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Research paper

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ABSTRACT

A new in situ technique is introduced and tested for the field tracer study in meandering rivers. Real-time position data from a global positioning system were integrated with in situ fluorometer data, thereby providing a 2D spatial distribution of the tracer concentration. The method was used in an intensive tracer field survey over an 83 km reach of the North Saskatchewan River downstream of the capital region wastewater treatment plant. Hydrodynamics data were also collected simultaneously by measuring streamwise water velocity and depth using an acoustic Doppler current profiler. The full mixing length for this surface bank outfall at the observed low flow condition was inferred to be 130 km. The employed technique effectively improved the understanding of mixing patterns in complex flows by providing tracer and hydrodynamic data with high spatial and temporal resolution.

Keywords: aDcp; full mixing length; in situ fluorometer; meandering river; mixing; transverse dispersion; wastewater effluent

1 Introduction and literature review

Understanding of contaminant mixing in meandering rivers is important for the management of environmental and water resources, with consequences for drinking water, irrigation, and recreational uses. Dissolved oxygen (DO) is one of the most effective parameter in aquatic life. The level of DO in a flowing stream is highly influenced by biochemical oxygen demand loading introduced by wastewater effluent discharged into rivers. This paper reports a detailed study of transverse mixing of a wastewater effluent in a natural meandering river.

Summarizing the reported transverse dispersion coefficient results from various previous field and laboratory studies in straight, meandering, ice-covered, and sinuous natural channels, Rutherford (1994) suggested the value of 100–300 times the channel width as the approximate river reach length required for transverse full mixing downstream of a point source near the middle of a river section. For a source near the bank, the value should be increased four times. In mixing studies, the transverse mixing distance (Lz) is used as the distance from the outfall where tracer becomes fully mixed across the channel. The fully mixed condition can be assumed when the ratio of minimum to maximum concentration (Pm) reaches the range between 0.9 and 0.98 across the channel (Rutherford, 1994). Considering Pm = 0.98 and assuming a monotonic decrease in concentration gradient in relation to increased distance from the source, Rutherford (1994) suggested Lz = 0.536νb²/kₚ in the case of bank outfalls, where ν is the reach-averaged velocity, b is the river width, and kₚ is the bed roughness. The other important parameter is the distance downstream of the source where the tracer reaches the opposite bank (Lc). This parameter has been termed the cross distance by Holley, Siemons, & Abraham (1972). Rutherford (1994) suggested Lc = 0.0546νb²/kₚ as the
distance from the bank source where tracer concentration at the opposite bank reaches 2% of the near-bank concentration.

It is generally accepted in the literature that the transverse mixing coefficient in a river is affected by several main parameters, such as river geometry, depth, discharge, width, ice cover, and shear velocity (Zhang & Zhu, 2011). Much effort has been expended to identify the level of importance of these parameters in the transverse mixing process. Lau & Krishnappan (1981) summarized that higher sinuosity in a meandering channel increased transverse mixing. In one of the most recent field studies, Zhang & Zhu (2011) observed the effect of flow rate and ice-cover on transverse mixing in a meandering river. They found that transverse mixing coefficient increased linearly with the flow rate. The ice-covered condition was also found to have a negative effect on the transverse mixing process.

Transverse mixing in rivers is due to molecular diffusion (usually insignificant), turbulent diffusion, and advection due to secondary currents (Gualtieri, 2009). In a numerical or analytical mixing model, a dispersion coefficient is used to account for processes that are not directly modelled. Dispersion accounts for mixing resulting from velocity gradients “i.e. velocity shear” over the depth and width. In a 2D model, dispersion accounts for both turbulent and molecular diffusion processes. Advection due to secondary currents increases the rate of mixing by moving the particles in opposite directions at different depths (Fischer, 1969).

While many hydraulic and contaminant fate numerical models have been developed that consider each of these processes, prediction of turbulent dispersion, i.e. mixing of pollutants due to turbulence, is challenging. In general, a mixing coefficient is required to quantify this process. The mixing coefficient can be estimated using either analytical or numerical approaches (Nikiema, Devenon, & Baklouti, 2007), but both of these approaches are ultimately driven by the experimental data.

Analytical methods can be defined as either observational or predictive methods (Jeon, Baek, & Seo, 2007), both of which require reliable sets of tracer and hydraulic data to verify their performance. The observational methods estimate mixing coefficients directly from hydraulic and tracer data that indicate dispersion of the tracer in the channel. Some of the observational methods are relatively simple such as the standard method of moments (Yotsukura & Sayre, 1976) and generalized method of moments (Beltaos, 1980; Rutherford, 1994), while others are more complicated such as the cumulative discharge method (Yotsukura & Cobb, 1972; Yotsukura & Sayre, 1976). Predictive approaches such as methods proposed by Fischer (1969), Bansal (1971), Gharbi & Verrette (1998), and Jeon et al. (2007) generalize observational results to provide a formula for estimating the average mixing coefficient. Analytical approaches employ simplifying assumptions such as uniform velocity and depth throughout the channel. These simplifying assumptions may lead to inaccurate predictions, especially where the region of study is a highly extended long reach. The desire to minimize errors in estimation of mixing coefficients has led researchers to utilize numerical approaches (Parker, Droste, & Rennie, 2012). Several turbulence closure models are available for estimation of the mixing coefficient, such as the k-ε model (Rodi, 1993). However, direct estimation of the mixing coefficient in rivers by field measurement is usually necessary for validating such models.

