Turbulent flow structure at a 90-degree open channel confluence: accounting for the distortion of the shear layer

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Abstract: City channels often have a smaller width-to-depth ratio in comparison to natural rivers due to the limited land availability. The penetration of the tributary into the main channel can cause the distortion of the shear layer. The main purpose of the present study is to investigate the mean and turbulent flow structure in the distorted shear layer in a discharge-adjustable plexiglass circulating flume. Three-dimensional velocities were collected and hydrodynamics and turbulence characteristics such as mean velocity field, turbulent kinetic energy, Reynolds shear stress, turbulence spectrum, and occurrence probabilities of quadrant events were analyzed. The results showed that a stronger helical cell was formed and extended for a longer distance

downstream when the tributary channel had a higher flow rate than the main channel. The maximum Reynolds shear stress and the ejection and sweep events were mainly distributed at the middle zone of the water depth, rather than near the water surface, which were coincident with the shear layer as indicated by the turbulence kinetic energy. No obvious energy concentration was observed, and the power law relations for individual velocity components all had an exponent slightly larger than $-5/3$ in the flow frequency. The distortion of the shear layer resulted in an increase in occurrence probabilities of ejection and sweep events within the shear layer, which were related to the turbulence presenting vortices induced by wall. If the discharge ratio remained unchanged, an increase in the discharge of both channels resulted in an increase in some parameters, such as velocity, turbulent kinetic energy, and the absolute values of Reynolds shear stress; while the shear layer was distorted to a larger extent as the discharge of each channel decreased. All these results suggested that sediment transport, bed morphology and contaminant transport in the distorted shear layer at city channel confluences may differ significantly from that at natural river confluences.

Keywords: Channel confluence; Distortion of the shear layer; Turbulence; Spectrum analysis; Quadrant analysis

1. Introduction

Open-channel confluence is a fairly common occurrence in natural river networks. The hydrodynamics and turbulence characteristics at a river confluence need to be better understood, because the confluence can induce mass and momentum transfer across the mixing layer between two streams and thus affect the temporal and spatial distribution of pollutants in river networks. Over the past 40 years, a large number of laboratory and field experiments have been performed to investigate the time-averaged flow structures at river confluences (Mosley, 1976; Ashmore, 1982). Best (1987, 1988) has conducted a series of studies on the flow structures at river confluences, and developed a conceptual model of confluence hydraulics that consisted of six distinct elements, including a flow stagnation zone, a flow deflection zone, a flow separation zone, a zone of maximum velocity, a gradual flow recovery area and shear layers associated with vortex generation. The shear layer is where there is a significant velocity gradient, and thus it can have a significant impact on the transport of pollutants. Rhoads and Kenworthy (1995, 1998) found twin surface-convergent helical cells on both sides of the shear layer in the vertical plane, which were later called ‘streamwise-oriented vortical (SOV) cells’ by Constantinescu et al. (2011). Previous studies have focused on these hydrodynamic zones, especially the separation zone (Best and Reid, 1984; Yang et al., 2009) and the shear layer (Rhoads and Sukhodolov, 2004), which are critical for pollutant transport and sediment deposition and erosion in the confluence zone. Best and Reid (1984) established the relationship between the dimensions of the separation zone and the discharge ratio, and discussed the influence of confluence angle. Rhoads and Sukhodolov (2008) analyzed the lateral momentum flux in a natural river confluence.

A comprehensive data set of three-dimensional (3D) flow field (at a sampling rate of 10Hz) within the confluence zone with a wide range of discharge ratios were provided by Weber et al. (2001), which is now available on the Internet. Much attention has also been paid to the influence of the bed morphology, especially the difference in bed height (bed discordance). Bryan and Kuhn (2002) carried out a laboratory experiment in artificial rectangular rill channels with fixed and erodible beds to identify the effect of confluence geometry on hydraulic conditions and scour patterns. Best and Roy (1991) found that bed discordance created a distortion of the shear layer, resulting in fluid upwelling at the downstream junction corner (Biron et al., 1996ab) and affecting bed morphology and sedimentology (Biron et al., 1993b). De Serres et al. (1999) investigated 3D velocities and the flow characteristics, such as flow deviation zone, strong fluid upwelling and distortion of the mixing layer, at a confluence of natural rivers with discordant beds. Riley and Rhoads (2012) extended the research on the confluence of two straight rivers by investigating the flow structure at a natural confluent meander bend.

The turbulent flow characteristics at a confluence, especially at the shear layer, have been well documented over the last two decades due to the advancement in the experimental equipment with a higher sampling rate (Biron et al., 1993a; Rhoads and Sukhodolov 2004) and numerical simulation methods (Bradbrook et al., 2000ab, 2001; Shakibainia et al., 2010). Intense turbulence within the shear layer has been the subject of many studies (Leite Ribeiro et al., 2012). Roy et al. (1999) linked high turbulence observed in the shear layer at the same field site to higher bedload transport rates. Boyer et al. (2006) measured the near-bed flow turbulence, bed load transport rates, and changes in bed morphology under eight flow conditions at a confluence with sandy discordant beds, and found that high sediment transport rates

