Dynamics of shallow lateral shear layers: Experimental study in a river with a sandy bed

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1Shallow lateral shear layers forming between flows with different velocities, though essential for mixing processes in natural streams, have been examined only in laboratory settings using smooth, fixed-bed channels. This paper reports the results of an experimental study of a shear layer in a straight reach of a natural river where the layer, in contrast to the two-dimensional structure observed in the laboratory, is highly three-dimensional. The study included pronounced transverse pressure gradients, which influenced shear layer structure compared to flume experiments. It also introduces an analysis that complements conventional theory on mixing layers. The lateral velocity gradient between the flows downstream from a splitter plate placed in the river, the principal controlling factor, was adjusted for three experimental runs to determine the influence of different gradients on shear-layer dynamics. In each run, detailed three-dimensional measurements of mean and turbulent characteristics were obtained at five cross sections downstream from the splitter plate. Although experimental results agreed with conventional mixing-layer theories with respect to turbulence, the dynamics of the shear layers were dominated by the mean lateral fluxes of momentum. After re-examining the governing equations, we developed a parabolic equation describing the shear layer evolution and several scaling relations for essential terms of the energy budget: mean and turbulent lateral fluxes of momentum, turbulent kinetic energy, and dissipation rates. The study also provides insight into the spectral dynamics of turbulence in the shear layer and clarifies previous observations reported for confluences in natural streams.


1. Introduction

2Lateral shear layers evolve at the interfaces between fast and slow streams in a fluvial system when the lateral velocity gradients are large enough to promote a notable exchange of momentum and mass. River confluences include shear layers as a distinctive feature that defines initial mixing of waters with different temperatures, suspended sediment loads, or chemical compositions of dissolved matter [Best, 1987; Rhoads, 1996; Rhoads and Sukhodolov, 2008]. They also develop along river reaches with pronounced lateral heterogeneities of roughness, for instance, between a floodplain and a main channel [Alavian and Chu, 1985; Nadaoka and Yagi, 1998; van Prooijen et al., 2005], at the margins of recirculating flows of channel expansions [Babarutsi et al., 1989; Talstra, 2006], and along sequences of groynes in trained reaches [Uijttewaal et al., 2001; Sukhodolov et al., 2008].

3Hitherto, knowledge of lateral shear layers in fluvial systems has been provided mainly by experimental and analytical studies of shallow mixing layers [Chu and Babarutsi, 1988; Tukker, 1997; Uijttewaal and Booij, 2000; van Prooijen, 2004]. Shallow mixing layers are flows governed by lateral shear imposed by merging, parallel flows of different velocities that also experience pronounced vertical shear due to bed friction. Experimental research has focused on parallel flows in channels with smooth beds and sidewalls and a laterally uniform free surface, i.e., zero lateral flux of mean momentum. Laboratory experiments have also viewed turbulence as the principal mechanism governing the dynamics of shallow mixing layers.

4Paola [1997] explicitly distinguished shallow mixing layers from merging flows of different velocities with opposing mean transverse momentum, like those that occur at river confluences, which induce supererelevation of the water surface and force strong downwelling of water toward the bed. In these lateral shear layers, the downwelling water spreads sideways and up toward the surface to form a pair of counter-rotating helical cells [Rhoads and Sukhodolov, 2001]. Field studies of river confluences have indicated that the topography of the water surface exhibits distinct lateral nonuniformity [Biron et al., 2002] and that the magnitude of lateral fluxes of the mean momentum greatly exceeds the magnitude of turbulent fluxes [Rhoads and Sukhodolov, 2008]. Moreover, because visible contrast between conflu-
ent flows can persist far downstream of the zone of intense turbulence within the confluence [Mackay, 1970], the spatial extent of the shear layer is also not necessarily the same as the spatial extent of the mixing interface [Rhoads and Sukhodolov, 2001].

[5] There are several interrelated mechanisms that drive lateral fluxes of momentum and generate complex topography of the water surface [Best and Rhoads, 2008]. First, converging flows, through mutual deflection, often exhibit characteristic features of curved flows in which centrifugal forces produce superelevation of the water surface and drive the secondary flow. Second, the water level of the main river establishes the base level for tributaries, and confluences can serve as an accumulation zone for alluvium transported by the tributary through the development of confluence bars [Biron et al., 1996; De Serres et al., 1999; Best and Rhoads, 2008]. Sorting of bed material associated with bar development can result in a substantial lateral heterogeneity of roughness [Rhoads et al., 2009], a factor that might induce secondary flow. Although turbulent flow in shallow mixing layers has been the main focus of previous research, the understanding of complex three-dimensional lateral shear layers dominated by mean momentum fluxes is rather qualitative; hence, appeals for experimental research and theoretical analysis have been made [Rhoads and Sukhodolov, 2008].

[6] In this paper, we report the results of a field experiment that examines a lateral shear layer characterized by three-dimensional flow over an alluvial riverbed and by a cross-stream gradient in the free surface. The study was completed on a reach of a lowland river, thereby providing insight into the flow structure at Reynolds numbers characteristic of many natural fluvial systems and avoiding problems of upscaling of the results. The design of our study was aimed at obtaining directly detailed information on both mean flow and turbulence structure. This approach provided an opportunity for comparison with results of previous laboratory research on shallow mixing layers and for evaluation of three-dimensional effects on the shear layer structure. Theoretical analysis is revisited, and several scaling relationships for both mean and turbulent flow are deduced and evaluated using the field data.

2. Field Experiments

2.1. River Reach

[7] A mildly sinuous reach of the lower Spree River near Berlin, Germany served as an experimental site. Because the structure of the open-channel flow and its changes due to seasonal and stage variations were examined on the reach in detail through a series of previous field-measurement studies [Sukhodolov et al., 1998; Sukhodolov and Sukhodolova, 2010; Sukhodolov and Uijttewaal, 2010], the river reach was deemed ideally suited for the purposes of this research. The canalized reach of the river has a trapezoidal cross section 25 m wide and 2 m deep at bankfull stage and in the central part is composed of fine sand about 0.6 mm in diameter. The hydraulic regime of flow through the reach is regulated by a weir located 21 km upstream. Maximum discharges of 15–20 m³/s are normally supplied during the winter season, whereas in summer, discharges are only 3.5–5 m³/s. This hydraulic regime results in mean velocities of flow in the range of 0.15 to 0.70 m/s with average depths ranging from 0.8 to 1.8 m [Sukhodolov and Uijttewaal, 2010].

2.2. Experimental Facilities

[8] Lateral shear layers in our experiments were generated similarly to laboratory techniques [Chu and Babarutsi, 1988; Uijttewaal and Booij, 2000] by inserting a thin vertical splitter plate in the river and maintaining a velocity difference for the split flows. A 30 m long splitter plate was constructed from thin wooden panels (1.5 × 0.5 × 0.025 m) and mounted on a wooden frame secured to the riverbed (Figure 1a). A needle weir in the right-hand compartment of the upstream channel was used to control the velocity ratio between flows on opposite sides of the splitter plate (Figure 1b).