To obtain sufficient data to estimate mixing coefficients, several experimental tracer studies have been performed in controlled laboratory conditions. In one of the earliest experimental studies, Elder (1959) found that the concentration distribution from a point slug injection of tracer follows a Gaussian distribution. He proposed \( E_z = \beta H U^* \) for estimating the transverse mixing coefficient, where \( E_z \) is the transverse mixing coefficient, \( H \) is the mean channel depth, \( U^* \) is the average shear velocity, and \( \beta \) is an empirical coefficient which was found equal to 0.23 in that study. Of the laboratory studies carried out since then, some were conducted in straight channels (e.g. Holly, 1975; Lau & Krishnappan, 1981; Miller & Richardson, 1974; Nokes & Wood, 1988). On the other hand, several studies have been conducted in meandering channels, focusing on the influence of channel curvature on mixing (Boxall & Guymer, 2003; Chang, 1971; Fischer, 1969).

Although laboratory studies have been generally more popular, in some cases their controlled conditions may also cause discrepancy between laboratory and field results (Fischer, 1969). This is attributed to uncertainties in scaling laws, or irregularities in river geometry, depth, or side walls, which cannot be taken into account properly in laboratory studies. One of the earliest field transverse mixing studies was conducted by Glover (1964) in the Columbia River. Similar to laboratory experiments, field studies have been conducted on straight (Fischer, 1969) or meandering channels. The curvilinear flow in meandering channels produces transverse advection and secondary circulations (Blanckaert, 2011; Kashyap, Constantinescu, Rennie, Post, & Townsend, 2012) which enhance transverse mixing. This effect and its dominance were investigated in various field studies (Lau & Krishnappan, 1981; Seo, Baek, & Jeon, 2006). Conducting a laboratory experiment in a meandering channel, Lau & Krishnappan (1981) suggested using stream sinuosity to consider the effect of secondary currents in transverse mixing. Seo et al. (2006) concluded that secondary currents enhance transverse mixing in meandering channels and are directly related to the stream sinuosity and the ratio of width to depth in meandering channels.

Field tracer studies have also differed in the extent of the study region. Some of them have focused on the mixing pattern in the intermediate region from an outfall (Dow, Steffler, & Zhu, 2009), while others have focused on far-field mixing patterns (Zhang & Zhu, 2011). All tracer studies from the earlier ones like Elder (1959) to more recent ones (Seo et al., 2006) were conducted to provide a method or formulation that can represent the mixing mechanism more accurately. Rutherford (1994)
gathered different experimental and field work data and summarized them in non-dimensionalized graphs that are very useful for estimating the mixing.

In all of the mentioned experimental or field tracer studies, water sampling methods have been used for measuring tracer concentration. Sampling methods introduce time lags in the data acquisition process, especially in field measurements, which can be a source of error when the data are post-analysed. These methods cannot be used for real-time monitoring, and may create significant problems in studying dispersion in water bodies. Recent developments in field equipment, such as employing more accurate global positioning system (GPS) and acoustic Doppler current profiler (aDcp) instruments, have improved the quality of field data and increased the tendency towards conducting field studies. For example, vertical velocity profiles measured with an aDcp have been used in recent studies to estimate the longitudinal dispersion coefficient (Carr & Rehmann, 2007; Shen, Niu, Anderson, & Phanikumar, 2010).

In recent years the limitations of sampling methods have also been reduced by the advent and recent employment of in situ fluorometers. In one of the earliest studies, Katz, Chadwick, Rohr, Hyman, & Ondercin (2003) used an in situ fluorometer to study the mixing field of the discharged waste from a vessel into its wake zone. Later, Hunt et al. (2010) used an in situ fluorometer to study the initial dilution, near field, and far mixing of a sewage outfall plume in Boston harbour. Rowiński, Guymier, & Kwiatkowski (2008) also used an in situ fluorometer to investigate mixing and transport processes in a 90-km reach of the Upper Narew River in the northeast of Poland. In Rowiński’s study, the in situ fluorometer was mounted at a fixed position in the middle of the surveyed sections. Therefore, the fully 2D spatial distribution of the tracer concentration was not provided.

Studying the full mixing length of natural meandering rivers with small mixing coefficients has always suffered from logistical difficulties which may negatively affect the output of the study. The full mixing in these cases occurs far from the discharge point. Therefore, the steady injection of the tracer during the field work may not be applicable due to the massive amount of the required tracer. In these rivers, the full mixing condition is not commonly reached within a one day of field work. Finding the plume in the next day of field work is an essential task which greatly affects the accuracy of the study. Therefore, the accuracy of the traditional sampling methods, which suffers from the time lags in the data acquisition process, depends directly on correctly locating of the plume in the river. This is more important in the cases for which the field campaign is continued for several days.

The error in estimating the travel time of the plume may lead to inaccuracy in estimating the mixing coefficient or the mixing pattern of the plume along the river path. Therefore, having an extensive set of tracer and hydrodynamic data with high spatial and temporal resolution is essential in understanding the mixing pattern of the plume in an extended region of interest with complex flow patterns. The novel contribution of this paper is to integrate real-time position data into both in situ fluorometer and aDcp data collected at each surveyed point in the river, and thereby provide a fully 2D spatial distribution of the tracer concentration in a natural meandering river. Due to the wide cross section of the river in this study as well as the outfall location which was on the bank side, providing a spatial distribution of the tracer concentration is critical for understanding the behaviour of the plume along the river path. The main objective of this study is to introduce a new technique for tracer field study by using the latest technology in field measurement and to show the effectiveness of this technique for studying the mixing pattern of extended natural meandering rivers. Furthermore, the observations are used to infer the stream path length required to achieve full mixing of the effluent.

In this study, Rhodamine WT was injected as the tracer at the outfall of capital region wastewater treatment plant (WWTP), which disposes its treated waste water effluent into the North Saskatchewan River downstream of the City of Edmonton, Canada. The tracer concentration was then tracked using an in situ fluorometer in 17 sub-reaches along an extended 83 km long reach of the river from a boat moving across and along the river. The hydraulic characteristics of the flow, including depth-averaged velocity and bed elevation, were also collected simultaneously using an aDcp. The shear velocity, as one of the most effective parameters on the mixing coefficient, was also calculated from collected velocity profiles.