were located at the edges of the shear layer where the horizontal-vertical cross stresses were high. De Serres et al. (1999) observed very high intensity of turbulence (peaks up to 50%) and turbulent kinetic energy in the shear layer. Best (1987) revealed that a shear layer was created between the two convergent flows along which powerful, vertical vortices were generated. Rhoads and Sukhodolov (2004) showed the process of eddy development in the shear layer in the horizontal plane appeared to be similar to traditional vortex pairing. These quasi-two-dimensional vortices with near vertical axes may lead to substantial lateral transfer of fluid between two combining flows (Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2001). Constantinescu et al. (2011) used an eddy-resolving numerical model to simulate the large-scale turbulence structure in an asymmetrical river confluence when the momentum ratio was close to 1, and the results showed that the shear layer structure resembled that of a wake behind a bluff body, and successive eddies had opposing senses of rotation. Constantinescu et al. (2012) concluded that the types of coherent structures were affected by the discharge ratio. If the discharges of two rivers were comparable and the discharge ratio was close to unity, the shear layer was populated by quasi two-dimensional eddies with opposing sense of rotation; otherwise, the shear layer contained predominantly co-rotating large-scale quasi two-dimensional eddies driven by Kelvin-Helmholtz instability and vortex pairing. Sukhodolov et al. (2010) adjusted the length of a splitter plate placed in a straight channel to change the lateral velocity gradient between the flows downstream, and to determine the influence of different gradients on shear layer dynamics.

However, for field observations, the influence of many factors such as bed morphology (e.g., bars, scour hole and bed discordance) and planform geometries of upstream channels cannot be reliably quantified. Furthermore, natural rivers usually

have a large width-to-depth ratio which can protect against the distortion of the shear layer. As far as we know, there is scant literature on the distortion of the shear layer in the confluent flow, which is common in city channels with a small width-to-depth ratio. The study of Weber et al. (2001) is the only study investigating the flow structure in the distorted shear layer caused by the penetration of large tributary flow. The 3D flow velocities were measured using an ADV at a sampling rate of 10 Hz in this study, which, however, may be insufficient for turbulence analysis, especially for city channels where the shear layer between two streams tends to be distorted due to the small width-to-depth ratio. The main purpose of this study is to investigate the hydrodynamics and turbulent structure within the distorted shear layer at a 90-degree channel confluence with a small width-to-depth ratio.

2. Experimental setup and measurement

The experimental setup is not a scaled model of a particular confluence channel, but a schematized configuration that aims to simulate dominant hydraulic processes and turbulence structure in a broader range of configurations, as shown in Figure 1. Flow is pumped from the downstream tank to two upstream tanks through PVC pipes (inner diameter: 110 mm), and the flow discharges through these two pipes are strictly controlled by two ultrasonic flowmeters and pump-valve systems. Honey comb is used to ensure uniform water flow through the channels. The water level could be adjusted by the tailgate downstream. All channels have a rectangular cross section. The upstream channels are 30 cm wide and 3 m long, while the confluent channel is slightly longer (7 m) and wider (40 cm) than the upstream ones, which is common in confluent rivers.

[Figure 1 near here]

Two different discharge ratios are considered in this study. In case one, the discharge of the main channel, Q_1 , is 6.0 L/s with a water depth of 16.3 cm, and the discharge of the tributary channel, Q_2 , is 3.9 L/s with the same water depth. Thus, the discharge ratio ($\gamma=Q_2/(Q_1+Q_2)$) is about 0.4. In case two, Q_1 is 3.9 L/s and Q_2 is 6.0 L/s, and thus the discharge ratio is about 0.6. The discharge ratios in this study are within the range reported for natural river confluences (0.27 to 0.68) (Boyer et al., 2006; Rhoads and Sukhodolov, 2008).

Three-dimensional flow velocities in the confluence hydrodynamic zone (CHZ) were measured using an acoustic Doppler velocimeter (ADV, NorTek Vectrino+; maximum velocity: 4 m/s; accuracy: ± 1 mm/s). Seeding material consisted of small concentrations of neutrally buoyant hollow glass spheres (Potter Industries Sphericell) were added to provide acoustic scattering signals for ADV during the tests.

3. Data collection and analysis

The test area is shown in Figure 1, and the measurement cross sections and points are marked in Figure 1(b) and (c). Three-dimensional velocities in the CHZ were measured with an ADV at a sampling frequency of 100 Hz over a duration of 120 s. In order to obtain accurate ADV estimates, the strength of the received backscattered signals should exceed the strength of the system noise. The backscattered signal strength or signal-to-noise ratio (SNR) for each ADV beam was used for quality control in the post-processing of the measured flow velocity (Yuan et

al., 2014). Lack of seeding may cause a low signal strength and SNR. The ADV data with SNRs less than 30 were removed, and only those data with SNRs equal to or higher than 30 were retained.

Inaccurate velocity estimates may be obtained when the returns from different scatters within the pairs of acoustic pulses are used to estimate the Doppler shift. The correlations between successive returns are low when excessive scatters near the sample volume reflect acoustic side lobe energy. Thus, the along-beam correlation averaged over the sample period can be used to identify and subsequently replace potentially inaccurate data points. The ADV data with signal correlations less than 90 percent were removed, and only the ADV data with signal correlations equal to or higher than 90 percent were retained (Lane et al., 1998).

The phase-space threshold method was used to remove suspected spikes based on the concept of 3D Poincare map, or phase-space plot (Goring and Nikora, 2002). The variable was plotted against its derivatives. The points were enclosed by an ellipsoid defined by the Universal criterion, and the points outside the ellipsoid were designated as spikes. The method iterated until the number of reasonable data points became constant. The interpolation between the ends of the spike was used to replace the spike.

Figure 2 gives an example of the time series of 3D velocities. The raw streamwise velocity, cross-stream velocity and vertical velocity were processed by removing weak signals (<30 signal-to-noise ratio), poor correlated signals ($<90\%$ correlation), and despiking. The Doppler noise is inherent in an Acoustic Doppler Instrument system. The accuracy of the estimates of time-averaged flow velocities measured by an Acoustic Doppler Instrument is typically better than 4% (Rolland, 1994; Lemmin and Rolland, 1997). The noise of different receivers is statistically

independent, which suggests that the estimates of turbulent shear stresses are noise-free. The noise may cause an uncertainty of about 20% in the turbulent normal stresses and the turbulent kinetic energy (Blanckaert, 2010).

