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Abstract

Sediment erosion and deposition rates are two of the most important factors that influence fluvial geomorphology. Several experimental devices have been constructed to estimate cohesive sediment erosion rate. However, estimated erosion rates may not be reliable for large rivers due to limited soil sampling and a high dependency of cohesive sediment behaviour on several physical, mechanical, and electrochemical properties of the sediment and eroding fluid. A new methodology has been developed to estimate the erosion and deposition rate of wide rivers using in-situ measurements. To test this methodology, an acoustic Doppler current profiler (ADCP) was used to collect bathymetry and velocity profiles over a study area along the Red River in Winnipeg, Canada. Sediment concentration profiles along an 8.5 km reach of the river were measured several times under different flow conditions. Finally, an advection-dispersion equation was numerically solved using measured and calculated streamwise dispersion coefficients, flow and channel characteristics to calculate net erosion and deposition over the study area. Moreover, an exponential relationship was obtained between the river discharge and longitudinal dispersion coefficient for the Red River.

Keywords: cohesive sediment transport; ADCP; erosion rate; deposition rate; MIKE 21

Introduction

The field of cohesive sediment transport has not yet been fully understood, in large part due to the complex behavior of cohesive sediment. The presence of at least 10% clay in a soil structure is enough to control the behavior of the soil ([Debnath and Chaudhuri 2010](#)). Several researchers have conducted experimental studies to find a relationship between critical shear stress, erosion rate, and deposition rate with different mechanical, physical, electro-chemical, and biological soil properties ([Winterwerp et al. 1990](#); [Berkhovskikh et al. 1991](#); [Huang et al. 2006](#); [Meng et al. 2012](#); [Kimiaghalam et al. 2015a](#)). Many in-situ and laboratory devices have been constructed for measuring critical shear stress and erosion rate of cohesive soil. However, it still remains to be seen how reliable these devices are for natural rivers.

Most erosion measurement devices are only able to measure the erosion rate, but in low gradient rivers, deposition can play an important role in the geomorphological changes along the river. Therefore, it is essential to develop a new methodology for estimating both the erosion and deposition rate. Generally, three types of erosion measurement devices have been constructed by researchers: piston-type, rotating-type, and submerged jet-type.

SEDFlume ([McNeil et al. 1996](#)), ASSET ([Roberts et al. 1998](#)), EFA ([Briudad et al. 2001](#)), SERF ([Crowley et al. 2012](#)), EMD ([Jianfar 2014](#)) are examples of the piston-type erosion measurement devices. Usually, these devices are used in laboratories for estimating erosion rate under different flow rates. There are also several similar portable devices that can be used in situ like ISEF ([Houwing and Van Rijn 1997](#)). Generally, piston-type devices contain a circular or rectangular flume; a sampling tube to push a soil sample into the flow; and a pump to regulate flow in the flume. The general testing procedure for these kinds of erosion measurement devices

is to push the soil sample a small distance into the flow or keep it flush with the flume bottom and measure how much erosion happens over time, under a particular applied shear stress. After obtaining several measurements, with the assumption of an exponential or power function relating erosion rate and applied shear stress, critical shear stress and erosion rate can be estimated (Partheniades 1965; Parchure and Mehta 1985; Maa et al. 1998). Figure (1a) shows a typical piston-type erosion measurement device and experimental setup. Soil samples are taken using ASTM standard Shelby tubes or boxes to obtain relatively undisturbed samples for experiments. Undisturbed samples are essential for such studies since cohesive soil behavior is highly impacted by changes in natural conditions. Soil conditions may also be altered due to natural subaerial processes like seasonal freezing-thawing and wetting-drying. Several criticisms exist for the application of these devices. The first criticism is related to the soil sampling procedure and the number of soil samples that are used for predicting riverbank or riverbed geomorphologic changes. Using standard tubes to take samples does not entirely avoid the disturbance of soil, but it does help to reduce the soil disturbance. In addition, many precautions need to be taken for transferring soil samples into laboratories such as properly sealing samples to maintain the natural water content. Moreover, transferring a soil sample from a Shelby tube to a testing tube has the potential to create another source of soil sample disturbance. Therefore, the sampling procedure can cause uncertainty in the final results. In addition, acquiring minimally-disturbed soil samples from a riverbed requires more effort and has higher costs than sampling from riverbanks. The presence of vegetation can greatly influence the performance of the test, since it is difficult to quantify the amount of vegetation in the soil structure and in the study area. The assumption of a homogeneous soil distribution throughout the study area may not be reasonable, and has the potential to introduce significant uncertainty if an insufficient number of