In the next step, a filtering process was performed on the collected data. The filtered data were then mapped and interpolated with the kriging method. The mean value of interpolated data was then calculated as the representative of that parameter in the surveyed sub-reach.

This study provides reliable data sets of the basic hydraulic parameters as well as tracer results, which can be used in different hydraulic and mixing studies. For example, the summary of data presented herein is used in a companion paper (Pilechi, Mohammadian, Rennie, & Zhu, 2014) to develop a numerical model to simulate mixing of a natural conservative substance in a meandering river. The model employs an orthogonal stream tube coordinate system and considers the effect of fluctuating river discharge in simulating the mixing pattern in the river. The dispersion coefficients were also estimated using the standard and general method of moments for the first quarter of the study length and the results were compared with the numerical model. The mixing coefficient was estimated in different surveyed sub-reaches along the river path and the averaged dispersion coefficient was calculated for the total surveyed reach.

This paper is prepared as follows. First, the methodology for conducting the field work is explained in detail. Subsequently, in the post processing section, the methods used for filtering and mapping the collected data are discussed. In the results section, the output tracer concentration, water velocity, flow depth, and shear velocity across several sections in the extended
reach are presented. A detailed analysis of velocity, depth, and tracer concentration distributions in a particular meander bend is also conducted. A discussion of the observed mixing patterns follows, including an assessment of the influence of channel morphology on mixing. The paper concludes with a summary of the presented results, and limitations of the study.

2 Field work

The field work was started by injecting tracer at the outfall location of Capital Region WWTP, which is the fourth largest wastewater treatment facility in Alberta, Canada. The plant has a surface outfall located at the right bank side of the river, facing downstream (Fig. 1) at 53°38.297′ North (latitude) and 113°18.489′ West (longitude).

Following government of Alberta environmental guidelines, in this study Rhodamine WT was used as a tracer of the wastewater effluent in the river. The density of Rhodamine WT is 1.26 g cm$^{-3}$, thus it was diluted with an equal volume of methanol with 0.791 g cm$^{-3}$ density to produce a neutrally buoyant mixture with lower viscosity and surface tension characteristics. This minimized the effect of buoyancy on transverse mixing rate. In addition, the injection rate was chosen so that the concentration of Rhodamine WT did not exceed 10 ppb at the full mixing condition or at any withdrawal point.

In most cases the outfall of a wastewater treatment plant acts as a steady source of pollution to the receiving river. Ideally, to study the effluent plume from source to the point of far-field full mixing, tracer should be injected continuously into the source at a steady rate. However, for large rivers this requires an enormous quantity of tracer. In this study, the tracer was injected for 13 h on 26 October 2011, at a steady rate of 64 mg s$^{-1}$ using a peristaltic pump. This created a tracer slug that could be tracked as it mixed into the river. The mixing pattern was tracked from a boat moving across and along the river using an in situ fluorometer. The Rhodamine plume was traced for a period of three days (26–28 October 2011) by surveying a total of 17 sub-reaches over a total distance of 83 km along the river path. As described below, survey data within each sub-reach were projected onto a single section (Fig. 2). The spatial location of the surveyed sections as well as the surveying dates are provided in Table 1.

The innovative aspect of this study is real-time tracer data collection and data display with the in situ fluorometer. Real-time in situ measurements allowed for a much higher sampling intensity, thus the plume was characterized in much greater detail than was possible with conventional water sampling. Furthermore, real-time display of tracer concentration along the survey path allowed for the identification of the plume location while in the field, which allowed for on-the-fly optimization of the survey path to best characterize the effluent plume. This greatly increased the utility of the collected data. Integrating the GPS position data with fluorometer data in real time allowed for the measurement of the spatial distribution of tracer concentration while it mixed along the river path.

![Figure 1](https://via.placeholder.com/150)

(a) Capital Region WWTP outfall; (b) site location (adapted from Google Earth). Copyright 2014 Google

![Figure 2](https://via.placeholder.com/150)

Sections surveyed on (a) 26 October; (b) sections surveyed on 27 October; (c) sections surveyed on 28 October.
The fluorometer used in the present study was a WetlabECO-RHRY, integrated within a Seabird SBE19-Plus Conductivity-Temperature-Depth (CTD) probe. This fluorometer can detect Rhodamine WT concentrations ranging from 0.01 to 230 ppb with 0.01 ppb sensitivity (i.e. resolution). Rhodamine WT concentrations were recorded with a sampling frequency of 4 Hz. Fluorometer data were collected at one elevation in the flow, assuming zero vertical concentration gradient. This was a reasonable assumption because the river was very shallow at the outfall (less than 1 m), thus full vertical mixing occurred very close to the outfall.

The river hydrodynamics were also measured using a SonTek M9 Riversurveyor aDcp. This aDcp has a small “blanking distance” of 20 cm, i.e. it obtains its first measurement bin only 20 cm from the transducers, which was essential for this study because the river was shallow with depths of only O(1 m) during the survey. The aDcp measured water velocities and depths at 1 Hz sampling frequency, using bottom tracking for the boat velocity reference. The surveying procedure started 3 h after the start of the Rhodamine injection, which was sufficient time for the tracer concentration spatial distribution to stabilize in the near and medium fields. The fluorometer and aDcp data were collected simultaneously and synchronized by means of the GPS position and time-stamp data that were integrated into the data streams collected by both the fluorometer and the aDcp. A survey grade dual frequency real-time kinematic (RTK) Global Differential Positioning System was employed on the boat to locate the measurements. The GPS was manufactured by Novatel, and included a Novatel DL-V3-L1L2 base receiver and a Novatel Propak LB+ rover receiver with reported relative horizontal position accuracy of ±2 cm circular error probable (i.e. 50% of position estimates have error <2 cm). The precision of the real-time kinematic differential global positioning system RTK-DGPS system was previously evaluated by Rennie & Rainville (2006), wherein average error of the measured RTK-DGPS velocity equalled 2.6 cm s⁻¹. The radio communication between base and receiver had a range of about 10 km, which limited RTK accuracy to this range. For sampling at larger distances from the outlet, differential correction was obtained conventionally using the Wide Area Augmentation Strategy, which has a position accuracy of O(1 m) and an average velocity error of about 0.1 cm s⁻¹. Position data were collected at 10 Hz, and were integrated into the fluorometer and aDcp data sets for correct positioning and synchronization of the fluorometer and aDcp data.

