Using high-resolution bedload transport tracer measurements to investigate the characteristics of bedload transport over a large urban flood event

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Abstract. Channel morphological change is often evaluated by employing sediment transport models since field data during high magnitude low frequency events is rarely available. However, sediment transport rate estimates are heuristic at best to within 1 – 3 orders of magnitude. Mimico Creek is an urban gravel-bed channel in Southern Ontario, Canada that has undergone intensive event-based sediment transport sampling and inter-event bed material particle tracking over a three-year period. A HEC-RAS model was developed of the study reach and calibrated to a series of discharge events where in-situ bedload sampling occurred. Both step-wise discharge and unsteady flow simulations were evaluated to compare sediment transport rates for a range of transport models which included the *Meyer-Peter Müller* and the *Wilcock-Crowe*. Calibration curves were developed to estimate sediment discharge in Mimico Creek. The results of the calibrated model were used to calculate the mean travel distance of bed material using the expression for the volumetric rate of bed material transport. Results from the modelling exercise found mean travel distances were similar and in some cases larger than those observed from field measurements, considering both mobile and immobile particles.

1. Introduction

Many regions around the world have experienced an increased frequency of large magnitude flood events arising from changing climate patterns. Beyond the overt flooding issues which ensue, changes to river dynamics and rates of channel change can also be profoundly affected leading to compromised infrastructure and changes in aquatic habitat niches. The role of sediment transport in river dynamics is essential to evaluating the impacts of large magnitude events. Indeed the severity of an event is often the combined result of the flood wave and the ensuing sediment transport, particularly on the rising limb of the hydrograph [1]. A long-

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term analysis of a river's dynamics, is required to reasonably assess the quantity of sediment mobilized over the entire flow regime. However, there is a dearth of in-situ sediment transport data available for rivers around the world with even fewer studies obtaining observations during large magnitude events to authenticate the accuracy of event-based transport simulations [2].

The objective of this paper is to develop representative sediment transport models of a river reach where intensive in-situ event based and inter-event sediment transport investigations have been conducted (including a large magnitude storm event) and compare the results to pre- and post-event observations. Mean travel distances of bed material will be calculated using the volumetric rate expression of bed material transport and compared to bed material particle tracking measurements obtained before and after each event [3].

2. Study site

The study focuses on a 2.1 km reach of Mimico Creek (66.3 km^2) in southern Ontario, Canada. The majority of the watershed is urbanized with remaining areas zoned as industrial or transportation (airport). Immediately upstream of the study reach, the channel flows within a concrete trapezoidal channel (0.5 km) before transitioning into a gravel-bed channel at the beginning of the study reach. Through the study reach, floodplain connectivity is relatively consistent above the approximate 2-year return period which also supports a relatively narrow but contiguous riparian corridor. Within and upstream of the study reach, the urban landscape is dominated by manicured grasses contributing little sediment to the bed material supply other than bank erosion which has also been noted in other regional studies [e.g. 4, 5]. Complete bed material routing is observed throughout the concrete channel section.

On July 8th, 2013 a precipitation event occurred generating a flood exceeding the 100-year return period [6]. Pre and post erosion surveys along the 2.1 km reach combined with in-situ and inter-event sediment transport studies and a proximal hydrometric monitoring station afforded a unique opportunity to evaluate the performance of various sediment transport models applicable to gravel-bed rivers for flashy high magnitude events.

Fig. 1. Mimico Creek: study reach.

3. Methods

3.1. Sediment transport measurements

Bedload sampling, necessary to calibrate a HEC-RAS model was conducted during competent floods using the modified single width increment method with 0.076m Helley-Smith samplers over a two-year period between 2012 and 2013 [3, 7, 8]. Sampling of the coarse particle transport, necessary to compare the mean travel distances from the modelling results, were conducted using tracer particles embedded with RFID (radio-frequency identification) tags over a three-year period between 2011 and 2013 [3, 9, 10]. Representative results from the bed material surface and subsurface sampling are shown in Figure 2.