sampling locations is used. Uncertainty in measuring erosion rate using experimental results from small soil samples may also be an issue. Common irregular erosion patterns at the surface of the sample may result in considerable uncertainty in estimating the applied shear stress over a soil sample due to the roughness variation over the sample surface (Crowley et al. 2014). Moreover, using natural river water with the same chemical and physical properties can result in different erosion rates than using regular tap water in a laboratory.

Rotating-type erosion measurement devices were developed for measuring erosion rates on stiff cohesive sediment and rocks (Henderson 1999; Kerr 2001; Sheppard et al. 2005; Bloomquist et al. 2012). These kinds of devices are comprised of a soil sample that is placed inside of a rotating cylinder with water filling the space between the inner cylinder wall and the soil sample (Fig. 1b). The cylinder rotates and causes an applied shear stress on the surface of the soil sample. The applied torque is measured with and converted to applied shear stress with a simple calculation. However, these devices have limitations that restrict their applicability in some cases. They can be used only for self-supporting samples like stiff clay and rocks; however, surface fluvial erosion may often occur with very soft sediment and unconfined soil. Moreover, like the piston-type devices, soil sampling procedures can cause uncertainty in the estimation of erosion rate. A distinct disadvantage of using rotating devices is the curved shape of the devices which results in a different shear stress distribution over the sample than the natural process observed in channels. Also, secondary flow is generated in these devices that can accelerate the erosion rate in an unrealistic fashion (Graham et al. 1992).

The submerged jet-type device was developed and used by several researchers (Rouse 1940; Moore and Masch 1962; Hanson 1991; Mazurek et al. 2001; Hanson and Cook 2004). This device can be used to perform an in-situ erosion rate test on an exposed riverbank and several

researchers suggested that these kinds of erosion measurement devices are more reliable for measuring in-situ local scour properties than the other devices such as in-situ flume erosion measurement devices ([Charonko 2010](#); [Weidner 2012](#)). However, it cannot be used in-situ for an unexposed surface like a riverbed, thereby requiring an undisturbed soil sample to be taken for testing ([ASTM D5852, 2011](#)). Figure (1c) shows a typical jet device. A submerged jet erodes the soil sample surface constantly for a certain duration, after which the amount of erosion underneath of the jet is measured and the process is repeated for different applied shear stresses. These methods have the limitation of location and sampling scale while studying long reaches and wide channels.

Recent development in the field of acoustic Doppler in-situ measurement techniques has led to the use of acoustic Doppler velocimeters (ADV) for estimating cohesive sediment transport characteristics. [Andersen et al. \(2007\)](#) suggested a method for in-situ estimation of erosion and deposition thresholds and local erosion rate in coastal areas using two ADVs. Using long and short term ADV data, applied shear stress and local bed elevation changes were calculated under different flow conditions. [Fugate and Friedrichs \(2002\)](#) used an ADV to calculate cohesive sediment settling velocity based on the expression of turbulent diffusion that leads to the following equation for estimating particle fall velocity ([Maa and Kwon 2007](#)):

$$w_s C = \langle w' C' \rangle \quad (1)$$

where w_s is the fall velocity, $\langle \quad \rangle$ represents time-average, w' is the vertical velocity fluctuation, and $C = \langle C' \rangle$ is the time average suspended sediment concentration. The ADV was used to calculate w' from its velocity measurements and C' from the acoustic scatter signal strength. Moreover, several studies have been conducted to calibrate available numerical models such as

MIKE 21C using ADCP measurements and measured sediment flux to assess morphodynamic changes in rivers (Guerrero et al. 2013a; Guerrero et al. 2013b; Guerrero et al. 2015).