The stationarity analysis of the velocity data involved dividing each time series into 24 intervals of equal length and then progressively cumulating the variance over the 24 intervals (Figure 2). The systematic convergence of the cumulative variance on a constant value is indicative of a stationary variance and that the record length is sufficient to capture major sources of variation in velocity. The plots for the ambient flow and shear layer exhibited convergence, and the record length was defined to be equal to 90% of the long-term mean variance. These values, which served as sampling intervals for the flow measurements, were 40 s for the ambient fluid and 60 s for the shear layer (Figure 2). The power spectra of 3D velocities within and outside the shear layer were also plotted, and a value characteristic ($-5/3$) of the systematic cascade of turbulence energy within the inertial subrange was observed within both the shear layer and the ambient fluid.

[Figure 2 near here]

The shear layer is usually distinguished by injecting visual dye to detect the division line between clean water and dyed water (the mixing interface; Sukhodolov and Rhoads, 2001). This method is applicable when the shear layer is vertical or nearly vertical. However, significant biases may occur when the shear layer is distorted since the dye motion can be observed only near the water surface. With the injection of white dye in the upstream tributary channel (Figure 3a and b), the division line could be observed with eyes. The cross sections for velocity

measurements were perpendicular to the division line as far as possible (Figure 1b and c). There were a total of 6 cross sections in case one (S1 to S6) and 7 cross sections in case two (C1 to C7). The locations of measurement points (P1 to Pn) in each cross section are marked in Figure 1b and c. The interval between two adjacent measurement points in the vertical direction was 1 cm.

Figure 3 also plots the time-averaged horizontal velocity fields near the flow surface (red arrows) and near the bottom (black arrows). It is noted that the horizontal velocities in case two are much larger than that in case one due to the squeezing of large-area separation zone in case two (blue curve in Figure 3b). The difference of the velocity direction between flow near the surface and that near the bottom indicates the presence of helical flow, especially on the tributary side.

[Figure 3 near here]

4. Results

4.1 Three-dimensional velocity field

Figure 4 plots the 3D velocity field for the two cases using *Tecplot 360*®, where the streamwise velocity, u , is the horizontal velocity component perpendicular to the cross sections; the lateral velocity, v , is the horizontal velocity component that parallels to the cross sections; and the vertical velocity, w , is counting positively what goes to the z axis direction.

The u -field plots show that the main channel flow with a velocity of 11 ~ 12 cm/s is squeezed by the tributary flow, and its streamwise velocity is increased to about 16 cm/s in case one. The flow from the tributary with a much lower streamwise velocity

is sheared by the fast-speed flow, and the two flows tend to have comparable velocities when $x > 10$ cm. The layer with the largest velocity gradient (or the shear layer) is nearly vertical. In case two, the first cross section is mainly located within the stagnation area near the confluent point, where the velocities tend to zero. The two flows are accelerated to about 20 cm/s due to the large-area separation zone. The velocities of the two flows are comparable when $x > 20$ cm, which is much longer than that in case one. The layer with the largest velocity gradient is distorted counterclockwise.

The v -field plots show that the main channel flow with positive lateral velocities is located at the first two cross sections. However, flow moves laterally because the cross sections are not exactly perpendicular to the streamwise direction, which can be achieved only when the measurement cross sections are bent. The streamlines in other cross section are bent to be perpendicular to the cross sections, and the lateral velocities tend to zero on the main-channel side. However, on the tributary channel side, flow moves laterally with negative velocities upside and positive velocities downside. Similar to the case one, the laterally moving flow with positive velocities is located near the main-channel side in case two. The lateraling moving flow on the tributary channel side is much stronger and covers a larger-area than that in Case one. The region with an absolute value of v larger than 2 cm/s could reach $y = -25$ cm, while it is about -15 cm in case one.

In the w -field plots, downward flow is observed at the same location of the largest streamwise velocity gradient and gradually disappears when $x > 10$ cm, which is consistent with the inconspicuous velocity gradient in u -field plot. Both downward flow and large streamwise-velocity gradient could be used to indicate the shear layer. In case two, the downward flow is distorted counterclockwise, which is also

consistent with the distorted velocity gradient in the u -field plots. However, unlike case one, a strong downward flow could still be observed when $x > 10$ cm. The upward flow could be found near the tributary-channel side.

[Figure 4 near here]

4.2 Kinetic energy of turbulence

The turbulent kinetic energy was calculated as the sum of the intensity of velocity fluctuations:

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \quad (1)$$

where k is the turbulent kinetic energy, and velocity fluctuations, u'^2 , v'^2 , w'^2 , were calculated by the variance of velocity:

$$u_i'^2 = \text{var}(u_i) = \frac{1}{n} \sum_1^n (u_i - \overline{u_i})^2 \quad (2)$$

where u_i is the component of velocity, u , v and w ($i=1, 2$, or 3), and their mean values are represented as $\overline{u_i}$; $\text{var}()$ is the symbol for the variance; and n is the number of velocity data.

The distribution of turbulent kinetic energy within the cross sections can illustrate the time-averaged structure of turbulence within the confluences. Figure 5 plots the turbulent kinetic energy fields for the two cases. The location of the shear layer is clearly defined by the zones of large k within CHZ (Sukhodolov and Rhoads,

2001).

