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# Sediment transport and morphodynamics in an urbanized river: the effect of restoration on sediment fluxes

M. Chapuis, V. Bevan & B. MacVicar

*Department of Civil & Environmental Engineering, University of Waterloo, Ontario, Canada.*

A. G. Roy

*Faculty of Environment, University of Waterloo, Ontario, Canada.*

**ABSTRACT:** Urbanized rivers are heavily impacted by human activities that modify their hydrology and morphodynamics. This study focuses on Wilket Creek, a small gravel-bed river (14.5 km<sup>2</sup> drainage area, 12 m width, 1% slope, D50 = 0.039 m) located in the suburban area of Toronto. Existing infrastructures are threatened by incision and lateral migration of the channel. In 2012, a 400 m long reach has been restored with a riffle-pool design that was assumed to be the most efficient to dissipate flow energy. This project investigates the interactions between hydrology, sediment transport and morphodynamics to assess the stability of the restoration design. We used topographic surveys and RFID tracking to assess the sediment mobility and morphodynamics changes in unrestored and restored sections. After two bankfull events, adjustments of the riffle-pool design consist primarily of local bank erosion and local exposure of the underlying glacial till.

## 1 INTRODUCTION

Urbanized rivers are heavily impacted by human activities that modify their hydrology and morphodynamics. The increase of impervious areas within the watershed leads to a flashier hydrological regime. The response of the watershed to local rainy events is difficult to predict, both in terms of timing and intensity: consequently flooding risk is increased. The new hydrological and sedimentological regimes correspond to a new balance between flow input and sediment input in the river system. In particular, given a certain hydrological input, the amount of sediment ‘easily’ available in the watershed may not match the new ‘needed’ input to reach a new dynamic equilibrium state. In addition, previous attempts to stabilize the river system may prevent the mobilization of the necessary sediment stock, leading to destabilization of the existing infrastructures (embankments, weirs, bridges...).

Consequently, the modification of the hydrological regime due to urbanization leads to a conflict between the adjustments of the river system and human use of the riverscape. New restoration techniques in high energy river systems attempt to better accommodate the hydraulics by dissipating excess flow energy. For example, instead of restoration based on hydraulic efficiency, new designs relying on natural river processes may be employed (Riley 1998, Downs & Thorne 2000, Gregory 2006). These designs are inspired by morphological features found in similar undisturbed systems, such as

meandering channels associated with riffle-pool structures. They can also rely on bioengineering techniques that are more integrated in the visual aesthetics of the environment (Lachat 1998). However, the practice of stream restoration has leaped ahead of the science and the lack of a solid scientific basis for the technique of riffle-pool construction reduces their long term viability (Kondolf 1995, Milan et al. 2001, Thompson & Wohl 2009). Indeed, while morphodynamics and sediment mobility are key factors for river management, they are frequently not explicitly considered by river managers (Shields Jr 1996) and in many cases there is little to no information on sediment dynamics in the studied systems.

This project aims to investigate the interactions between hydrology, sediment transport and morphodynamics in a gravel-bed river located in the urban area of Toronto (Ontario, Canada). Existing infrastructures in the valley (foot path and sanitary sewage lines) are threatened by bed degradation and lateral migration of the channel. As a result the City of Toronto and the Toronto and Region Conservation Authority (TRCA) have spent a significant amount of money on engineering projects to stabilize the creek. In 2012, a 400 m long reach was restored with a riffle-pool morphology that was designed to efficiently dissipate flow energy. This design was based on the assumption that a riffle-pool morphology was most representative of natural gravel-bed rivers. The objectives of this study are to develop a sediment budget for the watershed and to

assess the stability of the riffle-pool design and its effect on sediments moving through the channel.