This paper outlines a methodology to estimate the average erosion and deposition rate in a wide river based on in-situ ADCP and sediment concentration measurements combined with the numerical solution of the cohesive sediment transport governing equation. The methodology attempts to minimize the uncertainties found in the other erosion measurement devices since it does not require the acquisition of undisturbed soil samples, and implicitly incorporates the effects of natural conditions such as seasonal freeze-thaw, sediment desiccation and vegetation, and sediment property heterogeneity. The methodology gives a realistic estimation of both erosion and deposition over the entire wetted perimeter of a natural channel which is helpful for research and practical purposes.

Methodology

Governing equation

The main governing cohesive sediment transport equation is the key component to this study and can be written as a 2-D advection-dispersion equation (Huang et al. 2006):

$$\frac{\partial(hc_i)}{\partial t} + \frac{\partial(huc_i)}{\partial x} + \frac{\partial(hvc_i)}{\partial y} = \frac{\partial}{\partial x} \left(D_x h \frac{\partial c_i}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y h \frac{\partial c_i}{\partial y} \right) + S \quad (2)$$

where h [m] is the water depth, c_i [m^3/m^3] is the depth-averaged volumetric sediment concentration, t [s] is time, u and v [m/s] are the depth-averaged velocity component in the streamwise and spanwise directions, respectively, D_x and D_y [m^2/s] are the dispersion coefficients in the streamwise and spanwise directions, respectively, and S [m/s] is the source (erosion) or sink (deposition) terms. Erosion increases sediment concentration in a river and

detached material from the bed or bank will be transported downstream and simultaneously undergo a mixing process. Longitudinal dispersion is the main mechanism of transport (Shen, et al. 2010) and the transverse dispersion coefficient becomes negligible. The sink and source terms can be calculated from the numerical solution of Eq. 2 if a calibrated hydrodynamic model is available and if D_x is also calculated.

Estimation of hydrodynamic parameters

Flow depth, stream wise and spanwise velocities, and dispersion coefficients are essential for the numerical solution of Eq. 2. To facilitate the calculation of these parameters over a range of hydraulic conditions it is convenient to use a calibrated hydrodynamic model. Many options are available for this task; however, for this study the MIKE 21 Flow Model HD was used since it had already been created for the case study location. For developing a good hydrodynamic model, three measurements are required: 1) study area bathymetry; 2) upstream and downstream boundary water surface elevations; 3) flow rate. Utilizing these measurements over time, the model can be calibrated by adjusting the Manning number. The complete methodology for modeling and field measurements will be discussed in the case study section.

Longitudinal dispersion coefficient is another important hydrodynamic parameter that is essential for the solution of the advection-dispersion equation. Several experimental equations to estimate this coefficient have been suggested by numerous researchers (Fischer et al. 1979; Seo and Cheong 1998; Deng et al. 2001; Kashefipour and Falconer 2002). Most of these studies are only valid for their specific study area and flow conditions, therefore, application of these experimental equations can result in high uncertainty for different locations. The dispersion coefficient is often estimated from tracer studies on small rivers. However, tracer studies can be costly and time consuming for large rivers (Shen, et al. 2010). Since hydrodynamic modeling

and measurements are an essential part of fluvial geomorphology studies, the dispersion coefficient can be estimated based on the theory of turbulent shear flow (Fischer et al. 1979):

$$D_x = -\frac{1}{A} \int_0^W u'(y) h(y) \int_0^y \frac{1}{D_y h(y)} \int_0^y u'(y) h(y) dy dy dy \quad (3)$$

where A [m²] is the cross sectional area, W [m] is the cross section top width, and $u'(y) = u(y) - U$; where $u(y)$ [m/s] is the depth-averaged streamwise velocity and U [m/s] is the cross sectional streamwise average velocity. The spanwise mixing coefficient can be estimated by (Rutherford 1994):

$$D_y = \theta u_* H \quad (4)$$

where H [m] is the cross section average depth and u_* [m/s] is the average frictional velocity which can be calculated as follows:

$$u_* = \sqrt{g R S_f} \quad (5)$$

Where g [m²/s] is the gravitational acceleration, R [m] is the hydraulic radius, and S_f [-] is the slope of the energy grade line. The coefficient θ is calculated using following equation (Deng et al. 2001):

$$\theta = 0.145 + \frac{1}{3520} \left(\frac{U}{u_*} \right) \left(\frac{W}{H} \right)^{1.38} \quad (6)$$