The river discharge during the field campaign was approximately 115 m³ s⁻¹ from Hydat data (Water Survey Canada) for the gauge station 05DF001, located at approximately 113° 28.634’ West (longitude) and 53° 32.385’ North (latitude), 26 km upstream of the outfall. The average October North Saskatchewan River flow rate between 2000 and 2009 was 163 m³ s⁻¹, and the average flow rate for 29 October was 135 m³ s⁻¹.

The hydrograph data (Fig. 3) for this gauge station show river discharge variation between 96 and 136 m³ s⁻¹ during our field campaign. The river discharge during the survey was slightly below the long-term average for the period of the survey. This discharge variation was not found to influence plume dispersion substantially, but did modify longitudinal advection of the plume (Pilechi et al., 2014).

The maximum variation in the discharge was about 35%, which occurred in 12 h. The duration of survey in each sub-reach was about 1 h and considering the average variation of 3% per hour for river discharge, the steady-state condition was assumed during each sub-reach survey. Furthermore, when calculating shear velocities at a section (see later text), it was assumed that flow unsteadiness was too weak to disrupt the formation of fully developed semi-log velocity profiles. Song & Graf (1996) evaluated velocity profiles in unsteady flows, similar to observations in steady uniform flows. Furthermore, they defined an unsteadiness parameter \( \Gamma_{HG} \), where \( \Delta D/\Delta T \) is the bed shear velocity before the
passage of the unsteady wave, $\Delta D$ is the change in depth with passage of the wave, and $\Delta T$ is the time duration of the wave. In their experiments, $\Gamma_{HG}$ ranged from $4E^{-3}$ to $18E^{-3}$. The largest possible value that could have been observed during our field measurements was more than an order of magnitude lower ($\Gamma_{HG} = 0.2E^{-4}$). Given that (a) the log-law holds in unsteady flows, and (b) the minimal degree of unsteadiness in the present case, the steady-state condition was assumed in calculating the shear velocities.

2.1 Post processing

The first post processing step was to remove the highest 5% of the collected tracer data from moving blocks of 50 data points. In the next step, a low-pass filter was implemented on each tracer data time series. The processed data (concentration, velocity, depth, longitude, and latitude) were then imported into ARCGIS(9.3) and superimposed on a North Saskatchewan river boundary shape file, downloaded from http://www.geobase.ca/geobase/en/index.html.

Due to river flow, the boat moving across the river was not on a straight line. Therefore, a straight line perpendicular to the river banks was drawn near the most parallel boat transects within a sub-reach. Adjacent upstream and downstream data points were snapped perpendicularly to this drawn line. As discussed below, the snapped data were then used to represent the concentration and/or velocity at this sub-reach. In order to be able to infer the pattern and characteristics of mixing from collected sample data, each cross section was split into 20 cross-sectional intervals, and the average tracer concentration was calculated for each interval.

As previously mentioned, shear velocity is an important parameter for predicting the mixing process. This important parameter is generally estimated as

$$u_\ast = \sqrt{ghS}$$

where $g$ is the gravity, $h$ is the average depth, and $S$ is the river slope. However, Boxall & Guymer (2003) found that Eq. (1) overestimates the shear velocity at bends. In the present study, shear velocity was estimated from the slope of the fitted log-law vertical profile of stream wise velocity measured with the aDcp (Eq. 2)

$$u = \frac{u_\ast}{k} \ln(z) + \frac{u_\ast}{k} \ln\left(\frac{30}{k_s}\right)$$

In Eq. (2) $u$ is the velocity in the bin at height $z$ above the mean bed elevation, $\kappa$ is the von Kármán constant (0.41), and $k_s$ is the bed roughness. Following Rennie & Church (2010), a moving average of 11 adjacent aDcp pings were employed to calculate the velocity profile for each shear velocity estimate. Shear velocity estimates were filtered if calculated $k_s$ exceeded 5 m or was less than 0.1 mm. This method had been successfully used by Rennie & Church (2010) for mapping the shear velocity in Fraser River, British Columbia.

Due to fewer velocity points, shear velocity uncertainty is greater for shallower profiles (Rennie & Church, 2010). In order to minimize the effect of this uncertainty, further filtering was implemented on estimated shear velocity within each of the surveyed sub-reaches. In the first step, the 95% confidence interval was estimated for each individual shear velocity estimate based on the lower and upper confidence limits for the log-law regression slope (Eqs. 3 and 4)

$$L = u_\ast - S t_{u/2,n-1}$$

$$U = u_\ast + S t_{u/2,n-1}$$

where $L$ and $U$ are, respectively, the lower and upper limits of the confidence range, and $u_\ast$ is the shear velocity estimated from the slope of the particular log-law velocity profile. The parameter $S$ is the standard error of the $u_\ast$ estimate from the log-law regression, which depends upon the number of points in the velocity profile ($n$) and the regression residuals. Finally, $t_{u/2,n-1}$ is the standard random variable from the $T$-distribution for a probability of $\alpha/2$, where $\alpha$ equals 0.05 for the 95% confidence interval.