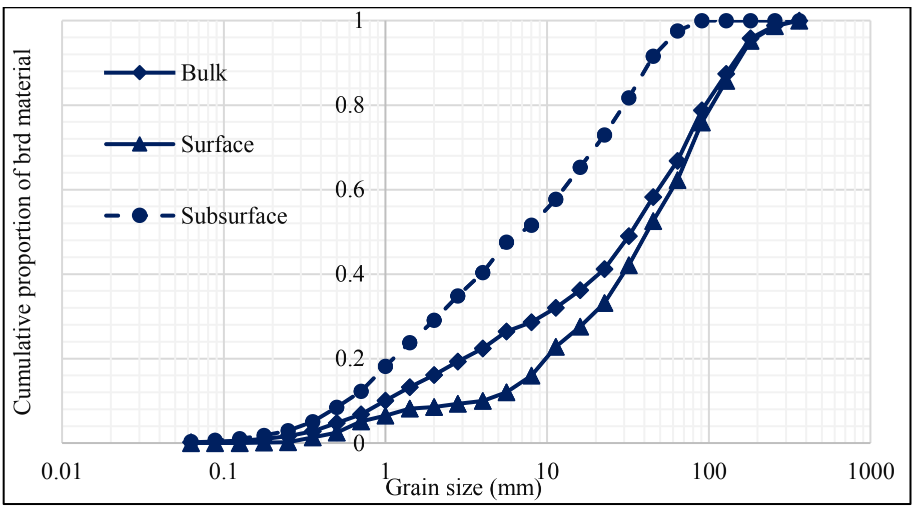

Fig. 2. Representative grain size distributions for Mimico Creek [3].

3.2. Sediment transport modelling

A HEC-RAS model was developed and calibrated to the study reach against a series of discharge events where in-situ bedload sampling occurred over a range of competent bed mobilizing events using the quasi-steady approximation [3]. This approximation was employed to account for the non-linearity in the sediment transport processes as slight changes in hydraulic parameters (e.g. roughness) are known to have large impacts on estimated sediment transport rates [11]. Both step-wise discharge and unsteady flow simulations were evaluated employing the *Meyer-Peter Müller* (M-PM) [12] and the *Wilcock and Crowe* (WC) [13] transport models.

Wilcock and Crowe is a surface-based transport model used for sand and gravel bed material mixtures [13]:

$$W_i^* = [(s-1)g\, q_{bi}]/(F_i\, u_o^3) \tag{1}$$

where W_i^* is the dimensionless transport rate of size fraction i, s is the ratio of sediment to water density, g is the gravity, q_{bi} is the volumetric transport rate per unit width of size i, F_i is the proportion of size i on the bed surface, u_o is the shear velocity ($u_o = [\tau/\rho]^{0.5}$, where τ is the bed shear stress and ρ is the water density).

This equation is based upon the theory that transport is primarily dependent on the material in direct contact with the flow. It accounts for the influence of the sand fraction on the mobility of the gravel fraction using a non-linear hiding function [14].

The M-PM equation is an empirical model of bed-load transport based upon experimental flume data with particles ranging from very fine sands to gravels [12]:

$$(k_r/k_r')^{3/2}\gamma RS = 0.047(\gamma_s-\gamma)d_m + 0.25(\gamma/g)^{1/3}[(\gamma_s-\gamma)/\gamma_s]^{2/3}g_s^{2/3} \tag{2}$$

where k_r is a roughness coefficient, k_r' is a roughness coefficient based on grains, γ is the unit weight of water, R is the hydraulic radius, S is the energy gradient, γ_s is the unit weight of the sediment, d_m is the median particle diameter, g is the acceleration of gravity and g_s is the unit sediment transport rate in weight/time/unit width. The M-PM equation development was mostly based upon relatively uniform gravel mixtures, making the transport equation largely applicable to streams with relatively unimodal grain size distributions. This equation tends to under predict transport of finer material [14]. For this reasons, the M-PM method was considered only for comparison purposes, using the grain size distribution of the bulk mixture.