The turbulent shear flow method is based on the assumption of a well-mixed flow and that the river width to the water depth ratio exceeds 10 (Fischer et al. 1975). Therefore, this method can be used only for wide rivers. Acoustic Doppler current profilers (ADCP) can be used for collecting channel bathymetry and water velocity data which are useful for developing hydrodynamic models and for determining D_x based on Eq. 3. Since the ADCP can obtain

measurements at a high spanwise resolution, the integrals in Eq. 3 can accurately be replaced by summing the relevant measured variables. Carr and Rehmann (2007) and Shen et al. (2010) showed that using turbulent shear flow theory and ADCP data can improve D_x calculation accuracy and reduces the cost of the tracer studies, in particular for wide rivers.

Estimation of erosion and deposition rate

The advection-dispersion equation can be solved using calculated hydrodynamic characteristics and dispersion coefficients if water sediment concentration profile measurements available within the study area. In this study, the MIKE 21 FM AD model was paired with the MIKE 21 FM HD model, and therefore, hydrodynamic characteristics of the calibrated model were used to solve Eq. 2 with the estimation of D_x and D_y from the previous section.

For a specific discharge, the average cross section sediment concentration can be measured between the upstream and downstream boundaries by sampling the water at particular intervals and depths. To estimate the erosion and deposition rate, the study reach can divided into small subareas. For each subarea average cross sectional sediment concentration can be measured. The measurements must be done in a stepwise fashion from upstream to downstream with respect to the flow velocity and sediment travel time.

The advection-dispersion model should be calibrated stepwise by adding sinks and sources in each subarea from upstream to downstream in order to obtain similar simulated concentrations to those that were measured. The terms sink and source are the erosion or deposition rate from each subarea, respectively, which are a function of flow rate, applied shear stresses, river bed and bank soil critical shear stresses and properties, and natural water properties through the river. This method gives a realistic estimation of the erosion and

deposition over an entire study area with consideration to all of the natural conditions such as vegetation and subaerial processes.

Case study: Red River in Winnipeg, Canada

The proposed methodology was applied to an 8.5 km reach of the Red River in Winnipeg, Manitoba, Canada extending from the South Perimeter Bridge ($49^{\circ}47'04''$ N and $97^{\circ}08'7''$ W) to the Fort Garry Bridge ($49^{\circ}49'17''$ N and $97^{\circ}08'35''$ W) (Fig. 2). The mean annual river discharge is $176 \text{ m}^3/\text{s}$, with peak discharge on the order of $1300 \text{ m}^3/\text{s}$ with an average gradient of 4 m per 100 km. Water surface elevation typically varies between 223 m and 229 m annually. At mean flow conditions the average channel top width and depth are 130 m and 4 m, respectively, resulting in a width to depth ratio far greater than 10. Therefore, application of Eq. 3 was reasonable for this river. Total suspended sediment concentration varies between 10 mg/L and 1500 mg/L, during low flow (ice-covered conditions) and high flow conditions, respectively. The suspended sediment contains silt and clay with grain sizes ranging between 0.0011-0.0062 mm (Goharrokhi and Clark, 2015). The riverbank mostly contains silt and clay (Kimiagharam et al. 2013; Kimiagharam et al. 2015a; Kimiagharam et al. 2015b).

Several researchers have tried to experimentally quantify the fluvial erosion rate on the Red River. Jianfar (2014) and Fernando (2009) focused on evaluating the effect of fluvial erosion on riverbank stability. Kimiagharam et al. (2015b) conducted a comprehensive numerical and experimental study on fluvial geomorphology through the Red River and they used a piston-type erosion measurement device to test the erodibility of riverbank material under natural conditions and after several freeze-thaw cycles at different freezing temperatures. They concluded that the common process through the river is deposition and it is important to quantify

the deposition rate as well as erosion rate to predict future fluvial geomorphological changes along the river. Goharrokhi and Clark (2015) found that sediment distribution over the depth and cross section of the Red River in Winnipeg was relatively uniform. Blanchard et al. (2011) found that 99% of the total sediment load through the Red River approximately 300 km upstream of the present study reach was suspended load, and that the bed load contribution in total sediment in the Red River was negligible. Goharrokhi and Clark (2015) confirmed that these results were true for the Red River within the city of Winnipeg as well.