## 2 METHODOLOGY AND FIELD SITE

### 2.1 Field site

Wilket Creek is a small river (14.5 km<sup>2</sup> drainage area, 12 m width, 1% slope) located in the urban area of Toronto (Ontario, Canada, Fig. 1). The bed material consists of a gravel and sand mix ( $D_{50} = 0.039$  m) with some local exposure of a compact glacial till. The watershed has been intensively urbanized between the 50's and the 60's. As observed in similar systems (McDonald 2011), the increase of impervious area associated with a lack of stormwater management increased the intensity and the frequency of flood events (Galster 2008). This

modification of the hydrological regime led to a flashier and more intense hydrograph. This resulted in a 34% increase of mean channel width (maximum width increase = 15 m) between 1947 and 2009 and riverbed degradation that could be up to 2 m. The study reach, which comprises 5 study sites (Fig. 1), is located in a naturalized park with extensive forest cover. The channel is vertically and laterally constrained by a sanitary sewer system located underneath the river bed and a paved foot path with several bridged crossings.

Three reaches have been restored in Wilket Creek since 2008 (Fig. 1). The restoration works attempt to stop lateral erosion and bed degradation. Their meandering riffle-pool design is expected to dissipate excess water energy and thus to help prevent further erosion of the bed. The two newest restored sites are part of a more comprehensive plan undertaken by the City of Toronto to restore 10 degraded reaches in Wilket Creek (Parish Geomorphic 2011).