In the next step, all estimates within a sub-reach were grouped into a single population, with the goal being to identify the average value for the sub-reach. Within a sub-reach population, profiles identified as producing outliers for any of the lower confidence limit, upper confidence limit, or the estimated shear velocity were removed. For each of these statistics, outliers were identified as the points where $A > 0$ or $B < 0$, where

$$A = Obs - (Q3 + 1.5IQR)$$

$$B = Obs - (Q1 - 1.5IQR)$$

In Eqs. (5) and (6), $Obs$ is the observation value, $Q1$ and $Q3$ are the first and third quartiles, respectively; and $IQR = Q3 - Q1$ is the interquartile range. The observation point was removed from the data set for the points where any of the upper, lower, or estimated shear velocity was an outlier. The statistical parameters for filtered and raw data for section S1 are provided in Table 2.

<table>
<thead>
<tr>
<th>Section (S1)</th>
<th>Number of observation</th>
<th>Mean value (m s$^{-1}$)</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>1516</td>
<td>0.085</td>
<td>0.073</td>
<td>85.68</td>
<td>6.51</td>
</tr>
<tr>
<td>Filtered</td>
<td>791</td>
<td>0.080</td>
<td>0.026</td>
<td>32.49</td>
<td>0.22</td>
</tr>
</tbody>
</table>
After removing the outliers of each sub-reach data set, the results were imported again into ARCGIS 9.3. The imported data set included depth-averaged velocity, bed elevation, estimated shear velocity, bed roughness, and position data of the surveyed points within each sub-reach. Within each of the surveyed sub-reaches, these parameters were then interpolated using the kriging method. The mean value of interpolated data was then chosen as representative of that parameter in the surveyed sub-reach.

3 Results

3.1 Tracer concentration

The cross-sectional transverse distributions of measured rhodamine tracer concentrations (µg l⁻¹, or equivalently, ppb) are plotted for river sections at different distances downstream of the outfall in Fig. 4. In all of the provided graphs, the x-axis is the transverse distance across the section normalized to the cross section width.
section width, which was calculated from the right bank side of the river (facing downstream). Due to shallow water depth, there were some sections in which the fluorometer could not be kept in the water for the whole section, thus no in situ tracer data are presented for those parts of the sections.

The tracer was injected at the outfall located at the right bank side of the river, thus in most of the sectional transverse concentration profiles (Fig. 4), the highest tracer concentration across the section was observed at the right bank side. Tracer concentration gradually reduced along the river path to 0.83 µg l⁻¹ at the last surveyed section (83 river km from the outfall). The rhodamine reached the left bank at the sharp bend 6.5 km from the outfall. The highest measured rhodamine concentration difference between left bank side and right bank side was reduced from 16 µg l⁻¹ in S2 to 0.27 µg l⁻¹ in S17.

In order to investigate the effect of the sharp bend located 6.5 km downstream of the outfall, sections S4–S6 were closely spaced in the beginning, middle, and end of the sharp bend. From the rapid change in the transverse distribution of tracer concentration between these sections (Fig. 4), it is apparent that the bend flow induced mixing towards the outer bank of the sharp bend. This mixing process is investigated in detail later in text and in Pilechi et al. (2014).

As the outfall is located at the right bank side of the river, it was generally expected to observe higher tracer concentrations in the right bank side of all sections upstream of the full transverse mixing condition. However, at some sections (e.g. S8 and S14) lower peak concentrations were observed near the right bank. This is because the fluorometer samples were not always taken in the longitudinal middle of the plume, and the river velocity and depth were not uniform across the river section. The higher depth-averaged velocity along the thalweg streamline caused the tracer to move faster within the deeper centre portion of the channel section. The influence of non-uniformity in the river velocity and depth is explained in the discussion section.

3.2 Velocity and depth

Flow velocity and depth are the basic parameters that affect the mixing process in rivers. These parameters are used in all of the transverse mixing prediction methods. In addition, Pilechi et al. (2014) found that even for cross sections located within a sub-reach, local bed features may result in different transverse mixing coefficients. The measured depth-averaged velocity and depth are presented in the appendix (Fig. A1) for all of the sections where tracer distribution was measured. Similar to Fig. 5, the horizontal axis shows the normalized transverse distance. The positive part of the vertical axis presents velocity in m s⁻¹ and the negative part presents depth in m.

The presented data were calculated by bin-averaging the values measured by the aDcp within 80 intervals across the section. Similar to the concentration graphs, portions of some sections were too shallow to survey with the aDcp (less than 0.5 m). For these portions, data have been generated using linear interpolation between measured neighbouring points.

Due to the topographic steering, it is generally expected to observe higher depth-averaged velocity along the thalweg streamline which follows the deeper part of the channel (Dietrich & Smith, 1983). In most of the surveyed sections in this study, the thalweg was located in the channel centre where increased depth-averaged velocity was observed (Fig. A1). The largest measured depth was 4.9 m in the middle part of section S5 which was located around the middle portion of the sharp bend.

Within each of the surveyed regions used to generate data at a section, the collected data were spatially interpolated using the kriging method and the averages of the interpolated data fields are presented in Table 3. The measured tracer concentration, streamwise velocity and depth at the sharp bend were presented at the three sections S4–S6 in Fig. 4 and Fig. A1. However, the average values of measured parameters were calculated for the entire data set collected along the bend and presented as sub-reach S4–S6 in Table 3.

3.3 Shear velocity and roughness

Shear velocity $u_\*\,$ is one of the most important parameters for describing the mixing process. The shear velocity is a measure of the bed shear stress, and is indicative of the near-bed velocity and fluid shear. In meandering rivers, a higher shear velocity is generally observed in the regions with higher bed roughness ($k_s$), turbulence, and secondary circulations.