In case one, the shear layer is nearly vertical in all cross sections (Figure 5a-1). The maximum values of k within the shear layer exceed those for the ambient flow by a factor of 3-5. The shear layer is positioned at the region where there is the strongest streamwise velocity gradient (Figure 4), which is generally coincident with the division line distinguished by the visual dye (Figure 3a) in all sections. The horizontal velocity (resultant velocity of u and v) is mainly perpendicular to the cross sections within the shear layer (Figure 3c). The maximum values of k are found near the junction apex, and gradually decrease downstream from S1 to S6. The strong turbulence on the right side of S5 and S6 indicates the separation zone, and its boundary within these two cross sections is mainly vertical ($-10 \text{ cm} < y < -13 \text{ cm}$). Figure 5(a-2) gives the vertical distribution of turbulent kinetic energy inside and outside the shear layer in S2, S3 and S4. The distribution of k outside the shear layer is typical of that for open channels, where the values decrease progressively from the bed to near the water surface. However, the values inside the shear layer decrease slightly at first from the bed and, and then increase gradually toward a maximum near the water surface with the turning point of $z/h = 0.15$. The difference in the turbulence intensities between flow near water surface and that near bed decreases gradually downstream from S2 (27%) to S4 (18%). Thus, the turbulence becomes more uniform downstream. The turbulent kinetic energy decays by about 25% downstream from S2 to S4 (about 14 cm), which is caused by the weak shear between the two incoming flows because their velocities become more comparable from S2 to S4.

In case two, the shear layer is obviously inclined for all sections (Figure 5b-1), and it is generally coincident with the strongest streamwise velocity gradient (Figure 4). The shear layer is not coincident with the division line distinguished by the visual

dye (Figure 3b) especially near the bed, and the horizontal velocity near the bed is not perpendicular to the cross sections within the shear layer (Figure 2), because the shear layer is distorted and the shear vortices are not vertical. In case one, the maximum values of k are mainly distributed near the water surface for all cross sections. However, in case two, the location of the maximum values of k are gradually moves from water surface to bed from upstream to downstream. Strong turbulence within the upper right side of C7 indicates the location of separation zone, and its boundary is located at $y > -18$ cm. The separation zone in case two is much larger than that in case one. Figure 5(b-2) gives the vertical distribution of turbulent kinetic energy inside and outside the shear layer in C2, C3 and C4. The values of k outside the shear layer decrease from the bed toward a minimum near the water surface except in C4. Actually, no vertical lines are observed outside the shear layer in C4. The values of k within the shear layer increase dramatically from the bed and decrease toward a minimum near the water surface, and the turning point descends from $z = 6.5$ cm in C2 to $z = 4.25$ cm in C4.

[Figure 5 near here]

4.3 Reynolds shear stress $\langle u'v' \rangle$

The distribution of Reynolds shear stress ($\langle u'v' \rangle$, where $\langle \rangle$ denotes a time average) indicates the fluctuations of horizontal velocities, u' and v' , and the time-averaged horizontal eddies motion within the confluences. The spectra permit a frequency-domain assessment of the stress. Let S_{ij} be the real part of the cross-spectrum of u and v . The Reynolds shear stress is defined as:

$$\langle u'_i u'_j \rangle = \text{cov}(u_i, u_j) = 2 \int_0^{+\infty} S_{ij}(f) df \quad (3)$$

where u_i and u_j are the three components of flow velocity; $\text{cov}()$ is the symbol of the covariance calculated by cross-spectrum using functions *detrend()* and *fft()* in *Matlab*®; and f is the frequency.

Figure 6 plots the contours for the Reynolds shear stress fields of the two cases with different discharge ratios. The location of the shear layer with large-scale rotational motions in the horizontal plane is clearly defined by the regions with large values of $\langle u'v' \rangle$ within the CHZ. In case one, large positive values of $\langle u'v' \rangle$ are mainly located within the shear layer, indicating the strong rotational motions in the horizontal plane which are the horizontal vortices caused by the shear of the two flows. The largest values of $\langle u'v' \rangle$ are distributed at the upstream four cross sections, which is coincident with the strongest streamwise velocity gradient and the strong turbulent kinetic energy. The Reynolds shear stress decreases downstream from S4 to S6. The $\langle u'v' \rangle$ values of the ambient flow are smaller than $0.2 \text{ cm}^2/\text{s}^2$. The $\langle u'v' \rangle$ values within the shear layer increase from the bed to the water surface, which could be easily observed in Figure 6(a-2). The $\langle u'v' \rangle$ values outside of the shear layer are very small and tend to zero, but increase from the bed ($0 \sim 0.5 \text{ cm}^2/\text{s}^2$) to the water surface ($1.5 \sim 2.2 \text{ cm}^2/\text{s}^2$) within the shear layer.

In case two, large negative values of $\langle u'v' \rangle$ are mainly located within the shear layer. The direction of the strong horizontal rotational motions is completely opposite to that in case one, because of the contrary streamwise velocity gradients. Large absolute values of $\langle u'v' \rangle$ can be found in the upstream five cross sections, especially in C3 where the absolute values can reach $1.9 \text{ cm}^2/\text{s}^2$, and become much smaller downstream ($x > 10 \text{ cm}$). The ambient flow also has a low value of $\langle u'v' \rangle$, whose

absolute value is smaller than $0.2 \text{ cm}^2/\text{s}^2$. Within the shear layer, the maximum values of $\langle u'v' \rangle$ are generally located in the middle of the water depth. Outside the shear layer, the values of $\langle u'v' \rangle$ are very small and tend to zero, but increase from the bed and then decrease to the water surface in the shear layer. The turning point is at $z/h = 0.18 \sim 0.43$.

