statistics of the particle positions, information about the transport characteristics can be determined. The one-dimensional longitudinal dispersion coefficient \( D_L \), as a measure of the spatially averaged spreading rate of a tracer cloud, can be determined by calculating the time change of the longitudinal variance \( \sigma_x^2 \) of the particle distribution (Rutherford 1994) as follows

\[
D_L = \frac{1}{2} \frac{\sigma_x^2(t_2) - \sigma_x^2(t_1)}{t_2 - t_1} \tag{11}
\]

A second result will be the skewness \( G_t \) of the particle cloud. The skewness is defined as the relation between the quotient of the third moment about and the third power of the standard deviation

\[
G_t = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^3}{(n-1)\sigma_x^3} \tag{12}
\]

where \( n \) is the number of particles at the positions \( x_i \) with mean position \( \bar{x} \) and \( \sigma_x \) is the standard deviation of the particle distribution. The skewness of a certain distribution describes the degree of asymmetry of a distribution. The skewness can be used as an indicator for the length of the advective zone, in order to define when it is acceptable to apply the Taylor solution to a pollutant transport problem.

Another parameter of interest is the transport velocity \( c \) of the tracer cloud, defined as the velocity of the center of mass of a particle ensemble. In the case of regular channel flow with ordinary reflective boundary conditions \( c \) is equal to the mean velocity if the particles are homogeneously distributed over the river cross section. In case of point sources this can be reached after the tracer has passed the advective zone. The transport velocity can be determined as follows

\[
c = \frac{\bar{x}(t_2) - \bar{x}(t_1)}{t_2 - t_1} \tag{13}
\]

where \( \bar{x} \) represents the center of mass of a particle cloud.

4 APPLICATION AND RESULTS

In this section the LPTM is applied to different flow fields, that have been investigated in the laboratory in order to determine the influence of river heterogeneities on the mass transport properties of a river. Three different cases will be analyzed in detail. First the behavior of the dispersive character of pure channel flow without the influence of groin fields is investigated. In a second step groin fields are implemented, and finally the influence of different residence times on the transport characteristics is determined.

4.1 Straight Open Channel Flow

A LPTM-simulation has been performed, in order to analyze transport phenomena in regular channels without groin fields. Therefore the measured velocity distribution has been approximated with an analytical function, that can be seen in Fig. 9 (i). The diffusion coefficient in this case has been chosen to be constant over the whole river cross section, with a value according to Fischer et al. (1979) for regular channels

\[
D_y = 0.15 u_s h \tag{14}
\]

In Tab. 1 the properties of the flow and the settings of the 2D-LPTM-simulation for the case of a straight channel flow are listed.

The equilibrium between longitudinal stretching and transverse diffusion, where the dispersion coefficient does not change any more is reached after about 800 times the channel’s half width. The final value of \( D_L/(u_s h) \) is 177, and is much larger (30 times) than the dispersion found in a channel with a laterally uniform velocity (Elder 1959).

4.2 Channel Flow with Groin Fields

The influence of groin fields is simulated with the transient-adhesion boundary condition (Sec. 3), that represents the mean residence time of a particle in
the groin field. These mean residence times have been measured in this study with two different approaches. Concentration measurements have been performed, where concentration decay in a single groin field has been tracked with digital video analysis. Starting with a known homogeneous concentration in the groin field and zero concentration in the main stream an exponential decay could be observed, leading to a typical time scale $T_a$ describing the mean residence time. These experiments are in principle analogous to the measurements that have been performed by Uijttewaal et al. (2001). An improvement could be achieved by the development of a multi-port injection device, that is able to produce reproducible homogeneous concentration fields as initial condition for the concentration measurement (Kurzke et al. 2002). Another possibility to determine the residence times is given by using the velocity fields for the determination of the mass exchange rate between groin field and main stream (Kurzke et al. 2002).

In order to determine the influence of groin fields, a LPTM-simulation has been performed with the same flow properties as in the described case above (Tab. 1). The difference lies in the transient-adhesion boundary condition at the channel wall. This simulation represents groin fields, where the ratio between the width $W$ of a groin field divided by the length $L$ is 0.4 (Fig. 2). These conditions correspond to laboratory measurements with a groin field length 1.25 m and a width of 0.5m. As the water depth in the groin field and the main stream is the same, the ratio between the cross sectional area of the dead water zone and the main stream is 0.5. The mean residence time $T_a$ of a tracer particle has been set to 90 seconds, which corresponds to the measured dimensionless exchange coefficient

$$k = \frac{W}{T_a U} = 0.028$$

where $W$ is the width of the groin field and $U$ represents the mean flow velocity in the main channel.