Mean bed material travel distances from simulation results were determined using the general expression for the volumetric rate of bed material transport. Sediment transport is the product of the virtual rate of travel for individual grains over the active cross section of the bed as expressed by [15, 16]:

$$Q_b = V_b D_s W_s (1-P) \tag{3}$$

where Q_b is the volumetric bed material transport rate, P is the porosity and D_s and W_s are the average depth and width of the streambed active sediment layer respectively. V_b is the mean virtual travel rate of the bed material as defined by:

$$V_b = L/\Delta t \tag{4}$$

where L is the mean displacement of the grains over time Δt. Hence, correlation of Q_b with mean flow properties is central in achieving consistent correlations of V_b (or L) and D_s with mean flow conditions.

Bed material porosity was estimated using the porosity-particle size relation developed by Carling and Reader for poorly sorted, consolidated channel sediment of the form [17, 18] :

$$P = 0.4665\, D_m^{-0.21} - 0.0333 \tag{5}$$

where D_m is the median grain size (expressed in millimetres).

Excess stream power $(\omega-\omega_o)$ [15, 19] was used in order to estimate the time interval Δt when $\omega > \omega_o$. Specific stream power ω was defined using Bagnold's Equation [15, 20]:

$$\omega = \rho\, g\, d\, S\, v = \tau v \tag{6}$$

where ρg is the specific weight of water of mean flow depth, d, S is the longitudinal slope and v is the mean channel velocity. τ is the reach averaged uniform flow estimate of the shear stress on the channelbed.

Stream power at the threshold of bed material cessation (ω_o) was estimated using Bagnold's Equation [15, 19] of the form:

$$\omega_o \sim 290\, (D_m)^{1.5} \log(12d/D_m) \tag{7}$$

4. Results and Discussion

4.1. Calibration procedures

Fine-grain fractions were notably under estimated within the main channel of in-situ bedload sampling as floodplain storage of fine-grained sediments was observed in the field. Therefore, particles sizes used in evaluating transport models ranged between 0.5 mm (sizes less than this were observed in floodplain deposits) and 32 mm (limited by the orifice of the bedload sampler) [3, 21, 22, 23]. All simulations prescribed that fine-grained fractions contributing to bed material supply originated from bank erosion.

Figure 3 illustrates the results of the two-year (2012-2013) bedload field sampling campaign for flow events exceeding the cessation threshold of the bed material. A calibration curve was developed using the WC transport model (considering both step-wise discharge and unsteady flow simulations) to determine bed material transport rates as a function of reference shear stress (Figure 4) and calibrated to observed transport rates utilizing the same flood events. The calibration parameter (reference shear stress) in the HEC-RAS model was modified to achieve, for each discrete flood event, comparable results between field observed and predicted transport rates.

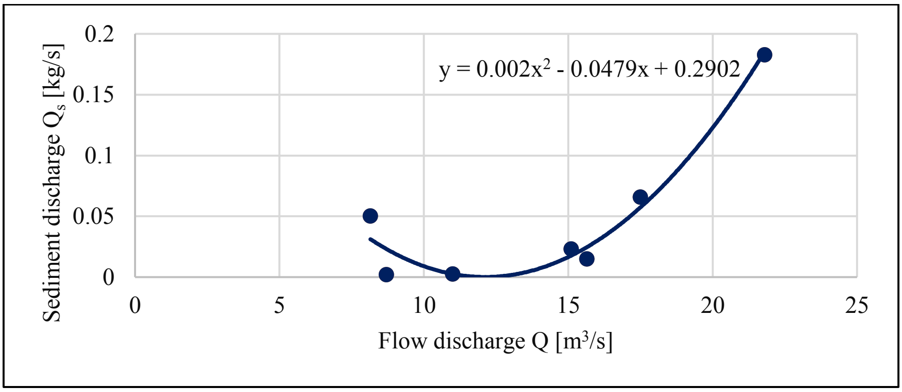

Fig. 3. Field measured bed material transport rates through Mimico Creek.