[9] Measurements of three components of the flow velocity were collected with an array of four acoustic Doppler velocimeters (ADVs). The ADV units were mounted on a custom-manufactured flat aluminium frame (Figure 1c). The velocimeters were operated by a portable computer from a floatable platform which was equipped with a shelter for an operator. Deployment of the velocimeters was assisted by a support boat (Figure 1c).

2.3. Experiments and Measurements

[10] The experimental program consisted of three runs in which the velocity differential between the merging flows was varied (Table 1). In each experimental run, two sets of measurements were taken. In the first set, velocities were sampled at five cross sections along the shear layer (Figure 1a). Eight vertical profiles were measured at each cross section, and each profile was composed of seven points uniformly distributed over the flow depth. Three-dimensional velocities were sampled at each point for a 180 s period at the rate of 25 Hz. The second set of measurements was taken immediately following completion of the first set and consisted of synchronous measurements with a pair of ADV units employing the technique described by Rhoads and Sukhodolov [2004]. In these measurements, one of the probes was positioned at a stationary location at the downstream part of the shear layer: 40, 30, and 30 m for runs 1, 2, and 3, respectively. The traversing probe was positioned at the middle flow depth upstream from the stationary probe, and after sampling long-period records (20 to 60 min in duration at a sampling rate of 25 Hz) was moved further upstream. In total, these longitudinal profiles included five to eight points.

[11] The postprocessing of velocity records was performed using the ExploreV software package (NORTEK AS) and included sporadic spike removal with acceleration and velocity threshold filters [Sukhodolov et al., 1998; Rhoads and Sukhodolov, 2008]. The contribution of acoustic noise was on average 5% of the total turbulent kinetic energy. Further processing consisted of locating the velocity profiles and measurement points within the local coordinate system. Depth-averaging of the measurements was performed over all seven points in each vertical excluding the near-bed (less than 3 cm from the bed) and near-surface regions (less than 5 cm from the surface).

2.4. Experimental Results

[12] In this section, we present an overview of the spatial patterns for the mean and turbulent flow characteristics measured in our field experiments. The overview focuses on qualitative analysis and aims at elucidating the main features of the flow structure, thereby providing the basis for further
theoretical analysis and more rigorous quantitative examination. Because of restrictions in space, illustrations of results are limited to experimental run 2, though features specific to other runs are also described and compared where necessary.

[13] The plots of downstream velocity $u(x, y)$ show that the two incoming parallel flows gradually merge along the experimental reach (Figure 2), where $x$ and $y$ are the streamwise and transverse coordinates, respectively. Initially strong lateral shearing (cross sections A and B), indicated by the verticality and closeness of velocity isovels, diminishes at the downstream sections D and E, and the high-velocity core shifts laterally toward the slow-flow side of the channel. Although the flow behavior depicted by the $u(x, y)$ contours is characteristic of shallow mixing layers, significant lateral flux, indicated by the cross-stream vector plots $\vec{V}$ (Figure 2a), differentiates this flow from those observed in the laboratory. Furthermore, vector plots of $\vec{V}(y, z) = \vec{v}(y, z) - \vec{V}(y)$, $\vec{W}(y, z) = \vec{w}(y, z) - \vec{W}(y)$, where $\vec{V}$ and $\vec{W}$ are the local depth-averaged values of the transverse and vertical velocity components, respectively, and $z$ is the vertical coordinate, (Figure 2b) depict a pattern characteristic of helical secondary flow. This pattern reveals the development of a weak recirculation cell on the fast-flow side of the shear layer that grows systematically in size and expands toward the slow stream as the distance from the splitter plate increases.

[14] Nonzero lateral flow drives significant mean momentum flux $\vec{F}$, the patterns of which are shown in Figure 3. Maximum values of $\vec{F}$ are observed in the central part of the flow. Just downstream of the splitter plate (cross sections A and B), the lateral flux is largely two-dimensional, and the magnitude of the flux is increasing over distance. Further downstream (cross section C), the magnitude reaches an absolute maximum for the entire layer, and still further downstream (D and E), it decreases. In the downstream sections, the pattern of flux becomes three-dimensional, and the maximum values occur far above the riverbed. This longitudinal evolution of the lateral momentum flux points to the influence of two mechanisms: redistribution of momentum between the two flows and the frictional influence of the riverbed. The magnitude of mean momentum flux was largest in the first run and smallest in the third, thus explicitly indicating the dependency of the flux on the velocity differential. Moreover, two-dimensional patterns were sustained over the longest downstream distances for run 3, which had the smallest value of bed friction coefficient compared to other runs (Table 1).

![Figure 1](image)

**Figure 1.** (a) Riverbed morphology, experimental facilities, and measuring cross sections, (b) weir and splitter, and (c) experimental setup with a scheme of the shear layer: 1, splitter plate; 2, measuring frame with velocimeters; 3, operator platform; 4, support boat.

<table>
<thead>
<tr>
<th>Run</th>
<th>$\Delta U_0$ (m/s)</th>
<th>$U_{01}$ (m/s)</th>
<th>$U_{02}$ (m/s)</th>
<th>$H$ (m)</th>
<th>$\lambda_0$</th>
<th>$C_f$</th>
<th>$S_s \times 10^5$</th>
<th>$F_{r01}$</th>
<th>$R_e01 \times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.52</td>
<td>0.49</td>
<td>-0.03</td>
<td>1.0</td>
<td>1.0022</td>
<td>9.5</td>
<td>0.16</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.31</td>
<td>0.37</td>
<td>0.06</td>
<td>0.9</td>
<td>0.019</td>
<td>6.3</td>
<td>0.13</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.18</td>
<td>0.28</td>
<td>0.10</td>
<td>0.8</td>
<td>0.009</td>
<td>2.7</td>
<td>0.10</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

*Abbreviations are as follows: $\Delta U_0$ is the initial velocity differential; $U_{01}$, $U_{02}$ are the bulk velocities of the fast and slow streams near the splitter, respectively; $H$ is the bulk flow depth on the reach; $\lambda_0 = \Delta U_0 / 2U_{01}$ is the initial relative velocity differential; $C_f$ is the friction coefficient; $S_s$ is the integral longitudinal slope on the reach; $F_r$ is the Froude number; and $R_e$ is the Reynolds number.
Insight into flow turbulence is provided by the patterns of turbulent kinetic energy $k = 0.5 \left( u'^2 + v'^2 + w'^2 \right)$ (Figure 4). The patterns show a relatively narrow vertical band of maximal values in the central part of the channel and a horizontal band of increased turbulence stretching near the riverbed toward the fast stream. As $k$ is a scalar characteristic, it represents cumulative energy from the two flows, which is amplified in the area of overlap (i.e., the shear layer). The pattern becomes gradually transformed into the pattern typical of an open-channel flow with maximum values near the

![Figure 2](image1.png)

Figure 2. Patterns of (a) primary mean flow field and (b) secondary flow along the lateral shear layer in experimental run 2.