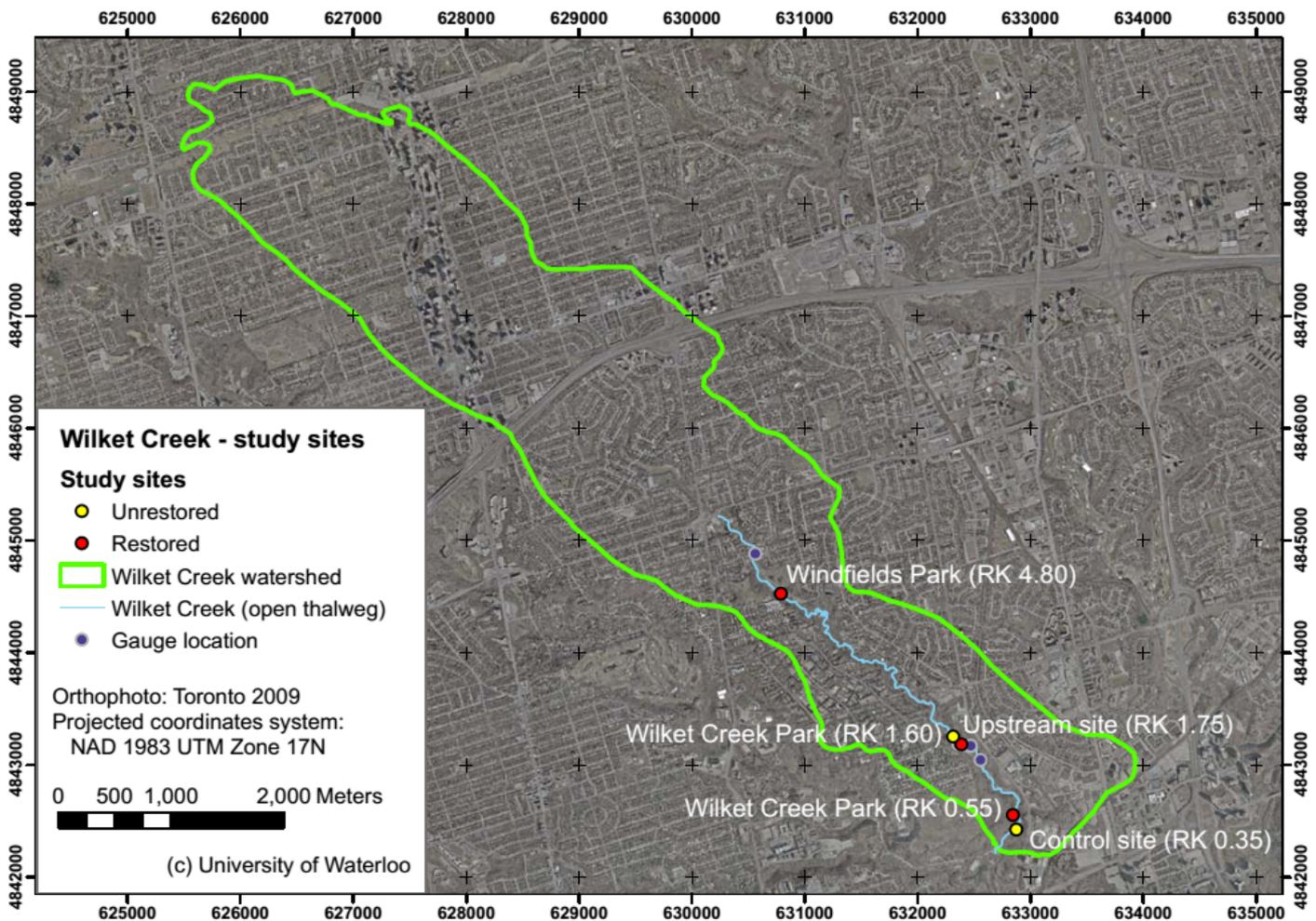


Figure 1. Location of the five study sites within the Wilket Creek catchment and indication of their river kilometer (RK). Wilket Creek is located within the suburban area of Toronto.

The first restored site is located in Windfields Park (river kilometer RK 4.80) on the upstream part of the creek. It is 110 m long and was undertaken as an emergency action in 2008 to protect infrastructure. The second restoration is located in the upstream part of Wilket Creek Park (RK 1.60) and is the main focus of this study. The restored section is 400 m long and was finished in July 2012. For this site, riffles are constituted by cobbles and boulders (design  $D_{50} = 0.686$  m) in addition to ribs ( $>1.024$  m) that constitute the riffle crests. The outer banks are also strengthened (design  $D_{50} = 0.500$  m) but no exogenous material is added to pools. The last restored reach is located further downstream (Wilket Creek Park, RK 0.55). It was completed in March 2013 and is 100 m long.

Each restored reach corresponds to a sinuous planform designed with riffle-pool features (Fig. 2). Both embankments and riffles are made from exogenous material which is greater in size than the natural bed material (in the upstream Wilket Creek Park site, RK 1.60:  $D_{50} = 0.048$  m and 0.056 m before and after the restoration works, respectively; design  $D_{50} = 0.700$  m). In addition riffles are strengthened by transversal ribs corresponding to large ( $>1$  m  $b$ -axis) boulders embedded in the streambed immediately upstream from the riffle crest.

As part of the study, the sediment mobility of two ‘natural’ sites will be compared with the three restored sites (Fig. 1). The unrestored reaches are 60 m in length. One (Upstream site, RK 1.75) is located upstream of the second restored site and is partially constrained laterally by gabions in its upstream part. It is morphologically typical of the whole creek. The other natural site (Control site, RK 0.35) is located downstream of the downstream restored site and is free of human-made lateral constraint.

## 2.2 Methods

We used topographic surveys to assess morphodynamics changes in restored (Wilket Creek Park, RK 1.60) and unrestored (Upstream site, RK 1.75 and Control site, RK 0.35) reaches after two over bankfull floods in the 2013 summer (29<sup>th</sup> of May and 8<sup>th</sup> of July). Unfortunately no water level measurements were available when these two over bankfull floods occurred. However, indications of woody debris elevations allowed us to assess that water levels were 2.1 m and 1.5 m over the Wilket Creek Park restored site (RK 1.60). Based on the subsequently developed rating curve, these water levels correspond to 12 m<sup>3</sup>/s and 8 m<sup>3</sup>/s for the May 29<sup>th</sup> and July 8<sup>th</sup> flood events, respectively. Additional visual observations on the two other restored reaches (Windfields Park, RK 4.80 and Wilket Creek Park, RK 0.55) were conducted after the floods. In the second restored reach (Wilket Creek Park, RK 1.60), topographic surveys were undertaken along 20 cross-sections. In addition, topographic data were collected as part of the RFID tracking for all reaches located in Wilket Creek Park (Wilket Creek Park, RK 1.60, Upstream site, RK 1.75 and Control site, RK 0.35).