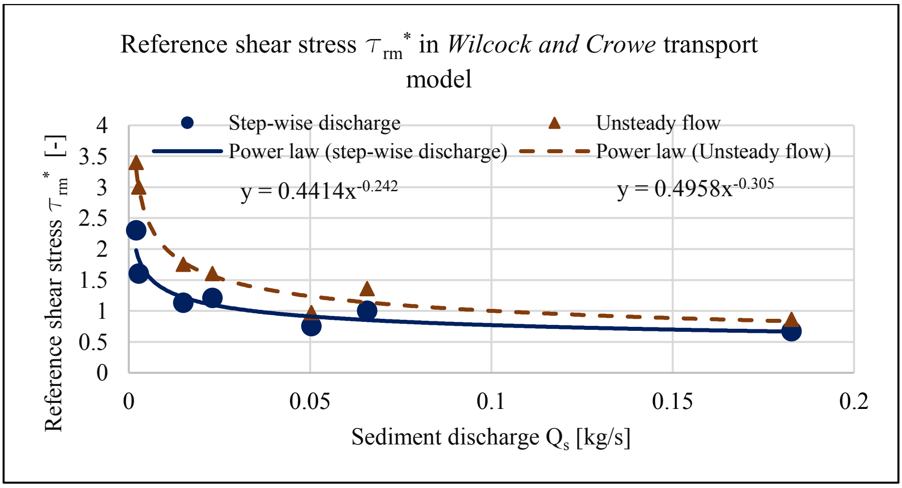

Fig. 4. Calibration curve for the *Wilcock and Crowe* transport model.

In the case of the higher magnitude flood events, the WC model was noted to more accurately portray the bulk in-situ sediment transport rates of field observations over the M-PM equation. Table 1 lists the comparison of discharge events between field observations and results of the WC model simulations. The M-PM equation is most applicable in streams with a tight unimodal bed material distribution, where particle sizes range from 0.4 to 29 mm [14]. Mimico Creek is a gravel-bed river with heterogeneous bed material distribution containing both sand and gravel fractions where more than 50% of the bed material is larger than 29 mm (Figure 2). To achieve a calibration with the field measurements using the M-PM equation, critical shear stress (τ_C^*) values (used as a calibration parameter) would had to have be set to values beyond the valid parameter range ($50 \leq \tau_C^* \leq 570$) [11].

Table 1. Comparison between sediment discharge measured in the field (Q_{b_field}) and calibrated modelling results (Q_{b_model}) using the *Wilcock and Crowe* equation.

Flood Event	Date	Q_{peak} (m³/s)	Q_{b_field} (tonnes/day)	Q_{b_model} (step-wise discharge) (tonnes/day)	Q_{b_model} (unsteady flow) (tonnes/day)
1	10/08/2012	15.6	4.35	4.66	4.33
2	04/09/2012	42.3	5.68	5.25	5.73
3	11/03/2013	15.7	0.23	0.31	0.25
4	09/04/2013	16.8	0.17	0.18	0.19
5	12/04/2013	21.4	1.3	1.33	1.28
6	29/05/2013	36.5	1.99	2.02	2.03
7	08/07/2013	38.7	15.79	15.9	15.80

4.2. Estimation of mean travel distance of bed material

For each of the seven flood events analyzed, the results of the calibrated HEC-RAS model were used to estimate the mean travel distance (L) of bed material using Equation 3 (Table 2). Mean values of volumetric bed material transport rates (Q_b), average active layer streambed depths (D_s) and widths (W_s) were estimated over the time interval Δt when $\omega > \omega_o$. The active thickness (D_s) was considered here to be the thickness of the active layer at the beginning of each computational time step whereas the effective width (W_s) was considered to be the bottom width at the end of the computational time step [11]. An average porosity of P = 0.18 was used for all WC simulations where a grain size distribution from the surface mixture was used.

Table 2. Simulation results using the *Wilcock and Crowe* equation for Q_b.