[Figure 6 near here]

4.5 Turbulence spectra

The distribution of turbulent kinetic energy at different scales can be obtained by estimating the power spectra for each velocity series. The Fourier transformation of the covariance function is used to calculate the spectral density:

$$S_{ii}(f) = 2 \int_0^{+\infty} R_{ii}(\tau) \cos 2\pi f \tau d\tau \quad (4)$$

$$R_{ii}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} u'_i(t+\tau) u'_i(t) dt, \quad i = u, v, w \quad (5)$$

where S is the spectral density, R is the autocovariance function, f is the frequency, τ is the time shift, and T is a period of time t . The periodograms of spectral density were smoothed with Parzen's correlation window (W):

$$W(\tau) = \begin{cases} 1 - 6(\tau/\tau_{\max})^2 + 6(\tau/\tau_{\max})^3 & \tau \leq \tau_{\max}/2 \\ 2(1 - \tau/\tau_{\max})^3 & \tau_{\max}/2 < \tau \leq \tau_{\max} \end{cases} \quad (6)$$

The analysis included the original time series after the removal of spikes with the $3\sigma_m$ filter. The maximum time lag was set at 15% of the time series length.

Figure 7 plots the power spectra of 3D flow velocities near the water surface ($z/h = 0.6$) within the shear layer in case one. The high-frequency region in this study ranges from 3 to 10 Hz in which the power law relations for individual velocity component have an exponent of about $-5/3$, which is characteristic of the systematic cascade of turbulence energy within the inertial subrange. Over this range all the three spectral curves are similar, indicating that turbulence is three-dimensional and isotropic. The electronic noise at the highest frequencies leads to flattening of the spectral curves and slight departures from the $-5/3$ as mentioned by Rhoads and Sukhodolov (2004). The intermediate frequency where $S_{uu} \approx S_{vv} > S_{ww}$ is approximately placed in the range of (1 ~ 3 Hz). The low-frequency spectral peak ranging from 1 to 1.5 Hz is best defined for the transverse velocity spectra, especially the averaged spectrums of horizontal velocities, S_{uu} and S_{vv} . A less prominent peak is observed for the averaged spectrum of S_{ww} with a slight hump. The transverse velocity spectra for all the six cross sections exhibit low-frequency peaks of roughly similar frequency (≈ 1.15 Hz). Low-frequency peaks for the S_{ww} spectra are less pronounced and more variable in frequency than that for the S_{uu} and S_{vv} spectra.

[Figure 7 near here]

Figure 8 plots the spectral peaks for the six cross sections in case one. All cross sections except S1 have almost the same spectral-peak frequency (1.15 Hz). S1 is closest to the flow stagnation, which might affect the generation of the horizontal vortices caused by flow shear. The peak spectral densities of S_{uu} and S_{vv} increase from

S1 to S3, and then decrease from S3 to S6. Thus, S3 may be the location where the two streams completely mix and the horizontal vortices completely develop. After S3, the uniformity increases and the energy of horizontal vortices may decay. S_{uu} and S_{vv} have comparable peak spectral densities, and S_{ww} has less peak power, which indicates that turbulence associated with intermittent large-scale coherent structures within the shear layer in case one is similar to vortex pairings related to u' and v' , but not w' .

[Figure 8 near here]

Figure 9 plots the turbulence spectra of 3D velocities in the vertical direction within the shear layer. Prominent humps are observed near the water surface ($z/h = 0.60$ and 0.47), and the peak at $z/h = 0.47$ is less prominent. However, slight or no peaks are observed for other measurement locations under those two points. The spectral peak power decreases from the water surface to the bottom, indicating the decay of the horizontal vortices with the peak frequency (≈ 1.15 Hz) in the downward direction.

[Figure 9 near here]

In case two, Figure 10 gives an example of the turbulence spectrum near the water surface within the shear layer. No prominent bump is observed at any cross section, indicating that no horizontal vortices at a specific frequency (like 1.15 Hz in case one) are generated within the shear layer. The power law relations for individual velocity components have an exponent slightly larger than $-5/3$ within the frequency range ($1 \sim 3$ Hz). There is no significant difference in the turbulence spectrum

between the flow velocity near the water surface and that at the bottom along the distorted shear layer in C2 (Figure 11). The spectral densities of lateral velocity S_{vv} are higher than the other two ($f < 3$ Hz). The power law relations also have an exponent slightly larger than $-5/3$ in the frequency range of (1 - 3 Hz).

[Figure 10 near here]

[Figure 11 near here]

4.6 Reynolds shear stress $\langle u'w' \rangle$ and quadrant analysis

The distortion of the shear layer may result in changes in the velocity fluctuations in the vertical plane, which could be illustrated by the horizontal-vertical cross stresses ($\rho \langle u'w' \rangle$). In addition, $\langle u'w' \rangle$ also plays an important role in sediment transport and bed morphology at confluences. Reynolds shear stress $\langle u'w' \rangle$ could be calculated by Eq. 3. Figure 12 plots the contours for spatial distribution of Reynolds shear stress $\langle u'w' \rangle$ for the two cases. In both cases, the zones of maximum $\langle u'w' \rangle$ are generally within or near the shear layers, which are indicated by $\langle u'v' \rangle$ and k contours, and the values of $\langle u'w' \rangle$ decrease downstream. There is a large region with negative values of $\langle u'w' \rangle$ on the main-channel side in case one, but this phenomenon is not observed in case two. The comparison of the spatial distribution of the two Reynolds shear stresses $\langle u'v' \rangle$ and $\langle u'w' \rangle$ shows that the zone of maximum $\langle u'w' \rangle$ is consistent with the shear layer in case two. The strongest horizontal-vertical cross stresses ($\rho \langle u'w' \rangle$) are mainly located in the range of $z/h \approx 0.12 \sim 0.44$, and the strip with large values of $\langle u'w' \rangle$ is inclined anticlockwise. However, in case one, the zone of maximum $\langle u'v' \rangle$ is slightly deviated from the shear layer to the left bottom direction.