We used RFID tracking to assess gravel mobility within restored (Wilket Creek Park, RK 1.60) and unrestored (Upstream site, RK 1.75 and Control site, RK 0.35) reaches during small floods that occurred in fall 2013. Tracer particles preparation consisted of drilling, inserting the transponder and hermetic sealing. Transponder sizes were 0.012, 0.023 or 0.032 m (Texas Instruments, TRPGR30TGC, RI-TRP-WR3P and RI-TRP-WR2B; Texas Instruments 2012, Texas Instruments 2001, Texas Instruments 2008, respectively). Tracer particles were measured ( $a$ ,  $b$ ,  $c$ -axis),

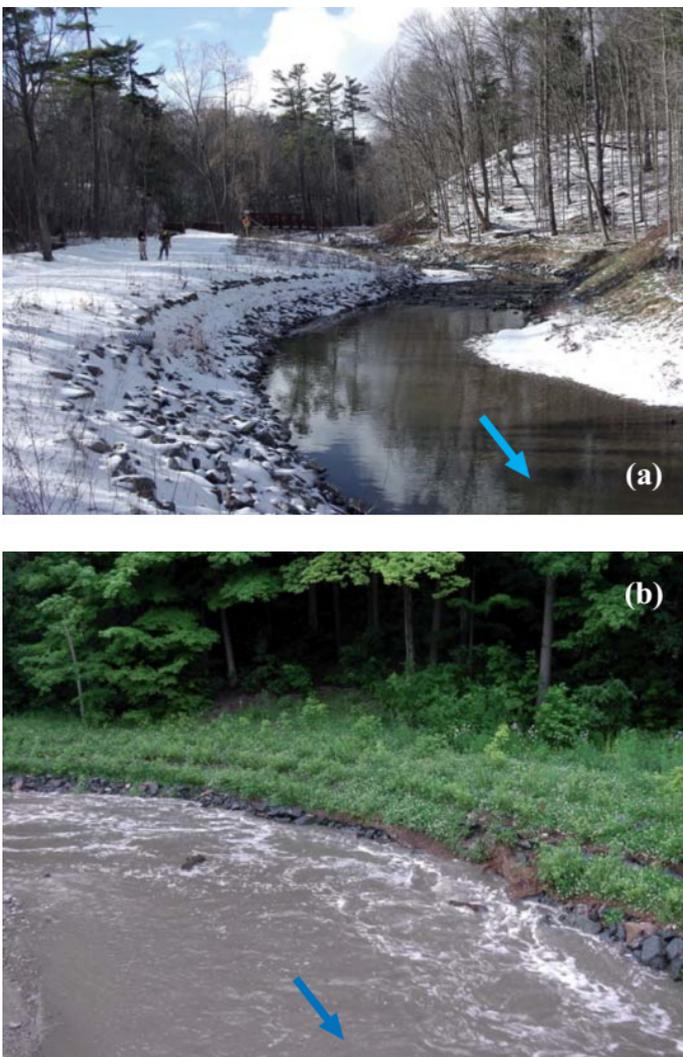


Figure 2. (a) Example of the restoration works in the main study site (Edwards Gardens, RK 1.60). The designed channel corresponds to a sinuous planform channel with riffle-pool features. Both embankments and riffles are made from exogenous material which size is greater than natural bed material. (b) Solicitation of the outer river bank by logs during a flashy flood (2013/06/13, Edwards Gardens, RK 1.60). Blue arrow indicates flow direction.

weighted, and their shape and volume were recorded. Particle sizes ranged from 0.016 to 0.724 m (corresponding phi-classes: -4.0 to -9.5). Tracer grain size distribution, even if less skewed, was similar to bed material after restoration work since the 0.008 - 0.016 m fraction of bed material could not be tagged with RFID transponders ( $D_{50 \text{ tracers}} = 0.088 \text{ m}$ , skewness = -0.07 (Folk and Ward 1957) vs.  $D_{50 \text{ bed after restoration}} = 0.111 \text{ m}$ , skewness = -0.15). Tracers were seeded every 0.50 m along cross-sections that corresponded to the active channel width and were spaced about 2 m in the streamwise direction. The seeding scheme was aimed at studying the link between particle mobility and bedform mobility and thus tracer sizes were evenly distributed within the seeding area. During seeding, the initial location of each tracer was recorded with a total station. In addition, topographic data were collected. Tracer recovery generally occurred after each significant flood event with a 0.50 m diameter Leonie antenna (Aqurtis 2011). Tracer locations were recorded with total station with an accuracy of  $\pm 1.5 \text{ m}$  (Chapuis, et al., submit.). This estimate takes into account the accuracy of the antenna tracking and the total station accuracy of measurement.