Field Observations [24]					***Simulations Results*** *(step-wise discharge)*		***Simulation Results*** *(unsteady flow)*	
Flood event	**Date**	Q_{peak} (m³/s)	L_{m_1} (m)	L_{m_2} (m)	Q_b (m³/s)	L_{mean} (m)	Q_b (m³/s)	L_{mean} (m)
1	10/08/2012	15.6	0.4	9.8	$1.3\ 10^{-5}$	1.12	$1.0\ 10^{-5}$	0.92
2	04/09/2012	42.3	1.4	8.5	$2.7\ 10^{-5}$	2.00	$6.2\ 10^{-5}$	4.82
3	11/03/2013	15.7			$1.8\ 10^{-6}$	0.16	$1.2\ 10^{-6}$	0.11
4	09/04/2013	16.8			$1.4\ 10^{-6}$	0.12	$1.4\ 10^{-6}$	0.12
5	12/04/2013	21.4			$9.9\ 10^{-6}$	0.80	$9.4\ 10^{-6}$	0.80
6	29/05/2013	36.5	3.5	14.4	$1.4\ 10^{-5}$	1.10	$1.8\ 10^{-5}$	1.51
7	08/07/2013	38.7			$6.9\ 10^{-5}$	5.70	$6.9\ 10^{-5}$	6.00

Notes: tracer surveys were conducted after the recession of each hydrograph. : L_{m_1} = mean transport distance of event-based particles (including immobile particles), L_{m_2} = mean transport distance of event-based particles (considering only mobile particles)

From the tracer surveys conducted between 2011 and 2013, the mean transport distance of event-based particles (L) ranged between 0.1 m < L < 3.5 m (which included tracking particles that did not move within any given discharge event) or ranged between 2.8 m < L < 16.2 m when immobile tracking particles were excluded [3]. Mean travel distances determined from the WC equation simulations were found to range between 0.12 m < L < 5.7 m and between 0.11 m < L < 6 m, considering respectively step-wise discharge and unsteady flow simulations. Modelling results found that mean travel distances varied widely (above and below mean observed transport distances) compared to calculated mean field distances (Table 2). For the second flood event (Table 2), the simulated (step-wise discharge) mean travel distance is similar to the observed one when immobile tracer particles are included (L_{m_1}).

It is clear from the field observations (Table 2) that particles travel similar distances independent of the peak discharge. No relationships were found between mean tracer transport distance and peak discharge [3]. The same situation is visible in simulation results, where there is not a monotone function relating peak discharge (Q_{peak}) and mean travel distance (Table 2). Indeed, the mean travel distance L_{mean} depends upon many factors (Q_{b}, Δt, D_{s}, W_{s}), not necessarily related to the peak discharge.

Considering tracer mobility, the event-based percentage of mobile particles (P_{mevb}) is equal to 4, 17 and 24 respectively for the 1st, the 2nd and the 6th flood events [24]. A general trend was found between L_{m_1} (and L_{m_2}) and P_{mevb}: higher values of L_{m_1} (and L_{m_2}) corresponded to higher values of P_{mevb}. Concerning simulation results, it was not possible to estimate P_{mevb}, but the volume of bed material could be evaluated as the product of the mean values of volumetric bed material transport rates (Q_{b}) and the time interval Δt, when $\omega > \omega_{\text{o}}$. A correlation between L_{mean} and the volume of bed material was observed such that higher values of L_{mean} corresponded to higher values of volumetric bed material transport rates.

5. Conclusions

This study employed the *Meyer-Peter Müller* and *Wilcock and Crowe* models within the HEC-RAS modelling framework to evaluate the representativeness of event-based estimates of sediment transport and bed material transport distances. Results were compared to three-year (2011-2013) field sampling campaign where in-situ bedload and inter-event particle tracking had occurred. Results showed that the *Wilcock and Crowe* transport model represented the poorly graded gravel bed channel conditions over the range of flows inventoried. Mean bed material transport distances using the *Wilcock and Crowe* model (0.12 m < L < 5.7 m and 0.11 m < L < 6 m, considering respectively step-wise discharge and unsteady flow simulations) compared relatively well against field observations (0.1 m < L < 3.5 m) and in some instances overestimated travel distances.

Findings from this study reinforce the importance of accounting for clast interactions in transport estimates. The *Wilcock and Crowe* model accounts for bulk inter-particle interactions (e.g. hiding and sand-dependent gravel transport) and the armor layering effects [14]. These could not be accounted for using the *Meyer-Peter Müller* equation, which could not be correlated to the field conditions and bed material gradation. The comparison of simulated transport distances against available field observations also provides another mechanism to validate appropriate transport equations; particularly where in-situ bedload sampling may not be available.

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