As described in the Post Processing section, in this study the shear velocity and the bed roughness were calculated from the slope and intercept of a fitted log-law velocity profile (Eq. 2). A filtering process was then implemented and the filtered data were interpolated using the kriging method. The sub-reach averages of interpolated values are presented in Table 3. The estimated shear velocity values of surveyed sub-reaches generally show a consistent trend especially in the neighbouring sub-reaches. The maximum and minimum estimated shear velocities were 0.09 and 0.04 m s⁻¹, respectively.

Estimating the shear velocity from the slope of the fitted log-law has been used successfully in various studies of fully developed two-dimensional flows (Kironoto &
Table 3 Summary of reach-averaged data from surveyed sub-reaches

<table>
<thead>
<tr>
<th>Sub-reach</th>
<th>Mean velocity ((m \ s^{-1}))</th>
<th>Width (m)</th>
<th>Mean depth (m)</th>
<th>Mean shear velocity ((m \ s^{-1}))</th>
<th>Bed roughness (m)</th>
<th>Total observation</th>
<th>Percentage of good observation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.69</td>
<td>133</td>
<td>1.3</td>
<td>0.08</td>
<td>0.21</td>
<td>1516</td>
<td>44</td>
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Graf, 1994). However, in meandering channels, the shear velocity is also affected by the secondary circulation generated at bends (Jamieson, Rennie, & Townsend, 2013; Jamieson, Ruta, Rennie, & Townsend, 2013; Kashyap et al., 2012). These secondary circulations prevent the development of a logarithmic velocity profile (Blanckaert & De Vriend, 2003). Therefore, the estimation of shear velocity and bed roughness on the basis of a log-law fit may not be accurate for the sub-reaches located within the bend region. In the current study, sub-reaches S4–S6 are located along a sharp bend. The estimated roughness for these sub-reaches is larger than other sub-reaches. However, the estimated shear velocity in this region is lower than other surveyed sub-reaches. This can be attributed to the measuring time which was carried out during the low flow season in the river when shear tends to be low in bends (cf. velocity reversal hypothesis, Keller, 1971; MacVicar, Rennie, & Roy, 2010).

3.4 Sharp bend

Due to the importance of bends in the mixing process within meandering rivers, interpolated spatial distributions of shear velocity, depth, and velocity are mapped (Figs. 6–8) for the sharp bend located 6.5 km downstream of the outfall (see Fig. 2, sections S4–S6). In recognition of streamwise variation along a sharp bend, the collected data were interpolated by kriging three sub-sets corresponding to the upstream, central, and downstream portions of the bend.

The spatial map of depth-averaged velocity (Fig. 6) shows two regions of high velocity. The first one is located closer to the outer bank of the bend. It is formed within the upstream portion of the sharp bend and extends till the bend exit. The second region, which has a larger maximum velocity (1.5 m s\(^{-1}\)), is located closer to the inner bank just upstream of the bend apex.

This second region moves towards the outer bank along the central portion of the bend and combines with the first region by the end of the central portion of the bend (cf. Kashyap et al., 2012). The higher velocity region stays close to the outer bank in the downstream portion of the bend.

Figure 7 illustrates the spatial distribution of the flow depth along the bend. The deepest portion of the bend is observed where the thalweg reaches the outer bank just downstream of the
Figure 7 Spatial distribution of depth (m) along the sharp bend. Flow is from bottom right to top. The survey track is shown as a zig-zag pattern. Underlying satellite image obtained from Google Earth. Copyright 2014 Google.

In the upstream portion of the bend, the thalweg is close to the inner bank of the bend. The thalweg moves towards the outer bank in the middle portion of the bend and again moves back towards the channel centre in the downstream portion of the bend. The observed bathymetry pattern is typical of sharp meander bends (Jamieson, Rennie, et al., 2013, Jamieson, Ruta, et al., 2013).

The higher shear velocity region is observed close to the outer bank, in the upstream and central portions of the bend (Fig. 8). This region of high shear velocity appears to correspond to local flow acceleration immediately upstream of a near-bank sediment deposit on the outer bank upstream of the bend apex. The high shear velocity region at the outer bank diminishes along the bend and moves towards the inner bank in the downstream portion of the bend. This is somewhat contrary to previous laboratory and numerical observations of bed shear stress distribution in channel bends, which suggest the zone of high bed shear stress within a bend transitions from the inner to the outer bank (Blanckaert, 2011; Kashyap et al., 2012). However, it should be recognized that the effect of the secondary flow generated at the sharp bend has not been considered in estimating the shear velocity, as the estimate is based on the assumption of a fully developed logarithmic velocity profile. Furthermore, the measurements were conducted during low flow conditions, which may have altered the observed spatial distribution of bed shear stress.

3.5 Cross section width

The effect of cross section width on transverse mixing coefficient was first introduced by Lau & Krishnappan (1981). Since then this parameter has been used in most of the methods developed for estimating transverse mixing coefficient in meandering rivers. In the present study, section surveys were limited to navigable portions of the channel. The presented value for cross section width in Table 3 is the value that produces the same discharge as measured by aDep from the measured flow depth and depth-averaged velocity. Therefore, the presented values for river width are less accurate than the measured values for depth and depth-averaged velocity. Nevertheless, the presented values in Table 3 can be used to show the variation of cross section width in different sub-reaches along the surveyed reach.

4 Discussion

The coherence between the presented cross-sectional distributions of tracer concentration (Fig. 4) suggests that the collected tracer data can be used to investigate the mixing pattern in the North Saskatchewan River. The tracer was injected for 13 h and the approximate length of the tracer plume was expected to be approximately 25 km. As the rhodamine was injected from the right bank into the river, it was highly concentrated in the right bank side of the river and the measured concentration on the left...
bank side was zero for the initial sections. The tracer reached the left bank at section S5, located 6.5 km downstream the outfall. At sections S4–S6, a shift is observed in the centroid of tracer distribution towards the centre of the channel. This lateral translation of the locus of the tracer concentration is essential for the transverse mixing process, and is attributed to two mechanisms: (1) the transverse velocity as a result of transverse and longitudinal variation of depth and velocity at the sharp bend (Blankaert, 2011; Kashyap et al., 2012) and (2) differential advection in the channel centre versus near the channel banks.