In the case of channel flow with groin fields the velocity profile is slightly changed compared to the pure channel flow, because in the presence of groin fields the velocity profile has to represent the mixing layer between groin field and main stream and can be approximated with a $tanh$ function, where the velocity is still positive at $y = 0$.

The distribution of the diffusivity in that case is not constant over the channel cross section, see Fig. 4. Turbulence measurements showed, that the velocity fluctuations in the region of the mixing layer between groin field and main channel are much stronger than in the undisturbed main channel. Therefore the diffusivity given by Eq. 14 is amplified in the region of the mixing layer, proportional to the increasing transverse velocity fluctuations. This has been done, by fitting a gaussian curve to the transverse $rms$-values of the channel flow, such, that the diffusivity in the mixing layer is three times larger than in the main channel (Weitbrecht et al. 2002).

In Fig. 10 the LPTM-simulation with groin fields is visualized after 200 time steps. The main difference with respect to pure channel flow is found in the particle clouds that travel far behind the main tracer cloud, a phenomenon that is also observed in the laboratory flume. These small particle clouds arise by the effect of the dead water zones. Particles that have crossed the lower boundary layer during the simulation, remain at the same x-position for the mean residence

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth $b$ [m]</td>
<td>0.046</td>
</tr>
<tr>
<td>Channel half width $B$ [m]</td>
<td>1</td>
</tr>
<tr>
<td>Mean velocity [m/s]</td>
<td>0.19</td>
</tr>
<tr>
<td>Horizontal velocity profile</td>
<td>Fig. 9 (i)</td>
</tr>
<tr>
<td>Channel slope $I$ [%]</td>
<td>0.032</td>
</tr>
<tr>
<td>No. of particles</td>
<td>5,000</td>
</tr>
<tr>
<td>No. of time steps</td>
<td>40,000</td>
</tr>
<tr>
<td>Length of time step $\Delta t$ [s]</td>
<td>1</td>
</tr>
<tr>
<td>Diffusivity $D_y$ [m$^2$/s]</td>
<td>(Eq. 14)</td>
</tr>
</tbody>
</table>

#### Table 1: Parameter values for the pure channel flow simulation, taken from the measurements

Figure 9: Result of LPTM-simulation with pure channel flow, after first time step. i) Particle position according to the fitted velocity profile and the measured velocities taken from the experiment; ii) particle density in longitudinal direction.

![Particle density](image1.png)

![LPTM vs Measured Values](image2.png)
time $T_a$. After $T_a$ has elapsed the particles get back to the flow. The mean distance between those clouds corresponds to the mean residence time $T_a$.

The final stage of mixing in the case with groins shows again, that after a long period the tracer cloud approximates a Gaussian distribution in longitudinal direction Fig. 11.

![Figure 11: Result of LPTM-simulation after 40000 time steps with a mean residence time of $T_a = 90$s, that corresponds to a width to length ratio of a groin field of 0.4 and $W/B = 0.5$; i) particle position; ii) particle density in longitudinal direction](image)

The interesting properties of this simulation are the evolution of the dispersion coefficient and of the skewness, as visualized in Fig. 12. The final value of $D_L/(u_sh)$ is in that case approximately 24.800 which is a factor 140 higher than in the case of pure channel flow, and about ten times higher than the values common for natural rivers without groin fields. This can be explained by the exaggerated ratio between the cross sectional area of the dead water zone $A_d$ and the cross sectional area of the main channel, which is 0.5 for this experiment, a value rather high compared to natural rivers.

The equilibrium between longitudinal stretching and transverse diffusion is achieved after approximately 800 times the channel width (Fig. 12), which indicates that the advective zone has the same length irrespective of the presence of groins.

![Figure 12: Evolution of Dispersion coefficient $D_L \cdot 10^{-4}$ normalized with the $u_s$ and the water depth $h$ and the evolution of the skewness. $D_L$ is smoothed with a sliding average filter of increasing window size. ($W/B = 0.5$)](image)

In the case of a straight channel flow, the transport velocity $c$, which is defined as the translation velocity of the center of mass of the tracer cloud Eq. 13, always equals the mean flow velocity in the channel. In the case with groin fields the transport velocity of the tracer cloud decreases in time until an equilibrium distribution between the particles in the dead water zones and in the main channel is established, see Fig. 13. In this simulation the transport velocity does not change further after the tracer cloud has travelled approximately 1000 times the channel half width. The final transport velocity is 64% of the mean flow velocity in the main channel.

![Figure 13: Evolution of transport velocity $c$ of a tracer cloud normalized with mean velocity of the main channel.](image)

According to the one-dimensional dead-zone-models by Valentine and Wood (1979, van Mazijk (2002), the transport velocity in the far field can be estimated from the ratio between the cross sectional area of the dead water zone $A_d$ and the cross sectional area of the main stream $A_s$

$$c = \frac{U}{1 + A_d/A_s}$$  \hspace{1cm} (16)

In the presented case this relation would provide a value of 67% of the mean flow velocity, which is close to the result of the LPTM-simulation.