### 3 RESULTS AND INTERPRETATION

#### 3.1 Design of the riffle-pool system and hydrological regime prior to the studied period

Although no water level measurements were available between July 2012 and May 2013, the May 29<sup>th</sup> and July 8<sup>th</sup> 2013 floods were by far the most powerful occurring after the restoration work (RK 1.60) was completed in July 2012.

By the time the May 29<sup>th</sup> and July 8<sup>th</sup> 2013 floods occurred, the riffle-pool design had already been put under strain by storm-triggered floods during late summer and fall 2012. In particular cobbles and boulders inserted in the bed during restoration had been reworked, especially in the riffles. However no significant bank erosion was observed prior to the two over bankfull events.

#### 3.2 Morphologic evolution of the restored reaches and associated sediment dynamics

Following the two over bankfull events, the Wilket Creek Park restored site (RK 1.60) exhibited vertical stability although some lateral adjustments did occur (Fig. 3).

The upstream and downstream restored sites showed different trends. In the upstream reach in Windfields Park (RK 4.80, Fig. 4) where there is an ongoing cut-off of the meander, our observations showed an increase in the degradation of the channel. The cut-off accelerated channel incision in the

bend behind the embankment. In contrast, the downstream restored site (Wilket Creek Park, RK 0.55) remained stable, showing only a slight destabilization of the embankment at the downstream end due to the confluence with a small tributary.

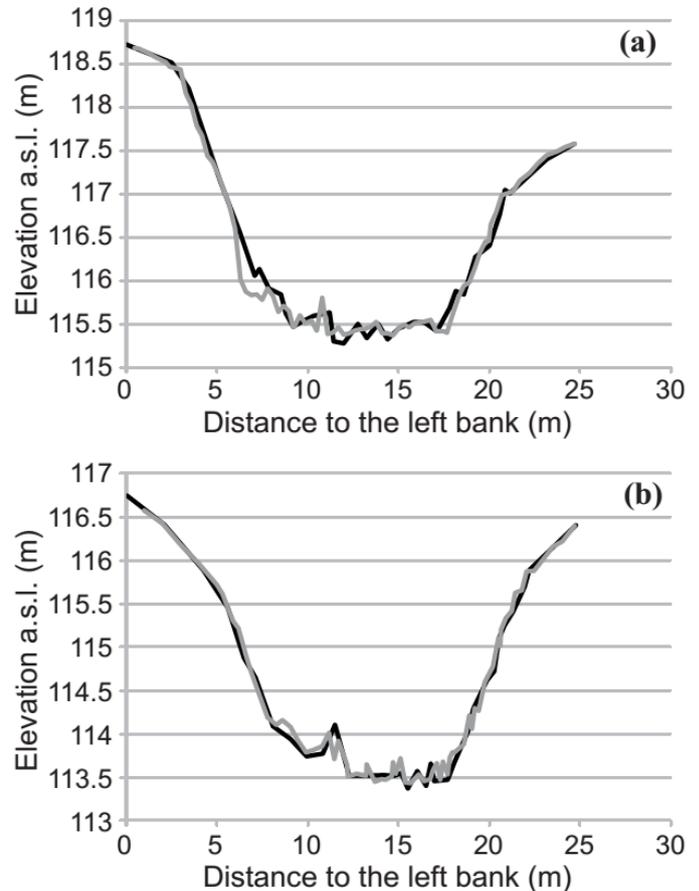


Figure 3. Topographic evolution of cross-sections 8 (subplot a) and 14 (subplot b) of the Wilket Creek Park site (RK 1.60) before (2013/02/01, black line) and after (2013/07/25, grey line) May 29<sup>th</sup> flood. These results show overall stability of the designed channel with some lateral adjustments on cross-section 8.



Figure 4. Cut-off (white arrow) of the meander on the upstream restored site (Windfields Park, RK 4.80). Blue arrow indicates flow direction.