The strongest horizontal-vertical cross stresses are mainly located in the range of $z/h \approx 0.25 \sim 0.5$, and the strip with large values of $\langle u'w' \rangle$ is also slightly inclined anticlockwise.

[Figure 12 near here]

Turbulence bursting is often used to account for the sediment incipient motion and transport. In this study, the quadrant technique (Nezu and Nakagawa, 1993) is used to identify the bursting trends using 3D velocity data recorded by ADV. An ejection event can be identified if a low-speed fluid $u' < 0$ and an upward velocity $w' > 0$ occur simultaneously (the 2nd quadrant). Likewise, a sweep event can be identified by simultaneous occurrence of a high speed fluid moving towards the bed $u' > 0$ and $w' < 0$ (the 4th quadrant). Outward interaction is defined as $u' > 0$ and $w' > 0$ (the 1st quadrant), and inward interaction is defined as $u' < 0$ and $w' < 0$ (the 3rd quadrant). However, these two events are less dominant in the flow field compared to the ejection and sweep events.

At any point in a stationary flow, the contribution of the total Reynolds shear stress from the quadrant excluding a hyperbolic hole of size H is

$$\langle u'w' \rangle_{i,H} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)w'(t)I_{i,H}(u'w')dt \quad (8)$$

The indicator function $I_{i,H}$ follows

$$I(u'w') = \begin{cases} 1 & \text{if } (u'w') \text{ is the } i^{\text{th}} \text{ quadrant and if } |u'w'| > H|\langle u'w' \rangle| \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

where H is the threshold parameter in the Reynolds shear stress signals, which enables to extract those values of $u'w'$ greater than H times $|\langle u'w' \rangle|$ from the whole data set.

The stress fraction for the i^{th} quadrant can be defined as

$$S_{i,H} = |\langle u'w' \rangle_{i,H}| / |\langle u'w' \rangle| \quad (10)$$

where $S_{i,H}$ indicatively defines the occurrence probability of a particular event.

Figure 13 plots the contours for the occurrence probabilities of the four quadrant events where the threshold parameter H equals zero. In case one, the occurrence probabilities of outward interaction, ejection, inward interaction and sweep events are roughly similar (20-30%) within the shear layer. The probability of inward interaction events is larger than the other events, and some regions within the shear layer have an occurrence probability of about 40%. However, outside the shear layer, the highest occurrence probability is found for ejection (> 40%), followed by sweep (35% to 40%) on the main-channel side. The occurrence probability of the other two events is as low as about 10%. The comparable occurrence probability of the four events can be attributed to the horizontal vortices within the shear layer; while the turbulence presenting vortices induced by wall in the vertical plane outside the shear layer lead to a higher occurrence probability of ejection and sweep events near the wall (or the flume bottom). The area of intense ejection and sweep events on the main channel side decreases downstream; while the area of intense inward and outward events on the tributary side increases downstream induced by the separation zone. The similar phenomenon is also observed for strong ejection and sweep events on the main-channel side of the shear layer in case two. However, within the shear layer, the

ejection and sweep events still have a very high occurrence probability, which is contrary to case one. The regions for the highest probabilities of ejection and sweep events are roughly consistent with $u'w'$. The occurrence probabilities of other two events are low in most cross sections. The distortion of the shear layer makes the vortices inclined, resulting in the reinforcement of ejection and sweep events of turbulence structure within the shear layer.

[Figure 13 near here]

The comparison of the distributions of Reynolds shear stresses $\langle u'w' \rangle$ and occurrence probabilities of the four quadrants events shows that the region for high probability of outward interaction and inward interaction is consistent with the strip for large values of $\langle u'w' \rangle$ in case one, and the probability of inward interaction event is much higher. However, the region for high probability of sweep and ejection events (over 35% and 40%, respectively) is mostly located on the left side. In case two, the probabilities of outward interaction and inward interaction at all cross sections are smaller than 30%. However, the region for high probability of sweep and ejection events is mostly located on the left side (over 30-35%) and within the shear layer (over 40%), respectively.

5. Discussions

City channels often have a smaller width-to-depth ratio than natural rivers due to limited land availability. The penetration of the tributary flow into the main channel can cause the distortion of the shear layer. The main purpose of this study was to investigate the mean and turbulent flow structure in the distorted shear layer in a

discharge-adjusted plexiglass circulating flume. Two discharge ratios (2: 3 and 3: 2) were considered in this study. Three-dimensional velocities were collected using an ADV, and hydrodynamics and turbulence characteristics such as mean velocity field, turbulent kinetic energy, Reynolds shear stress, turbulence spectrum, and occurrence probability of quadrant events were analyzed. The ADV data with a SNR of <30 or a signal correlation of $<90\%$ were removed prior to analysis. The results show an obvious helical-motion flow (lateral moving flow with negative velocity upside and positive velocity downside, together with the downward flow leftside and upward flow rightside on the tributary-channel side), which is consistent with the filed observations by Rhoads and Kenworth (1995). For case one, the helical cell is strong at the junction of the two streams, but disappears downstream. For case two, the helical cell is stronger and persists for a longer distance, which is helpful for the mixing and exchange of matters between the two flows.