![Figure 3](image2.png)

Figure 3. Patterns of $u'v'$ along the lateral shear layer in run 2.
The magnitude of $k$ varied greatly between the experimental runs, reflecting both the effect of the velocity differential and that of riverbed roughness as a function of the mean velocity. There were also some differences in the pattern of $k$ for cross section E, run 1. In this run, the location of cross section E is coincident with the downstream margin of return flow on the slow-stream side of the channel, and the pattern of $k$ indicates rapid advection of turbulent energy near the surface of the flow from the shear layer toward the slow stream.

Conventional analysis of shallow turbulent flows often relies on a two-dimensional representation of the flow to examine depth-averaged characteristics. The analysis also partitions the flow domain into different areas, fast stream, slow stream, and shear layer, and determines the boundaries and length scales of these areas. Depth-averaged flow patterns for experimental run 2 illustrate characteristic features of shallow lateral shear layers (Figure 7). Downstream of the splitter plate, two parallel flows of different velocity start to mix, and strong lateral gradients of mean streamwise velocity gradually decay in the downstream sections. Velocity vectors (Figure 7a) indicate substantial lateral mean fluxes of momentum, which attain maximum values in the central part of the flow (Figure 7b) and exceed by an order of magnitude the lateral turbulent fluxes of momentum (Figure 7c). The riverbed roughness is inhomogeneous across the flow, reflecting dependency on the magnitude of velocity in the fast and slow streams (Figure 7d).

The shear layer width $\delta$ is the cross-stream distance between locations where velocities inside the shear layer attain values of the ambient flows within 10%, $\delta(x) = y_{0.0}(x) - y_{0.1}(x)$ [Pope, 2000]. For practical purposes, the width can be more accurately determined using the vorticity thickness of the layer $\delta_v = \delta/2 = \Delta U/\delta U/\partial y_{1\text{max}}$ [Uijttewaal and Booij, 2000]. The boundaries of the shear layer in our experiments were calculated from depth-averaged patterns using vorticity thickness because of a low resolution of measurements away from the central part of the flow and are depicted by dashed...
Figure 5. Patterns of $-u'v'$ along the lateral shear layer in run 2.

Figure 6. Patterns of $-u'w'$ along the lateral shear layer in run 2.
In general, the results of our large-scale experiments differ from those for shallow mixing layers in small-scale laboratory models with smooth beds \cite{Chu and Babarutsi, 1988; Uijttewaal and Booij, 2000} in that lateral mean fluxes of momentum exceed the turbulent fluxes by an order of magnitude, thereby reproducing characteristic features of natural river flows at confluences \cite{Rhoads and Sukhodolov, 2008}. The arrangement of the flows into parallel streams lines in Figure 7. Characteristics of experimental streams are summarized in Tables 2 and 3.

Table 2. Characteristics of Experimental Streams

<table>
<thead>
<tr>
<th>Run</th>
<th>Stream</th>
<th>$h$ (m)</th>
<th>$U$ (m/s)</th>
<th>$C_f$</th>
<th>$S_e \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>fast</td>
<td>1.20</td>
<td>0.49</td>
<td>0.011</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>slow</td>
<td>1.20</td>
<td>−0.03</td>
<td>0.033</td>
<td>−0.1</td>
</tr>
<tr>
<td>2</td>
<td>fast</td>
<td>1.10</td>
<td>0.37</td>
<td>0.011</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>slow</td>
<td>1.10</td>
<td>0.06</td>
<td>0.027</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>fast</td>
<td>1.00</td>
<td>0.28</td>
<td>0.006</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>slow</td>
<td>1.00</td>
<td>0.10</td>
<td>0.012</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 7. Pattern of depth-averaged mean flow (a) $\bar{V}(\bar{u}, \bar{v})$, (b) $-\langle uv \rangle$, (c) $\bar{u} \bar{v}$, and (d) $\tau_0/\rho$ along the lateral shear layer in run 2. Dashed lines indicate shear layer boundaries.
and hence losses of energy that result in the reduction of the velocity differential, slowing the rate of spreading.

Chu and Babarutsi [1988] examined shallow mixing layers with a laterally uniform free surface in a horizontal smooth channel at relatively small Reynolds numbers and minimal difference between friction coefficients for the fast and slow streams. These simplifications allowed a solution for the one-dimensional equations of gradually varying flow, yielding an exponential decrease of velocity differential with distance from the origin of the layer,

$$\frac{\Delta U(x)}{U_c} = \frac{\Delta U_0}{U_{c0}} \exp\left(-\frac{x}{R}\right).$$

Integration of (1) with substitution of the velocity differential in equation (2) provides a solution for mixing layer width in a shallow open-channel flow [van Prooijen, 2004],

$$\delta(x) = \delta_0 + \frac{\Delta U_0}{U_{c0}} h \left(1 - \exp\left(-\frac{x}{R}\right)\right),$$

where $\delta_0$ is the initial mixing layer width introduced as a constant of integration. An important feature of equation (3) is that it describes stabilization of the mixing layer growth, which has been observed in laboratory experiments [Chu and Babarutsi, 1988; Uijttewaal and Booij, 2000; van Prooijen, 2004].

Similar to results of laboratory experiments, the velocity differential in our experiments decreases with distance from the splitter apex (Figure 8). However, the rates of decay in the velocity differential are significantly lower than predicted by the conventional theory of shallow mixing layers (equation 2). In fact, the measured streamwise distributions are best approximated by a linear function, $\Delta U = \Delta U_0 - \beta x$. The substitution of a linear function and integration of (1) yields a parabolic function for a lateral shear layer,

$$\delta(x) = \delta_0 + \frac{\Delta U_0}{U_{c0}} x \left(1 - \frac{\beta}{2\Delta U_0} x\right).$$

A comparison of the measured and computed values of shear layer width is shown in Figure 9. The value of spreading coefficient $\alpha = 0.11$ was used to normalize both measured and computed widths. The thick solid line $a$ in Figure 9 corre-

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Table 3. Characteristics of Lateral Shear Layers$^a$