![Figure 14: Particle density distribution in river cross-section as a function of the distance $x/B$.](image)

Considering the particle distribution in transverse direction of the river cross section, it can be stated that the initial homogeneous distribution (Fig. 14, i) remains homogeneous in the case of a pure channel flow. The distribution is affected in the presence of groin fields (Fig. 14, ii, iii, iv). A substantial part of the particles accumulate in the dead-zone area during the LPTM-simulation. In the final stage of mixing (Fig. 14, iv) almost 40% of the tracer material is...
found in the region of the dead water zones. The remaining 60% of the material is travelling in the main stream.

4.3 Groin Fields with Different Exchange Rates

The dimensionless exchange coefficient \( k \) (Eq. 15), can be found in the literature to be in the order \( 0.02 \pm 0.01 \) (Valentine and Wood 1979; Uijttewaal et al. 2001), with no clear dependency to the shape of the dead water zone. With our laboratory experiments, we could demonstrate that \( k \) varies with the width to length ratio of the groin fields within the range of \( 0.015 - 0.035 \). Here the longest groin fields \( (W/L = 0.3) \) are leading to the highest \( k \)-values and the shortest groin fields \( (W/L = 3.5) \) correspond to the lowest \( k \)-value (Weitbrecht and Jirka 2001). In all cases the groin field width \( W \) was constant. According to Eq. 16 the transport velocity is supposed to be the same in those cases. In order to explore the possible influences of the changing \( k \)-values, two extra LPTM-simulations have been performed, where the mean residence time has been set to 75, 95 and 130 seconds, respectively. Consequently, the respective \( k \)-values used, are 0.035, 0.028 and 0.020.

Table 2: Results of LPTM-simulations with different exchange coefficients and \( B/W = 0.5 \), compared with the case of pure channel flow \( (k = \infty) \).

<table>
<thead>
<tr>
<th>( k )</th>
<th>( D_L/\left(u_\star h\right) )</th>
<th>( c/U \star )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k = \infty )</td>
<td>177</td>
<td>0.68</td>
</tr>
<tr>
<td>( k = 0.035 )</td>
<td>19800</td>
<td>0.64</td>
</tr>
<tr>
<td>( k = 0.028 )</td>
<td>24800</td>
<td>0.56</td>
</tr>
<tr>
<td>( k = 0.02 )</td>
<td>32400</td>
<td></td>
</tr>
</tbody>
</table>

In Tab. 2 the results of the simulations with changing \( k \)-values are summarized. It can be seen that the dimensionless dispersion coefficient \( D_L/\left(u_\star h\right) \) is proportional to the residence time \( T_a \). The longer the residence time, the higher the stretching rate of the tracer cloud.

It can be seen that the influence of the different \( k \)-values on the transport velocities is at maximum 10% for the presented configuration. According to these simulations, the results of the one-dimensional dead-zone-model mentioned above predicts the transport velocity correctly, for a \( k \)-value of about 0.035, which corresponds to groin fields with an aspect ratio of about \( W/L = 0.33 \).

An equilibrium between longitudinal stretching and transverse diffusion is reached in all cases after approximately 800 times the channel’s half width \( B \). That again indicates that the dominant time scale is not \( T_a \), but the diffusive time scale \( B^2/(2D_\nu) \) associated with the time needed for a particle to cross \( B \). If we determine the length \( x/B \) that corresponds to this time, we get

\[
\frac{x}{B} = \frac{cB}{2D} = 750
\]  

which corresponds very well to the observed behavior of the particle clouds in the LPTM-simulations.

5 CONCLUSIONS

Our approach in which laboratory experiments and LPTM are combined, creates the possibility to determine transport characteristics in the far field of a pollutant spill in shallow, predominantly two-dimensional river flows. Detailed velocity and concentration measurements are used to determine local flow and transport phenomena in the presence of groin fields. A translation is made via the LPTM, to convert these findings into transport velocities, longitudinal dispersion and skewness coefficients of the cross sectional averaged pollutant cloud in the far field. This information can be used to improve the accuracy of one-dimensional alarm-models, and to reduce the need for calibration with tracer experiments.

The finding, that the transverse tracer distribution is influenced by the presence of dead water zones should be taken into account for the planning of future field experiments, and for the interpretation of existing data. In addition to the concentration distribution it is likely that other properties depend also on the lateral coordinate.

The computationally simple two-dimensional approach allows for studying near field effects as well. Point releases of contaminants near one of the banks and not fully mixed states are impossible to predict with a one-dimensional approach. The same holds for strongly varying flow geometries with confluences, weirs, bends etc.

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