The strip with the maximum turbulent kinetic energy is often defined as the shear layer. The results of this study show that when the discharge of the tributary channel is small, the shear layer is less distorted and nearly vertical for all cross sections. The turbulent kinetic energy decreases from the first cross section to the last one. In each cross section, it decreases from near the water surface to the bottom. However, when the discharge of the tributary channel is large, the shear layer is completely distorted, especially at some upstream cross sections. The turbulent kinetic energy also decreases from the first cross section to the last one. However, in each cross section, there is a turning point at the middle of the water depth where there is the maximum turbulent kinetic energy.

The distribution of turbulence kinetic energy at different scales can be obtained by estimating the power spectra for each velocity series. Rhoads and Sukhodolov

(2004) have demonstrated that the most notable characteristics of energy spectra for turbulent flow within the shear layer are (1) a high-frequency region of power law scaling between $S_{\xi\xi}$ and f , (2) an intermediate frequency range where $S_{uu} \approx S_{vv} > S_{ww}$, and (3) a low-frequency region with a well-defined spectral peak in S_{vv} . These characteristics are also observed in our flume experiments when the discharge of the tributary channel is small. Firstly, all the power law relations for individual velocity components have an exponent of approximately $-5/3$ in the high-frequency region. Secondly, a low-frequency spectral peak range is best defined for the transverse velocity spectra, and the S_{ww} spectra have a less prominent peak. Their peaks correspond to the roughly similar frequency of about 1.15 Hz, indicating the existence of horizontal vortices which are similar to the traditional vortex pairing (Rhoads and Sukhodolov, 2004). The strongest energy concentration is observed at S3 and decays downstream along the shear layer; while in individual cross section, it decays dramatically in the vertical direction. However, when the discharge of the tributary channel is large, the power law relations ($-5/3$) still exist for the systematic cascade of turbulence energy within the inertial subrange. In the low frequency, all the power law relations all have an exponent slightly larger than $-5/3$, and the spectral densities of S_{vv} are larger than the other two. However, unlike the vortice pairing observed in case one, different scales of horizontal vortices are observed using dye injection, and the boundary of dyed water is nearly a smooth curve. No obvious energy concentration is observed in the shear layer.

The shear layer is directly associated with the intermittent large-scale coherent structures which are similar to the traditional vortex pairing. These structures are two-dimensional vortices with near vertical axes if the shear layer is nearly vertical, or 3D vortices if the shear layer is distorted. $\langle u'v' \rangle$ and $\langle u'w' \rangle$ could illustrate these

time-average eddies motion in the horizontal and vertical plane. Large values of Reynolds shear stress $\langle u'v' \rangle$ can illustrate the time-averaged horizontal eddies motion within the shear layer. This is the reason why it could also be applied as an indicator of the location of shear layer. When the discharge of the tributary channel is small, the spatial distribution of $\langle u'v' \rangle$ is similar to that of turbulent kinetic energy. The Reynolds shear stress decreases downstream within the shear layer in the horizontal plane and decreases downward in individual cross section. When the discharge of the tributary channel is large, the values of $\langle u'v' \rangle$ in the upstream two cross sections are small due to the influence of flow stagnation. The values of $\langle u'v' \rangle$ decrease downstream from C3 within the shear layer. However, in individual cross section, there is a turning point at the middle of the water depth where the maximum $\langle u'v' \rangle$ is located. The distribution of $\langle u'w' \rangle$ is also shown in this study. When the discharge of the tributary channel is small, the shear layer is vertical near the water surface and slightly distorted in the middle of the water depth, resulting in smaller $\langle u'w' \rangle$ near the water surface and larger $\langle u'w' \rangle$ in the middle of the water depth within the shear layer. However, in the other case, the shear layer is completely distorted, thus the distribution of $\langle u'w' \rangle$ is more consistent with $\langle u'v' \rangle$, and their values are comparable.

Quadrant technique has been widely used to analyzed wall turbulence such as turbulence in rough bed forms and its impacts upon bed scour (Mazumder et al. 2009; Maity et al. 2014; Mazumder and Sarker, 2014; Jain et al. 2015). Unlike wall turbulence, the large-scale coherent structures observed in this study are caused by the shear of two flows. When the shear layer is distorted, larger values of $\langle u'w' \rangle$ are observed. Quadrant technique could be used to analyze the bursting events of turbulence in the confluence zone, which have an important influence on the sediment

transport (Boyer et al., 2006). Of the four quadrant events, ejections are most responsible for taking sediment particles away from the bed, and sweeps provide an avenue for entraining particles (Mazumder and Sarker, 2014). In both cases, ejections and sweeps near the wall are much stronger than the other two events due to the turbulence presenting vortices induced by wall in the vertical plane outside the shear layer (Maity et al. 2014; Jain et al. 2015). When the shear layer is nearly vertical, the occurrence probabilities of the four quadrant events are comparable, and inward interactions make a larger contribution than the other three events. This phenomenon may be related to the nearly horizontal vortices. When the shear layer is distorted, intense ejections contribute largely to the shear stress $\langle u'w' \rangle$ within the shear layer, while intense sweeps occupy the region slightly downside the shear layer. These intense events together with the large shear stress $\langle u'w' \rangle$ may contribute to the sediment transport in these regions. Similar with the shear stress $\langle u'v' \rangle$, the intensity of ejections and sweeps decays downstream because the shear of the two incoming flows become weaker.