<table>
<thead>
<tr>
<th>Run</th>
<th>Cross Section</th>
<th>$x$(m)</th>
<th>$x_r$(m)</th>
<th>$\delta$(m)</th>
<th>$U_c$(m/s)</th>
<th>$\Delta U$(m/s)</th>
<th>$S_\gamma \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>4.8</td>
<td>0.08</td>
<td>3.2</td>
<td>0.25</td>
<td>0.48</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>9.9</td>
<td>0.54</td>
<td>4.4</td>
<td>0.22</td>
<td>0.47</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>20.9</td>
<td>1.49</td>
<td>7.6</td>
<td>0.21</td>
<td>0.50</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>31.4</td>
<td>2.00</td>
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<td>0.41</td>
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</tr>
<tr>
<td></td>
<td>E</td>
<td>42.3</td>
<td>2.79</td>
<td>10.4</td>
<td>0.22</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
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<td>2.2</td>
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<td>0.31</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>0.42</td>
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</tr>
<tr>
<td></td>
<td>C</td>
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<td>5.4</td>
<td>0.22</td>
<td>0.31</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>31.4</td>
<td>2.12</td>
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<td>0.21</td>
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<td>0.63</td>
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<tr>
<td></td>
<td>E</td>
<td>42.3</td>
<td>2.48</td>
<td>9.0</td>
<td>0.21</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
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<td>A</td>
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<td>1.88</td>
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<tr>
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<td>0.17</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
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<td>D</td>
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<td>1.69</td>
<td>5.4</td>
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<td>1.80</td>
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<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

$^a$Here $y_r$ is the location of the shear layer’s center and $S_\gamma = \Delta \gamma/\delta$ is the lateral free surface slope.

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[20] The evolution of a canonical free mixing layer is described by an ordinary differential equation [Brown and Roshko, 1974],

$$\frac{d\delta}{dx} = \frac{\alpha \Delta U}{U_c},$$

where $\alpha$ is the spreading coefficient, which has a value of 0.11 ± 0.03 for both free mixing layers [Pope, 2000] and open-channel shallow mixing layers [Uijttewaal and Booij, 2000]. In free mixing layers, the velocity differential is constant along the length of the layer, and thus the width of the layer increases linearly. However, in shallow flows, the presence of a solid boundary induces strong frictional effects separated by a thin impermeable wall has eliminated ambiguities associated with a nonparallel planform geometry and the formation of shallow wakes at the stagnation zone, which typically complicate comparisons between confluence shear layers and traditional shallow mixing layers.

3. Analysis

3.1. Shear Layer Evolution

[21] Similar to results of laboratory experiments, the velocity differential in our experiments decreases with distance from the splitter apex (Figure 8). However, the rates of decay in the velocity differential are significantly lower than predicted by the conventional theory of shallow mixing layers (equation 2). In fact, the measured streamwise distributions are best approximated by a linear function, $\Delta U = \Delta U_0 - \beta x$. The substitution of a linear function and integration of (1) yields a parabolic function for a lateral shear layer,
values are \( \leq 0 + \partial - \Delta \) determined for a trend of \( \partial /C_28 = /C_0 h_b h_0 + \partial \) at three times the value for \( /C_0 h_T(\partial /C_0) \). \( U_x = /C_0 \) is the slope of \( U_x = /C_0 \). The normalized width of lateral shear layers as a function of distance along the shear layer (symbols represent experimental runs). Solid and dashed lines are described in section 3.1.

Figure 9. Normalized width of lateral shear layers as a function of distance along the shear layer (symbols represent experimental runs). Solid and dashed lines are described in section 3.1.

[23] Measured values of the shear layer width are in agreement with both the parabolic function (4) and the theory of free mixing layers at short and intermediate distances \( (x \leq 30 \, m) \) from the origin of the layer (cross sections A, B, C, and D), while at large distances \( (x \geq 30 \, m) \), the trends deviate from the free mixing layer model (line a) to a minor extent. Deviations correspond to the negative decay rates in velocity differential that are notable and especially strong for run 3 (Figure 8). The parabolic model (4) is capable of reproducing this effect, whereas the conventional theory of shallow mixing layers, equation (3), overpredicts the effect of bed friction on the dynamics of the lateral shear layer.

[24] The analysis presented in this section has indicated that: (1) the investigated flow is in agreement with the theory of free mixing layers regarding the initial spreading rate of the layer; (2) the shear layers in the field experiment exhibit a linear decay of velocity differential; and (3) the conventional theory of shallow mixing layers overestimates the effect of riverbed friction and underpredicts the layer growth by about 30% to 50%. The results raise the question: What factors are responsible for the discrepancy in shear-layer dynamics between laboratory results and the findings of this field experiment? One way to explore this question is to examine the governing equations by analyzing the contributions of different terms in these equations to the balance of momentum flux [e.g., Rhoads and Sukhodolov, 2008]. In the following sections, we revisit the governing equations, explore scaling relationships for their principal terms, and then using scaling relationships and experimental data to examine decay rates in the velocity differential.

3.2. Governing Equations and Scaling Laws

[25] The depth-averaged momentum equations for shallow open-channel flow provide a starting point for theoretical consideration of lateral shear layers [Vreugdenhil, 1994] and can be rewritten for the conditions characteristic for lowland rivers as

\[
\frac{\partial (hU_x)}{\partial x} + \frac{\partial (hU_y)}{\partial y} - \frac{\partial (hT_{xy})}{\partial y} = -gh \left( i_o + \frac{\partial^2 \zeta}{\partial x^2} - \frac{\tau_y}{\rho} \right), \tag{5}
\]

\[
\frac{\partial (hU_y)}{\partial x} - \frac{\partial (hT_{xy})}{\partial x} = -gh \frac{\partial \zeta}{\partial y}, \tag{6}
\]

where \( \zeta \) is the elevation of the water surface, \( i_o \) is the slope of the riverbed, \( T_{xy} = \frac{1}{2} \int_{x_0}^{x_f} (u - U)(v - \bar{v}) - (u'v') \, dz \), \( \rho \) is the density of water, and \( \tau_y \) is the bed shear stress.

[26] Though equations (5) and (6) describe more complex flow than free mixing layers [Brown and Roshko, 1974], they can easily be transformed into a system that is formally analogous to equations for free mixing layers. The system, when solved with respect to the streamwise velocity component, yields a scaling law, that is, an error function. This scaling relationship is approximated by a hyperbolic tangent profile

\[
\frac{\bar{U}(x,y) - U}{\Delta U} = \frac{1}{2} \tanh \xi, \quad \xi = \frac{2[y_e - y(x)]}{\delta(x)} \tag{7}
\]

that represents a convenient tool for theoretical analysis. Experimental data from our study, scaled by velocity differential and shear layer width (Table 3), are shown in Figure 10. The solid lines on these plots correspond to the hyperbolic tangent profile (7). The data indicate remarkable agreement with the theory and therefore indirectly reveal observed quasi-linearity in the shear layer dynamics via similarity in the velocity profiles [Pope, 2000].