As flow enters a meander bend the inertia of the fluid causes it to advect towards the outer bank. In very sharp bends this can lead to flow separation at the inner wall, but even in more moderate bends without flow separation, a shear layer can be observed between low speed fluid near the inner wall and the high velocity core advecting to the outer wall (Constantinescu, Kashyap, Tokay, Rennie, & Townsend, 2013). Advection to the outer wall leads to superelevation of the water surface along the outer bank, which sets up a pressure gradient that drives the formation of secondary circulation cells, with flow directed towards the inner wall near the bed and towards the outer wall near the water surface. The secondary circulation dramatically enhances transverse mixing. Importantly, the advection of the high velocity core towards the outer wall encourages transverse dispersion towards the outer wall. This was observed in the present study, as seen in S4–S6 in Fig. 6.

The shift along the reach in locus of tracer concentration towards the channel centre can also be attributed to the difference in advection speed between the channel centre versus the edges of the channel. This was important because the tracer was released for 13 h to form a tracer slug as opposed to a continuous release, thus steady state was not achieved at the leading and trailing edges of the plume. Due to the higher flow velocity in the deeper part of the section (Dietrich & Smith, 1983), the tracer advected faster in the thalweg which was located in the middle of the channel for most of the surveyed sections in this study. This influenced the observed transverse distributions of tracer concentration at individual sections, depending upon when they were surveyed with respect to the advection time of the plume. In sections such as S7, S8, S10, S11, S12, and S14, which were located in front of the tracer plume at the time of their survey, a higher tracer concentration was observed in the middle of the section (e.g. Fig. 4g and 4h). This was determined by comparing velocities measured near the bank and in the centre of the channel. Between the outfall and S8, the average measured flow velocities near the right bank and the middle of the section were 0.38 and 0.7 m s\(^{-1}\), respectively. Considering the period between starting the injection and the measurement time for S7 and S8, it is concluded that the tracer should have reached the middle of these sections but not the right bank. In contrast, in sections S15–S17, which were located in the rear part of the plume at the time of their survey, lower tracer concentration was observed in the middle part of the section (Fig. 5). This influence of differential advection speed across the section has been confirmed by numerical simulation results (Pilechi et al., 2014).

As mentioned in Section 1, the main goal of field studies is to provide data sets which can be used to estimate the mixing coefficients. Both analytical and numerical approaches have been used in the literature for estimating the mixing coefficients in the meandering rivers. The numerical methods allow for considering the effect of discharge variation in the river as well as unsteady tracer injection. The provided tracer data in this study were used in a developed numerical model by Pilechi et al. (2014) in a stream-tube orthogonal curvilinear coordinate system. The transverse mixing coefficient was estimated in different surveyed sub-reaches. The numerical model results were also compared with the estimated transverse mixing coefficient from the standard and general method of moments. Due to the high range of discharge variation, the influence of the varying discharge on transverse mixing coefficient was also studied by comparing the numerical model results in steady and unsteady flow conditions. The unsteady discharge condition changed the estimated averaged transverse mixing coefficient by 10%. The highest transverse mixing coefficient was found in the sharp bend, which was attributed to the high sinuosity and the effect of secondary circulation on the mixing process. The higher transverse mixing coefficients were generally found in the sub-reaches with high shear velocity. From the transverse mixing coefficients estimated in different sub-reaches, an average transverse mixing coefficient of 0.037 m\(^2\) s\(^{-1}\) was calculated for the entire surveyed reach of the North Saskatchewan River. Using the estimated shear velocity, depth, and depth-averaged velocity in this study, the average transverse mixing coefficient of 0.0423 m\(^2\) s\(^{-1}\) was calculated using the Jeon et al. (2007) formula, which was in good agreement with the estimated value from the numerical approach.

Comparing the presented averaged values for velocity, depth, and width in Table 3, a consistent trend is observed between variation of average velocity, depth, and river section width in different sub-reaches. The average streamwise velocities measured at sub-reaches surveyed on 26 and 28 October were 0.66 and 0.68 m s\(^{-1}\), respectively, which are higher than the average velocity in the sub-reaches surveyed on 27 October (0.5 m s\(^{-1}\)). The higher velocity for 26 October, in spite of lower average discharge on that day, is attributed to a lower average cross section area for the sections surveyed on 26 October.

The highest average depth in a sub-reach (2.4 m) was measured at the sharp bend located 6.5 km downstream of the outfall (S4–S6). This is attributed to induced secondary flow creating high average shear stress in the sharp bend at channel forming flow, although our measurements at low flow did not yield highest shear velocity in this sub-reach. The second largest depth (2.3 m) was observed at S10 downstream of an island located in the middle of the channel. The higher averaged depth in this sub-reach is attributed to higher shear stress in the anabranch confluence downstream of the island. In the other surveyed sub-reaches, the averaged depth varied between 1 and 1.8 m.
The high rhodamine concentration difference between left bank side and right bank side reduced from 100 ppb at the outfall to 0.27 ppb at S17. However, this value is still 46% of the average rhodamine concentration at the 83 km section, which means that the full mixing condition was not achieved. The 64% mixing at section S17 located about 83 km downstream of the outfall suggests a full mixing length of 130 km for the effluent discharged from Capital Region WWTP in the North Saskatchewan River. This is also in agreement with Pilechi, Rennie, Mohammadian, Zhu, & Delatolla (2012), which inferred 123 km as the full mixing length of the discharged effluent from Goldbar WWTP into the North Saskatchewan River based on measurements up to 110 km downstream of the outfall. Therefore, \( L_z = 130 \text{ km} \) is inferred as the maximum full mixing length for the surface bank outfall in the North Saskatchewan River at low flow. From the average velocity, width, and roughness data in Table 3, the full mixing length of 66 km as well as cross distance of 3.7 km were calculated from the proposed formula by Rutherford (1994). Although the observed full mixing length falls within the suggested range by Rutherford (1994) for a point source near the bank, it is much higher than the calculated value from the proposed formula. This discrepancy is attributed to the simplifying assumption in the proposed formula which is based on a monotonic decrease in concentration gradient in relation to increased distance from the source. The observed cross distance of 6.5 km is also higher than the calculated value from the proposed by Rutherford’s (1994) formula (3.7 km). Both Rutherford’s cross distance and full mixing length formulae were underpredicted by a factor of approximately two.