Two additional tests were conducted to investigate the influence of the changes of hydrodynamics and turbulence at confluence zones, in which the discharge ratio and other conditions (i.e. water depth) were the same as the previous two cases, but the discharges were changed to $Q_1=5.85$ L/s and $Q_2=9$ L/s in case A; and $Q_1=2.6$ L/s and $Q_2=4$ L/s in case A2. The flow and turbulence at C3 are compared, as shown in Figure 14. Apparently, the discharge of each channel has a significant influence on the confluent flow. An increase in the discharge of both channels results in an increase in some parameters, such as velocity, turbulent kinetic energy, and the absolute values of $\langle u'v' \rangle$ and $\langle u'w' \rangle$. Furthermore, the shear layer is distorted to a larger extent as the discharge of each channel decreases, and the shear layer in case A2 is almost

vertical. In addition, these three cases have many other similar characteristics. For example, large turbulent kinetic energy and Reynolds shear stress $\langle u'v' \rangle$ are located far away from the water surface. The regions for the highest probability of ejection and sweep events are consistent with $\langle u'w' \rangle$, as well as the turbulent kinetic energy and Reynolds shear stress $\langle u'v' \rangle$.

[Figure 14 near here]

6. Conclusions

Several important characteristics for the flow structure and turbulence in the distorted shear layer are observed when the discharge of the tributary is large:

- a) A stronger helical cell develops in the cross sections and persists for a longer distance, which is helpful for the mixing and exchange of matters between the two flows.
- b) The maximum turbulent kinetic energy, Reynolds shear stress and occurrence probabilities of ejection and sweep events are mainly distributed within the middle zone of the water depth, rather than near the water surface, which is consistent with the distortion of shear layer.
- c) No obvious energy concentration is observed by the spectrum analysis. All the power law relations for individual velocity components have an exponent slightly larger than $-5/3$, and the spectral densities of lateral velocity are larger than the other two in the low frequency.
- d) The distortion of the shear layer results in an increase in the occurrence probabilities of ejection and sweep events within the shear layer, but a decrease in

the occurrence probabilities of ejection and sweep events outside the shear layer which are related to the turbulence presenting vortices induced by wall.

- e) If the discharge ratio remains unchanged, increasing the discharge of both channels results in an increase in some parameters, such as velocity, turbulent kinetic energy, absolute values of $\langle u'v' \rangle$ and $\langle u'w' \rangle$; while the shear layer is distorted to a larger extent as the discharge of each channel decreases.

Sediment and contaminant transport and bed morphology in the distorted shear layer at city channel confluences could differ significantly from that at natural river confluences. Knowledge of the hydrodynamics and turbulence characteristics in these confluence zones, especially within the distorted shear layer, is essential to better understand the convection and diffusion of pollutants, which is critical for the design of sewage outlets and water intakes.

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Figures Caption List

Figure 1. Sketch of the experimental setup: a confluence channel flume with a 90-degree junction angel (a); and measurement locations (the values in the brackets represent the endpoint coordinates; the values along each cross section represent the transverse distance between the adjacent measurement points): (b) case one, (c) case two.

Figure 2. Examples of time series (2a and 2d), stationarity analysis (2b and 2e) and power spectra (2c and 2f) of 3D velocities within and outside the shear layer.

Figure 3. White dye injection in the tributary channel to visualize the shear layer within the test area (Figure 1): (a) case one and (b) case two; and time-averaged horizontal velocity fields near the flow surface (red arrows, $z = 8$ cm) and near the bottom (black arrows; $z = 2$ cm): (c) case one and (d) case two.

Figure 4. Contours for spatial distributions of 3D velocities (in units of cm/s) of two cases, with the letters (a and b) representing different cases: (a) case one, (b) case two, and the numbers (1-3) representing three velocity components, u , v , and w , respectively.

Figure 5. Contours for distributions of turbulent kinetic energy k (in units of cm^2/s^2) within and outside the shear layer, with the letters (a and b) representing different cases: (a) case one, (b) case two, and the numbers (1 and 2) representing spatial distributions and vertical distributions turbulent kinetic energy, respectively.

Figure 6. Contours for distributions of Reynolds shear stress $\langle u'v' \rangle$ (in units of cm^2/s^2) within and outside the shear layer, with the letters (a and b) representing different cases: (a) case one, (b) case two, and the numbers (1 and 2) representing spatial distributions and vertical distributions turbulent kinetic energy, respectively.

Figure 7. Energy spectrum of 3D velocity near the water surface within the shear layer from S1 to S6 in case one.

Figure 8. Frequencies and spectral densities of spectral peaks for 3D velocity in case one.

Figure 9. Spectral densities in the vertical within the shear layer of S3 in case one.

Figure 10. Spectral densities of 3D velocity near the water surface within the shear layer in C2 and C5.

Figure 11. Spectral densities along the inclined shear layer in the downward direction in C2.

Figure 12. Contours for spatial distribution of Reynolds shear stress $\langle u'w' \rangle$ (in units of cm^2/s^2) along the shear layer: (a) case one; (b) case two.

Figure 13. Contours for occurrence probabilities of four quadrants events ($H=0$), with the letters (a and b) representing different cases: (a) case one, (b) case two, and the numbers (1-4) representing occurrence probabilities of four quadrants events, S_1 , S_2 ,

S_3 , and S_4 , respectively.

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881 (b)

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888 (c)

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890 (d)

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895 area (Figure 1): (a) case one and (b) case two; and time-averaged horizontal velocity fields near
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961 (a)

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963 (b)

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967 **Figure 12.** Contours for spatial distribution of Reynolds shear stress $\langle u'w' \rangle$ (in units of cm^2/s^2)

968 along the shear layer: (a) case one; (b) case two.

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(a-1)

(b-1)

(a-2)

(b-2)

(a-3)

(b-3)

(a-4)

(b-4)

Figure 13. Contours for occurrence probabilities of four quadrants events ($H=0$), with the letters (a and b) representing different cases: (a) case one, (b) case two, and the numbers (1-4) representing occurrence probabilities of four quadrants events, S_1 , S_2 , S_3 , and S_4 , respectively.

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