[27] For the lateral shear layer, we assume that the transverse gradients of momentum and pressure are significantly larger than the longitudinal gradients and can be correspondingly neglected in equations (5) and (6). Subtracting equation (6) from (5) and performing simple transformations, one obtains

\[
\frac{d(hT_{xy})}{dy} = -ghS_x, \tag{8}
\]

where \( T'_{xy} = \bar{U} - \chi - (u'v') \), and \( \chi = (u - U)(v - \bar{v}) \). For further analysis, we introduce two hypotheses: (1) mean and turbulent flow fields are driven by different mechanisms and hence can be examined separately and (2) the topography of the water surface in a cross section of the shear layer can be approximated by a hyperbolic tangent function \( (\zeta' - \zeta')/\Delta \zeta' = 0.5 \tanh \xi \). Integration of equation (8) with the boundary conditions \( T'_{xy}(y_{\text{up}}) = 0 \), \( T'_{xy}(y_{\text{r}}) = \chi \) and substitution of the pressure gradient from the hyperbolic tangent function yield a scaling relation for the lateral flux of momentum.
where $U_{LS} = \sqrt{\frac{ghS_y}{4}}$ is the characteristic velocity scale of the lateral shear. Furthermore, because experimental data indicate that the magnitude of lateral mean momentum flux is an order of magnitude larger than the turbulence momentum flux and significantly exceeds the magnitude of secondary currents, the scaling relationship for mean momentum flux can be written as

$$\frac{-\Delta \bar{U}}{U_{LS}^2} = \frac{1}{\cosh^2 \xi}.$$  \hfill (9)

Normalized depth-averaged lateral momentum fluxes measured in our experiments are shown in Figure 11. The solid lines represent equation (9). In general, the experimental data agree in terms of maximal amplitude and general pattern with equation (9), though the measured distributions appear to be spatially skewed toward the fast flow.

The turbulent flux of momentum is related to the lateral gradient of streamwise velocity and can be modelled by the eddy viscosity approach [Wygnanski and Fiedler, 1970] $-\overline{u'v'} = \nu_T \frac{\partial \bar{U}}{\partial y}$, where $\overline{u'v'}$ is the depth-averaged cross-stream turbulent flux of momentum. Deriving the lateral velocity gradient from the hyperbolic tangent profile (7) $\frac{\partial \bar{U}}{\partial y} = \frac{D}{C_{14}^2} \frac{1}{\cosh^2 \xi}$ and substituting the gradient into the eddy viscosity, we obtain a scaling relation for $\overline{u'v'}$,

$$-\frac{\overline{u'v'}}{\Delta \bar{U}^2} = \frac{\nu_T}{\delta \Delta U \cosh^2 \xi}.$$  \hfill (10)

The ratio $\gamma = \nu_T / \delta \Delta U$ is a constant for free mixing layers equal to 0.01 [Rodi, 1993]. Normalized depth-averaged turbulent momentum fluxes measured in our experiments are compared to the solution of equation (10) (Figure 12). The data generally agree with the theoretical model, although the amount of scatter increases as the lateral velocity differential decreases and the frictional influence of bed morphology increases.

The dissipation $\varepsilon$ and production $\Pi$ are the dominant terms in the budget of turbulent kinetic energy in free mixing layers [Wygnanski and Fiedler, 1970; Pope, 2000]. For free mixing layers, analysis of the budget indicated that the production of turbulent energy is around 1.4 times larger than dissipation [Wygnanski and Fiedler, 1970]. This fact accounts for the growth of the free mixing layer. In shal-
low mixing layers [Chu and Babarutsi, 1988], the dissipation rate is approximately the same as the turbulence production, and the growth of the shear layers is arrested. Using the equilibrium concept for depth-averaged quantities
\[
\bar{\Pi} = -\left( u' \nu' \right)_{xy} = \nu_T \left( \frac{\Delta U}{\delta} \right) \cosh^2 \xi, = \bar{\tau},
\]
we readily obtain the scaling law for the dissipation rate in the stabilized mixing layer,
\[
\frac{\bar{\epsilon}}{\Delta U^3} = \frac{\gamma}{\cosh^2 \xi}. \tag{11}
\]

Depth-averaged dissipation rates were obtained by averaging the vertical profiles of local dissipation rates, which were estimated using spectral methods of analysis and Kolmogorov’s $-5/3$ relationship [Rhoads and Sukhodolov, 2004]. In Figure 13, normalized depth-averaged values of the dissipation rate are compared with scaling relationship (11). Dissipation rates are on average 1.4 times smaller than for stable mixing layers, and the maxima are grouped around 0.007 rather than 0.01. This result is consistent with our observation that the lateral shear layers were growing and unstable (Figure 7).

[30] The scaling relation for turbulent kinetic energy is easily obtained using formulations of the $k-\varepsilon$ model [Rodi, 1993], in which turbulent viscosity is related to the kinetic energy and dissipation rate as
\[
\nu_T = C_{\mu} \bar{\epsilon} \frac{k}{\varepsilon},
\]
where $C_{\mu}$ is an empirical coefficient equal to 0.09. Substitution of this relation into the ratio for $\gamma$ together with the scaling law for depth-averaged dissipation rate (11) yields
\[
\frac{\bar{k}}{\Delta U^2} = \frac{\gamma}{\sqrt{C_{\mu} \cosh^2 \xi}} \cdot \frac{\gamma}{\sqrt{C_{\mu}}} = 0.03. \tag{12}
\]

Normalized depth-averaged lateral distributions of turbulent kinetic energy measured in our experiments are compared with equation (12) in Figure 14. The experimental data agree in magnitude and pattern with scaling relationship (12) for large values of velocity differential and low contributions of background turbulence due to bed friction (run 1). As the contribution of background turbulence increases (runs 2 and 3), deviations from (12) become larger until the lateral shear layer appears to be “buried” in background turbulence (Figure 14, run 3). Increased levels of bed-generated turbulence in run 3 are evident in both the fast and slow streams. Arrows in Figure 14 indicate the average level of background turbulence in the fast stream. In contrast to the lateral turbulent momen-

![Figure 12.](image12)

![Figure 13.](image13)
tum flux $\langle u'^2 \rangle$, the distributions of $k$ are less accurate for determination of properties of shear layers, and the planning of field studies should take this fact into account. This result conforms to the findings of Rhoads and Sukhodolov [2008], who found that lateral momentum flux provides a clear indicator of the mixing interface even when $k$ within this layer approached background levels of $k$ in the adjacent flow.

[31] The analysis in this subsection has provided scaling laws that relate the principal terms of equations (5) and (6) to essential physical mechanisms governing the flow dynamics of lateral shear layers. Moreover, examination of the spatial structure of the flow indicates that slow and fast streams are affected differently by momentum exchange through the lateral shear layer. The structure of flow in the slow stream is practically unaffected by exchange, and the distributions of main flow characteristics are accurately described by theoretical models. The fast flow is affected by the lateral mean momentum exchange that produces reduced mean velocities near the interface (Figures 10 and 11).