The two regions of high streamwise velocity observed in the upstream portion of the sharp bend (Fig. 6) are attributed to the outer and inner bank cells of secondary flow (Blanckaert, 2011). Secondary flows are generally observed in meandering river bends and act as the driving force of the velocity excess (Blanckaert, 2011). The formation of the secondary flow is a function of the river plan form. Secondary flow causes transverse shear velocity and leads to the transverse bed slope with a higher flow depth in the outward direction of the bend (Fig. 7). The inner bank and outer bank regions of high stream wise velocity were also observed in Kashyap et al. (2012). The ratio of channel width to depth in the current study (61) is much higher than in Kashyap et al.’s (2012) test cases (5, 6.5). Regardless, a similarity is observed between the general spatial distribution patterns of stream wise velocity and depth in the current study and Kashyap et al. (2012).

The higher shear velocity at the outer bank side of the upstream portion of the bend may be due to the sediment deposition on the outer bank, or the effect of secondary flow on development of the logarithmic profile of velocity. It should be noted, as the measurements were carried out in low flow season (not channel forming flow), it might not be expected to see the same spatial pattern for shear as observed in lab studies.

5 Summary and conclusions

A field campaign was performed to study the mixing pattern over an 83 km reach of the North Saskatchewan river. Rhodamine WT was injected as a tracer of the wastewater effluent from the outfall of Capital Region WWTP. The tracer concentration was tracked with a new measurement technique by moving a boat across and along the river with an in situ fluorometer. The real-time in situ measurements allowed for much higher sampling intensity than conventional water sampling, and also facilitated locating the plume while in the field. The tracer data were integrated with GPS data and provided a spatial distribution of tracer across the river. The maximum measured rhodamine concentration was reduced from 100 ppb at close to the outfall to 0.83 ppb at 83 km downstream of the outfall. At the last surveyed section, a rhodamine concentration difference of 46% was observed across the section, thus the full mixing condition was not achieved by 83 km from the outfall. A full mixing length of 130 km was inferred for a surface bank outfall in the North Saskatchewan River at the observed low flow stage. The employed technique was found effective for investigating the mixing behaviour as well as full mixing length of meandering rivers by providing reliable and extensive data sets.

During the survey, the depth-averaged velocity and water depth were also measured with an aDcp. The average depth and depth-averaged velocity along the river were 1.36 m and 0.6 m s\(^{-1}\), respectively. Greater depth-averaged velocities were observed in the deeper parts of each section. This was attributed to topographic steering which causes higher depth-averaged velocity along the thalweg stream line (Dietrich & Smith, 1983). The shear velocity and roughness were also estimated from the slope and intercept of best fitted log-law on the collected depth-averaged velocity profiles.

The observed cross distance of 6.5 km from the outfall corresponded to the location of a sharp bend, thus confirming the importance of river meandering for the transverse mixing process. Due to the complex structure of flow in sharp bends as well as their importance in the mixing process, the spatial distributions of depth-averaged velocity, depth, and shear velocity were presented at this sharp bend. The maps of stream wise velocity and depth showed good agreement with previous studies on sharp bends. The spatial distribution of shear velocity in the bend did not show good agreement with similar previous studies.

Acknowledgements

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Appendix

Figure A1  Measured depth-averaged velocity (dashed line) and depth (solid line) for surveyed sections S1–S17. Transverse distance normalized by the cross section width.
Figure A1 Continued

**Notation**

- $\beta$ = empirical coefficient ($-$)
- $\kappa = 0.41$, von Kármán constant ($-$)
- $v = \text{river cross-sectional mean velocity } (\text{m s}^{-1})$
- $b = \text{river width (m)}$
- $E_z = \text{transverse mixing coefficient } (\text{m}^2\text{s}^{-1})$
- $H = \text{mean channel depth (m)}$
- $IQR = Q_3 - Q_1$, interquartile range ($\text{m s}^{-1}$)
- $k_s = \text{roughness (m)}$
- $L = \text{lower and upper limits of the confidence range} (\text{m})$
- $L_z = \text{full mixing length (m)}$
- $L_c = \text{distance downstream of the source where the tracer reaches the opposite bank (m)}$
- $n = \text{number of points in the velocity profile and the regression residuals}$
- $Obs = \text{observation value of shear velocity } (\text{m s}^{-1})$
- $P_m = \text{ratio of minimum to maximum concentration } (\text{m s}^{-1})$
- $Q_1 = \text{first quartiles (m s}^{-1})$
- $Q_3 = \text{third quartiles (m s}^{-1})$
- $s = \text{standard error (m s}^{-1})$
- $u = \text{velocity in the bin at height } z \text{ (m)}$
- $U = \text{upper limits of the confidence range } (\text{m s}^{-1})$
- $u^* = \text{shear velocity } (\text{m s}^{-1})$
- $U^* = \text{average shear velocity } (\text{m s}^{-1})$
- $t_{n/2,n-1} = \text{standard random variable}$

**References**