Field measurements

Field measurements were a critical part of the methodology, and included ADCP measurements to collect bathymetric data, velocity profiles over the study reach, and discharge, as well as water sampling to measure sediment concentration. Measuring high-resolution bathymetry and flow data were essential to develop an accurate numerical model since bathymetry was a primary input parameter in the hydrodynamic numerical model and velocity profiles were necessary to calculate the longitudinal dispersion coefficients.

A Sontek River Surveyor M9 ADCP was used to collect bathymetric data and flow characteristics in 2013 and 2015. This device was equipped with a RTK-GPS system with ± 3 cm horizontal resolution. To collect bathymetry data, the ADCP was mounted to a hydroboard and pulled from the boat at a speed of less than 1 m/s over the entire study area. The procedure was to combine stream wise profiles with spanwise transects spaced at approximately 12 m in the streamwise direction. For discharge and velocity profile measurements, the ADCP was pulled at a speed less than the mean current velocity. This procedure was repeated over these two years for different flow rates and cross sections to find a relation between flow rate and the longitudinal

dispersion coefficient.

Water samples were taken at 10 cross sections (L0-L9) between the upstream and downstream boundary spaced at approximately 1 km intervals on June 12, August 15, and October 10 in 2013, and May 27 and June 18 in 2015 (Fig. 2). These dates were selected based on the flow rates in the river to cover common discharges during low, average, and relatively high flow events. Figure 3 shows the sampling date conditions on 2013 and 2015 Red River hydrographs. The sampling procedure started from the upstream boundary and finished at the downstream boundary. Six water samples were taken from each cross section, close to the left and right bank and center of the river near from the surface and at depth. The sampling volume was 500 ml and ASTM standard D3977-97 ([ASTM 2013](#)) was used to measure the water sample sediment concentrations. Since the sediment concentration distribution was relatively uniform, the average of all water samples at each cross section was used in the numerical model.

Numerical modelling

The measured bathymetry was used to develop a hydrodynamic model using the MIKE 21 Flow Model. MIKE 21 FM HD is a 2-D numerical hydrodynamic model that solves the depth-averaged Navier Stokes equations. Using this model, essential flow parameters like flow depth, stream wise and spanwise velocities are calculated. the model domain was created using measured bathymetric data and a grid spacing of 20 m. Upstream discharge and downstream water surface elevation were used as the upstream and downstream boundary conditions. These data were obtained from a continuous Environment Canada gauge at the South Perimeter Bridge and a City of Winnipeg water surface elevation gauge at the Fort Garry Bridge. The initial water elevation was set as the average water surface elevation between these two boundaries, and a

sufficient model spin-up time was used. A Manning number of 0.025 was found through calibration to obtain the best fit between measured and simulated upstream water surface elevations. The model was validated for 4 years between 2010 and 2014 and produced $R^2 = 0.98$ (Kimiaghalam et al. 2015b).

An advection-dispersion (AD) model was paired with the HD model to simulate sediment concentration along the Red River. The model solves the general 2-D advection-dispersion equation (Eq. 2) that $S = Q_s(c_s - c)$; where Q_s [$\text{m}^3/\text{s}/\text{m}^2$] is the sink and source discharge, c_s [m^3/m^3] is the concentration of compound in the source and sink discharge, and c [m^3/m^3] is the compound concentration (DHI 2012). The computational grid was fixed at 20 m*20 m. Five separate models were developed based on the calibrated model to simulate sediment concentration on June 12, August 15, and October 10 in 2013, and May 27 and June 18 in 2015. The measured upstream and downstream concentrations (South Perimeter Bridge and Fort Garry Bridge) were the primary boundary conditions of the AD model and initial upstream concentration was considered as the initial condition. The dispersion coefficient for each was obtained based on the ADCP measurements and Eq. 3. Therefore, this parameter was considered as a known input and the AD module was calibrated based on adding sink and source parameters. Distributed sinks and sources were added starting from the upstream and ending at the downstream boundary to obtain the best fit between simulated and measured sediment concentration. Sinks or sources in the models were added at the downstream of each subarea (L0-L9 cross sections) that sediment concentrations were measured (Fig. 2). The sink and source discharge was assumed equal to 1 and the model was calibrated for c_s to obtain the best fit between measured and simulated concentration. Finally, the sink and source term (S) was calculated using the final c_s and c values.