### 3.3. Velocity Differential and Decay Rates

[32] The conventional approach to the analysis of the velocity differential dynamics is to consider equations (5) and (6) for each converging flow separately and then subtract the equation for the slow stream from the equation for the fast flow. Transformation of the resulting equation under some assumptions [Chu and Babarutsi, 1988] and integration leads to the exponential decay of the velocity differential (2). Following this approach, but preserving terms for lateral momentum exchange for the fast flow, which are large compared to friction-generated fluxes of momentum, one can specify the following equations for fast and slow flow, respectively:

$$\frac{1}{2} \frac{d \langle h U^2 \rangle}{dx} - \frac{d \langle h T_{xy} \rangle}{dx} - gh S_{x1} + c_1 U^2_1 = 0,$$

$$\frac{1}{2} \frac{d \langle h U^2 \rangle}{dx} - gh S_{x2} + c_2 U^2_2 = 0.$$

(13)

(14)

Substituting relation (8) into (13) and (14) for the lateral gradients of momentum fluxes, specifying the fourth term as $u^2 = 0.5c_f U^2$, subtracting (14) from (13), and performing transformations yields

$$\frac{d(U, \Delta U)}{dx} = g \left( \Delta S_y - \frac{S_{xy}}{2} - \frac{1}{h} \Delta u^2 \right),$$

(15)

where $S_{xy} = \Delta S_y / \Delta x$ is the local gradient of difference in water-surface elevations on each side of the shear layer. Integration of equation (15) with the assumption $U, (x) \approx U_0$, an assumption supported by results of experimental studies, yields the linear relationship

$$\Delta U = \Delta U_0 - \frac{g}{U_0} \left( \Delta S_y + \frac{S_{xy}}{2} - \Delta S_y \right),$$

(16)

where $\Delta S_y = \Delta u^2 / g h$ is the difference in friction slopes. Equation (16) provides an explanation for both the linear trend in the velocity differential decay and the formation of a decay rate $\beta$. Moreover, it is easy to show that exponential decay (2) of the velocity differential can be obtained from (16) as a particular case of laterally uniform free surface where $\Delta S_y = 0$, $\Delta S_{xy} = 0$ and a cross-sectional average of the bed friction used to express the differential of the friction slope.

[33] Values of $\beta$ were estimated with equation (16) using data from our field experiments (Tables 2 and 3). The calculations yield the following values of $\beta$: 0.0028, 0.0021, and 0.0017 for experimental runs 1, 2, and 3 respectively. Linear best fit decay rates were 0.0025, 0.0018, and 0.013, respectively (Figure 8). Neglecting streamwise and lateral gradients in equation (16), one obtains significantly larger decay rates: 0.0090, 0.0033, and 0.0018, respectively, which correspond to the exponential function (2) for the respective experimental runs. The decay rates for our experiments were predicted with reasonable accuracy ranging between 10% and 25%. As the lateral gradients of the free surface decrease, the predictions from exponential function (2) and parabolic function (4) coincide (Figure 9).

### 3.4. Vertical Structure of Turbulence

[34] The vertical structure of turbulence in open-channel parallel flows with shallow mixing layers has received less attention in experimental and theoretical studies than the...
horizontal structure. Hitherto, the vertical profiles of normalized components of turbulent fluxes for fast streams and the center of the shallow mixing layer were examined by Tukker [1997], and vertical distributions of turbulent kinetic energy at river confluences were studied by Sukhodolov and Rhoads [2001].

[35] The structure of parallel flows in this study is close to the structure of a uniform flow, as the longitudinal velocity gradients are small, and friction slopes do not differ greatly from the slopes of the free surface. Measured vertical profiles of normalized turbulence characteristics can be therefore compared to the theoretical profiles of a uniform open-channel flow with scaling variables obtained in previous laboratory and field investigations. The vertical distribution of turbulent shear stress $\tau_{xz}/\rho = -\overline{u'w'}/u'_w$ in a uniform flow is linear:

$$\frac{\tau_{xz}}{\rho} = -\frac{\overline{u'w'}}{u'_w} = 1 - \frac{z}{h}. \quad (17)$$

In rough channels, the experimental data agree with (17) only in the outer layer and are significantly reduced in the roughness sublayer near the riverbed, where fluxes of vertical mean momentum dominate flow dynamics [Nikora et al., 2001]. The turbulent kinetic energy and dissipation rate are described by the following semi-analytical relationships [Nezu and Nakagawa, 1993]

$$\frac{k}{u'_w} = D_k \exp\left(-2C_k \frac{z}{h}\right). \quad (18)$$

$$\frac{\varepsilon h}{u'_w} = E \sqrt{\frac{z}{h}} \exp\left(-3 \frac{z}{h}\right). \quad (19)$$

where $D_k = 4.72$, $C_k = 1$, and $E = 9.8$ are empirical coefficients determined in laboratory open-channel flows. The values of these coefficients can differ for rough open channels and natural rivers [Sukhodolov et al., 1998].

[36] Measured vertical profiles of turbulence characteristics were normalized with local values of $u_w$ determined from individual profiles, and then all normalized profiles were subdivided into three groups representing fast, shear layer, and slow streams. For each group separately the individual profiles were averaged as an ensemble, and this averaging yielded a single profile representative of the group. Vertical profiles of turbulent shear stresses are shown in Figure 15. Measured profiles generally conform to linear distribution (17). Correspondence to a linear profile is especially good for the fast stream, while data for the shear layer and slow stream exhibit considerable scatter. Comparison of measured distributions in different experimental runs indicates a decrease in riverbed roughness and a corresponding decrease in the height of the roughness sublayer with decreasing bulk velocity of the flows.

[37] Ensemble-averaged vertical distributions of turbulent kinetic energy indicate general agreement with semi-empirical relationship (18) for fast and slow streams (Figure 16). However, there are also some systematic deviations from (18) due to the effect of roughness. In the shear layer, turbulent kinetic energy is nearly uniformly distributed over the flow depth, thus revealing the planar quasi-two-dimensionality of the flow. Similar results were reported for laboratory shallow mixing layer flows [Tukker, 1997].

[38] Ensemble-averaged vertical profiles of dissipation rate also indicated a notable agreement with a semi-empirical scaling relationship (19) for fast and slow streams (Figure 17). Similar to the distributions of turbulent kinetic energy, the dissipation rates reveal the effect of riverbed roughness, which is especially strong near the riverbed. Dissipation rates are nearly uniformly distributed over the river depth in the shear layer.

[39] The analysis of vertical profiles indicates the similarity of the investigated flows to two-dimensional open-channel flows, though the flows in our field study are strongly affected by the nonhomogeneous distribution of roughness of the river bed. Despite some scatter, the measured vertical profiles indicate that characteristics of riverbed roughness, such as shear velocity, can be estimated reliably, which is crucial for the analysis of flow dynamics.

3.5. Spectral Dynamics and Periodicity

[40] Although the hyperbolic function (7) and measured data show smooth transitions between fast and slow streams, the interface between merging flows appears to be sharp and
corrugated owing to the presence of large-scale vortex structures [Ho and Huerre, 1984]. Initially, close to the origin, the downstream development of the shear layer is dominated by a linear instability mechanism. The basic vorticity distribution in parallel flows of different velocities has a distinctive maximum and hence is inviscidly unstable to small perturbations via Kelvin–Helmholtz instabilities, which grow with distance and roll up into vortices [Ho and Huerre, 1984].

The conventional approach to characterization of organized motions by means of probing techniques is an examination of auto-and cross-correlation functions and turbulence spectra [Uijttewaal and Booij, 2000; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004]. The auto-covariance $r(t)$ and cross-covariance $r_{1-2}(\Delta x, \tau)$ functions [Jenkins and Watts, 1968] are defined as

$$r(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} u_i'(t)u_i'(t+\tau)dt,$$  \hspace{1cm} (20)

$$r_{1-2}(\Delta x, \tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} u_i'(x_0,t)u_i'(x_0+\Delta x,t+\tau)dt.$$  \hspace{1cm} (21)

where $u_i$ is the velocity vector component, $T$ is the sampling period, $\Delta x$ is the spatial lag between stationary and traversing probes, and $\tau$ is the time lag. Spatial cross-covariance functions can be obtained by computing the ordinates of cross-covariance functions at zero spatial lag. The spatial cross-covariance functions can be further translated into the temporal domain by applying local mean velocities as the translation factor [Rhoads and Sukhodolov, 2004]. Power spectra are computed from covariance functions by applying Fourier transform

$$S(f) = 2 \int_{-\infty}^{\infty} r(\tau)e^{-j2\pi f\tau}d\tau = 2 \int_{-\infty}^{\infty} r(\tau)\cos(2\pi f\tau)d\tau,$$  \hspace{1cm} (22)

where $f$ is the frequency.

A distinctive feature of auto-correlation functions $R_{vi}$, covariance functions normalized by variance $R(\tau) = r(\tau)/u_i'^2$, measured at different locations along a shallow mixing layers is a systematic increase in characteristic period (modulation) with an increase in distance from the origin [Uijttewaal and Booij, 2000]. This behavior is also apparent in the auto-correlation functions of the transverse velocity component measured in our experiments (Figure 18). The

Figure 16. Normalized ensemble-averaged turbulent kinetic energy over the flow depth.

Figure 17. Normalized ensemble-averaged dissipation rate over the flow depth.
two-dimensional character of large-scale turbulent structures is demonstrated by separation of the downstream and cross-stream contributions to turbulence energy from the vertical velocity contribution at low frequencies (Figure 19). Power spectra for the lateral velocity component exhibit distinctive peaks at low frequencies that correspond to the time scales of the first local maxima of the auto-correlation functions (Figure 18). Modulation of the signal is also apparent in power spectra measured at different locations along the shear layer (Figure 20). The strength of the velocity shear has a pronounced effect on the signal strength of organized motions as reflected in reduced correlations for runs with small velocity differential (Figure 18).

The characteristic period \( t_v \) of vortices in free mixing layer is related to the bulk flow characteristics by the Strouhal number [Ho and Huerre, 1984]

\[
St = f \frac{\delta_{in}}{U_c} \frac{\delta}{4\sqrt{\pi}} \tag{23}
\]

where \( \delta_{in} \) is the momentum thickness, and \( f = 1/\tau_v \) is the frequency. The linear stability analysis completed using (7) provides the critical value of the Strouhal number \( St = 0.032 \).

Using equation (23), data from Table 3, and a Strouhal number of 0.032 yields periods that deviate substantially from the values associated with low-frequency spectral peaks (Figure 20). Similar discrepancies between computed values of vortex periodicity and measured values have been documented in laboratory experiments [Uijtewaal and Booij, 2000]. Two main factors can cause deviations: (1) difference in the critical Strouhal number and (2) difference in scaling variables. To explore these hypotheses, we explore the possibilities for obtaining a scaling relationship similar to (23) based on phenomenological principles rather than stability analysis.

The characteristic temporal scale of vortex revolution \( t_v \) can be related to the radius of the vortex \( r \) via the Richardson-Obukhov scaling law [Monin and Yaglom, 1971],

\[
t_v = \left( \frac{r^2}{\delta} \right)^{1/3} \tag{24}
\]

The value of the dissipation rate in the shear layer close to the riverbed is reasonably well scaled on the shear velocity, similarly to open-channel flow (Figure 17), and thus can be approximated by the following relation,

\[
\varepsilon \approx \frac{\rho}{\delta} \Delta U \frac{\delta}{\delta} \tag{25}
\]
Bed shear stress is related to the mean velocity in the shear layer as \( \tau_0 = 0.5c_f \rho U_c^2 \). Substituting (25) into (24) with the assumption \( r \approx \lambda \delta \), one obtains

\[
 f \approx \frac{U_c}{\delta} \left( \lambda \frac{2U_c}{c_f \Delta U} \right)^{-1/3}, \quad f = \frac{1}{t_E},
\]

where \( \lambda \) is a scaling coefficient between the size of the vortex and the mixing layer scale. Equation (26) indicates that the critical value of the Strouhal number in shallow mixing layers depends on the riverbed roughness and hence is not a constant as it is for free mixing layers. Moreover, equation (26) accounts for scaling of vortical structures with the shear layer width, and hence this equation provides grounds for evaluating our two hypotheses.

[46] The scaling coefficient \( \lambda \) can be understood by exploring the behavior of auto-correlation functions and their integrals \( T_E = \int_0^\infty R_z(\tau) d\tau \), i.e., the Eulerian integral scales of turbulence. Integral scales \( T_E \) in experimental runs 1 and 2 are proportional to the width of the shear layer scaled on the mean velocity in the layer \( T_E \approx \frac{\delta}{U_c} \), while in run 3 and laboratory experiments by Uijtewaal and Booij [2000], the integral scales less than half of the width of the layer. Selecting \( \lambda = 1 \) and 0.5 for these runs and applying the values from Table 3 to equation (26) yields estimates that correspond to measured frequencies within 10%–15%. The same computations were also performed for data reported in laboratory experiments [Uijtewaal and Booij, 2000] and yielded accurate estimates for those flows as well.