Results

Red River flow rate and longitudinal dispersion coefficient relationship

Table 1 shows a summary of measured and calculated hydraulic characteristics of the Red River using the ADCP measurements. The values of U , W , and H were found directly from the ADCP measurements; U^* was calculated using Eq. 5; the average applied shear stress (τ_a) was calculated as $0.5\rho U^{*2}$ where ρ [kg/m^3] is the density of the water; and D_x was calculated using Eq. 3. These results covered a wide range of typical Red River flow rates over the 2 year study duration, and should therefore be representative of much of the hydraulic conditions that typically occur on the River. The first important finding from the study was that D_x generally increased with increasing river discharge, and this relationship (Eq. 7) can be well represented by an exponential function with $R^2 = 0.70$ (Fig. 4).

$$D_x = 16.6 e^{0.0018Q} \quad (7)$$

This is the first study on the Red River near this study reach to estimate D_x , and results will be useful for future environmental research. Moreover, these results are based on measurements at different locations on the river, therefore, it can be concluded that the fitted curve can be used to estimate D_x along the entire study reach.

Red River erosion and deposition pattern

Figures (5a-5e) show the final simulated and measured sediment concentration profiles along the study reach for each field test based on the adding all sinks and sources to produce the best fit to the measured data. There is a general decrease in sediment concentration in the downstream direction indicating that deposition is the dominant mode of sediment transport when looking at the entire reach. The variability within these profiles indicates that subareas

within the reach have varying sediment transport rates, including some areas that experience erosion rather than deposition. Figure (6) summarizes the sink and source quantities for each of the nine subareas. Positive values represent sources of sediment to the flow (ie. erosion) and negative values represent sinks from the flow (ie. deposition). Riverbank erodibility varied within the study reach for each flow rate which indicates that riverbank material had different erodibility properties such as critical shear stress and erosion rate. This conclusion confirms the previous measurements by several researchers such as [Kimiaghali et al. 2015b](#), [Jianfar \(2014\)](#), and [Fernando \(2009\)](#). On average, most subareas besides subareas 4 and 6 experienced deposition at the different flow rates, therefore, it can be concluded that subareas 4 and 6 contained material with lower critical shear stress or erosion rate than the other subareas. Moreover, the average net erosion and deposition rate was negative along the entire study reach; therefore, it can be concluded that deposition is the most common fluvial process in the Red River since the average river flow rate is $176 \text{ m}^3/\text{s}$ and these current measurements varied between 73 and $739 \text{ m}^3/\text{s}$. As previously mentioned, peak flows on the Red River in this area can be on the order of $1300 \text{ m}^3/\text{s}$; however, it was unfortunately not possible to access the river using a boat during these high flows due to safety concerns from floating debris. It is anticipated that erosion does in fact become the dominant mode of sediment transport during high flow events; however, these events are relatively short in duration. The proposed methodology would be equally applicable to quantify erosion rates on wide rivers during a time of active erosion throughout the entire reach, and would have been used in this case study if it had been possible.

According to Table (1) the average applied shear stress increased with increasing flow rate; however, according to the Fig. 7a the average deposition rate did not have a clearly defined relationship with flow rate, hence it can be concluded that the deposition rate was not a function

of applied shear stresses alone. Figure 7b shows the variation of the average deposition rate with the reach-averaged sediment concentration. It was initially hypothesized that the deposition rate would increase with decreasing applied shear stress, and this found to be true for 4 of the 5 simulations. The exception was October 10, which experienced the lowest applied shear stress but also the lowest deposition rate. It is hypothesized that the deposition rate was not only a function of applied shear stress, but also a function of available sediment concentration in the river. In other words, although the very low applied shear stress on October 10 had a high potential to promote sediment deposition, the very low suspended sediment concentration in the river limited the deposition rate. This intuitively suggests that at times when very low sediment concentrations and flow rates occur simultaneously, such as during the late fall and winter, the amount of sediment deposition and erosion would be essentially zero.