4. Discussion and Conclusions

[47] This study was designed as an innovative approach to bridge the gap in understanding between laboratory studies of shallow mixing layers [Chu and Babarutsi, 1988; Uijtewaal and Booij, 2000] and studies of highly complex mixing interfaces in natural confluent streams [Best, 1987; Paola, 1997; De Serres et al., 1999; Biron et al., 2002; Rhoads and Sukhodolov, 2008]. The experimental part of the study consisted of the construction of a river-scale model of parallel merging streams and examination of the effects of both lateral velocity shear and riverbed friction on the dynamics of a shallow shear layer. Although the study in general was guided by the methodologies of previous laboratory studies and conventional theoretical approaches [Brown and Roshko, 1974; Chu and Babarutsi, 1988; Uijtewaal and Booij, 2000; van Prooijen, 2004], the flows examined here were more complex than their laboratory prototypes and provided insight into the effects of a laterally inhomogeneous pressure field on the dynamics of the layers. The simplified geometry of the parallel flows eliminated the effects of wake-like structures that commonly develop at the stagnation zone of natural confluences and that can influence shear layer dynamics [Rhoads and Sukhodolov, 2008]. Thus, the design permitted direct comparisons of shear layer structure with the structure of shear layers documented in the laboratory and with conventional mixing layer theory.

[48] The results of the study demonstrate that lateral variation in the free surface topography, which generates lateral pressure gradients, drives lateral fluxes of momentum, the magnitude of which exceeds the turbulent fluxes of momentum by an order of magnitude. These lateral fluxes of mean momentum reduce mean streamwise velocities on the fast-flow side of the layer, thereby contributing to the dynamics of velocity differential of the shear layer and affecting spatial evolution of the layer. Theoretical assessment of velocity differential dynamics, completed by applying one-dimensional analysis of open-channel flows, have shown that parabolic function (4) describing the dynamics of the shear layer can be considered as a more general solution for fluvial channels than the conventional exponential function (3).

[49] In natural fluvial systems, complex flows with lateral gradients of the free surface are common. They are most vividly evident at transitions between riffles and pools in reaches of high-gradient streams. An example of such a transitional zone is shown in Figure 21. Initially, supercritical and laterally uniform flow fully developed on a coarse graded riffle enters a pool with a sandy bed where the flow gradually attains a subcritical regime. Excess mean streamwise momentum in the central part of the flow is preserved over significant distances in the transition zone, shaping the flow into a jet-like structure. Super-elevation of the free surface in the jet is visually evident and can be as great as 30 cm (Figure 21). These excessive pressure gradients drive strong lateral fluxes of mean and turbulent momentum and contribute to the formation of recirculating flows along the banks. Two lateral shear layers form along the sides of the jet-like flow. Qualitatively, this flow is similar to the simplified flow that was examined in experimental run 1 of this study, though detailed assessment of such flows under field conditions is presently lacking, and further research on such flows is vital given their ecological importance [Sukhodolov et al., 2009].

[50] A significant lateral mean momentum flux reduces mean streamwise velocities on the side of the faster stream.
Figure 21. An example of a lateral shear layer in the transition of the riffle-pool sequence of an Alpine river (the upper Soča River near Bovec in Slovenia).

and the spatial arrangement of the cross-stream distribution of the momentum shifts about one half of the width of the shear layer toward the faster stream. This mechanism is the reason that the flow at transitions is shaped into jet-like structures due to fast protrusion of the interfacial layer into the core of the fast flow (Figure 21). Moreover, considering the mixing interface as the amalgamation of mean and turbulent momentum and mass exchange, one can explain previous observation at river confluences because the width of the mixing interface is sometimes larger than the width of the turbulent shear layer [Rhoads and Sukhodolov, 2001].

[51] Research on shallow mixing layers, including the present study, has focused on the effects of riverbed friction on the dynamics of shallow mixing layers. Past work has emphasized as a governing mechanism the reduction of the velocity differential, which causes stabilization of the layer growth. The results of this study show that a stabilization effect can also be achieved by lateral redistribution of mean momentum in gradually varying flow with near-equilibrium between a driving streamwise pressure gradients and bed friction. Studies of confluences of natural streams have shown that the mean velocity in the mixing interface can significantly increase over distance [Rhoads and Sukhodolov, 2004]. It is easy to show that integration of equation (1) for increasing mean velocity $U_c = U_{c0} + \alpha x$ in the layer will yield a logarithmic function,

$$\delta(x) = \delta_0 + \alpha \Delta U_0 \frac{\eta}{\eta} \ln \left(1 + \frac{\eta}{U_{c0}} x \right),$$  

(27)

which also demonstrates a strong stabilization effect on the shear layer dynamics. This conjecture is supported by measurements in natural streams [Sukhodolov and Rhoads, 2001, Figure 7].

[52] The study also provides insight into the structure of turbulent flow generated by both lateral and vertical shear due to bed friction. Comparison with theoretical functions indicates a good correspondence both in qualitative patterns of spatial distributions for principal variables and quantitative agreement with previous laboratory studies. In particular, empirical values of $\alpha$, $\beta$, and $C_\mu$ in our study were the same as for canonical free mixing layers [Brown and Roshko, 1974; Rodi, 1993].

[53] Despite similarities with canonical flows, the turbulent flows in our study also have important features that differ from those of canonical mixing layers. The study has shown that the periodicity of vortical structures depends on the riverbed roughness and the scales of individual vortices. In flows with relatively large velocity on the slow flow side ($\geq0.10$ m/s), the vortices scale with one half of the shear layer width, while for flows with almost stagnant or slightly recirculating flow ($<0.10$ m/s), the vortices scale with the width of the mixing layer. This experimental finding is in qualitative agreement with previously reported scales of vortices at confluences of natural streams [Sukhodolov and Rhoads, 2001, Figure 14]. The vortices that scale with one half the shear layer width correspond to structures with well-defined rotation around a vertical axis, while structures that scale on the width of the mixing layer are more like structures that inrush from the side, in which advection probably dominates over rotation [Rhoads and Sukhodolov, 2004]. An increased scale of vortices emerging at the interfaces of gyres has also been reported for flows with abrupt expansions and is interpreted as a “scale jump” related to merging of signlike vorticity [Faltsra et al., 2006].

[54] This paper has provided comprehensive insight into the mechanisms governing complex three-dimensional flows with horizontal shear. The innovative design of the study, a field-scale physical experiment, allowed investigation of a flow with high Reynolds numbers and hence avoided problems associated with upscaling of the results. Further research should explore additional factors that complicate the behavior of shear layers in natural fluvial systems, for example, the effect of wake or stagnation zones at the junction node [Rhoads and Sukhodolov, 2008].

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References


Rhoads, B. L. (1996), Mean structure of transport-effective flows at an asymmetrical confluence when the main stream is dominant, in *Coherent Flow Structures in Open Channels*, edited by P. J. Ashworth et al., pp. 491–517, John Wiley, Chichester, U.K.


Rhoads, B. L., J. D. Riley, and D. R. Mayer (2009), Response of bed morphology and bed material texture to hydrological conditions at an asymmetrical stream confluence, *Geomorphology*, 109, 161–173.


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