Conclusions

A methodology has been suggested using field measurements and numerical solution of cohesive sediment transport governing equation to have a reliable calculation of both erosion and deposition rate in wide rivers. The distinct advantage of this method is the direct in-situ measurement of the erosion and deposition rates over an entire study area and under natural conditions to minimize sampling and testing uncertainties. Reducing the distance between the sampling cross sections may improve the final resolution of the results; however, it may still not be a suitable replacement for direct measurement of a heterogeneous soil's susceptibility to local scour.

An equation has been suggested to estimate the longitudinal dispersion coefficient within the Red River which will be very useful for future sediment transport and environmental studies

on the Red River in Winnipeg. Also, estimation of the longitudinal dispersion coefficient is a very important parameter for estimating and managing the spread of contaminations through the river.

The present study gives a better understanding on the morphodynamics of the Red River in Winnipeg which is useful to combine with the current erosion studies to quantify geomorphological changes along the river. As results showed the deposition process was not only a function of the applied shear stress and many factors such as available sediment budget in the river can affect this process; However, study showed that there was not a strong relationship between the deposition rate, flow rate and sediment concentration over 2 year of the study. Therefore, other factors such as sediment and water electro-chemical properties may affect the process which further studies can answer these questions.

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Tables

Table 1: Red River flow characteristics and calculated longitudinal coefficient of dispersion

No.	Discharge (m ³ /s)	U (m/s)	W (m)	H (m)	U* (m/s)	τ_a (Pa)	D _x (m ² /s)
1	1231	1.09	180	6.75	0.063	3.97	173
2	1152	1.05	176	6.74	0.06	3.60	176
3	1143	1.07	178	5.7	0.062	3.84	141
4	1026	1.02	169	6.27	0.06	3.60	92
5	1021	1.05	179	5.9	0.061	3.72	93
6	1019	1.04	172	6.1	0.061	3.72	76
7	756	0.84	142	6.74	0.048	2.30	95
8	746	0.84	139	6.71	0.048	2.30	85
9	641	0.84	152	5.33	0.051	2.60	41
10	603	0.82	151	5.21	0.05	2.50	30
11	600	0.83	148	5.23	0.05	2.50	35
12	560	0.71	133	6.1	0.041	1.681	36
13	556	0.66	131	5.7	0.038	1.44	16
14	512	0.74	145	4.94	0.045	2.03	54
15	404	0.57	141	5.24	0.034	1.16	55
16	402	0.6	131	5.01	0.035	1.225	53
17	293	0.56	142	3.9	0.035	1.23	54
18	259	0.5	130	3.83	0.032	1.02	35
19	207	0.44	128	3.4	0.029	0.84	31
20	166	0.39	125	3.28	0.025	0.63	20
21	73	0.14	120	3.2	0.009	0.081	10

Figure captions

Fig. 1. Different types of erosion measurement devices: (a) piston-type erosion measurement device (b) rotating-type erosion measurement device (c) submerged jet-type erosion measurement device

Fig.2. Study reach through the Red River in Winnipeg, MB (coordinates are in UTM 14 coordinates). L0-L9 show the location of water sampling that distributed sinks and sources were added to the numerical model.

Fig.3. Water sampling dates on 2013 and 2015 Red River hydrographs.

Fig.4. Variation of longitudinal dispersion coefficient with Red River discharge

Fig.5. Variation of the measured and simulated average sediment concentration along the study reach and in different flow rates

Fig.6. Erosion and deposition rate on the Red River under different flow rates based on the results of the MIKE 21-FM AD model (+ is source (erosion) and – is sink (deposition))

Fig.7. (a) Effect of river discharge on the reach-averaged deposition rate, and (b) effect of reach-averaged sediment concentration on reach-averaged deposition rate

Fig. 1
96x77mm (300 x 300 DPI)

Fig. 2
105x68mm (300 x 300 DPI)

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