The May 29<sup>th</sup> and July 8<sup>th</sup> floods led to the flushing of bed material within the Wilket Creek Park restored site (RK 1.60). The removal of bed material occurred over a depth  $\leq 0.50$  m, uncovering the underlying glacial till (Fig. 5). We observed a fine gravel bedload sheet prograding at the upstream end of the reach. This corresponds to a gravel input on the Wilket Creek Park reach (RK 1.60). Within the central part of the reach, gravel and sand were flushed from the upstream pool of the reach. The bed material resulting from this erosion probably led to the growth of a bar that was observed 200 m downstream.

Subsequent floods (summer and fall 2013) confirmed the frequent mobilization of sand within the Wilket Creek Park restored reach (RK 1.60) and RFID tracking showed that gravel path lengths were short (maximum distance of  $22 \text{ m} \pm 1 \text{ m}$  within a 2.5 month survey).

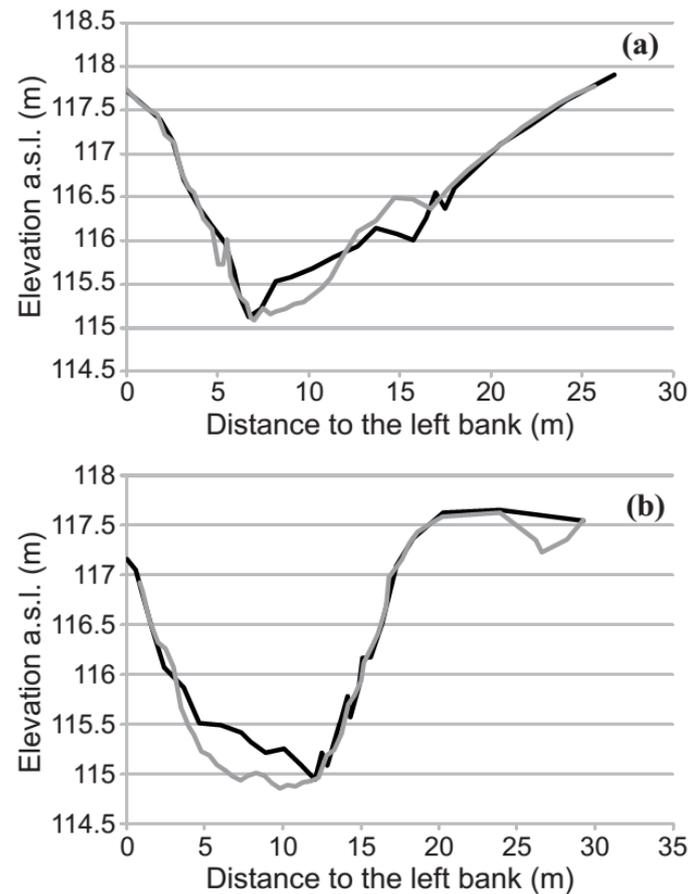


Figure 5. (a) Internal reworking of sediment (cross-section 6) between 2013/02/01 (black line) and 2013/07/25 (grey line) illustrating the effects of two over bankfull floods. (b) Flushing of fine sediments in pools (cross-section 9) between the same survey dates.

### 3.3 Sediment dynamics in the unrestored reaches

The bed in the downstream unrestored reach (Control site, RK 0.35) exhibited extensive mobility vertically and laterally with both deposition of sand on the bar (Fig. 6) and strong lateral erosion of the bank (bank retreat of 1.7 m along the monitored cross-section). Generally speaking, the river experienced flushing of the gravel layer uncovering the underlying glacial till.

No survey had been undertaken at the upstream site (RK 1.75) when the two over bankfull events occurred. Based on the RFID tracking of subsequent flood events (summer and fall 2013, Fig. 7), the gravel layer within this reach is mobile (more than 80% of the particles constituting each size class were mobile between 2013/09/22 and 2013/11/25) and thus will eventually supply gravel to the downstream restored site (RK 1.60).



Figure 6. Strong modification of the bed on the upstream unrestored site (Control site, RK 0.35) before (a) and after (b) the May 29<sup>th</sup> flood. (a) Picture taken on the 2012/10/26. (b) Picture taken on the 2013/06/13. Blue arrow indicates flow direction.

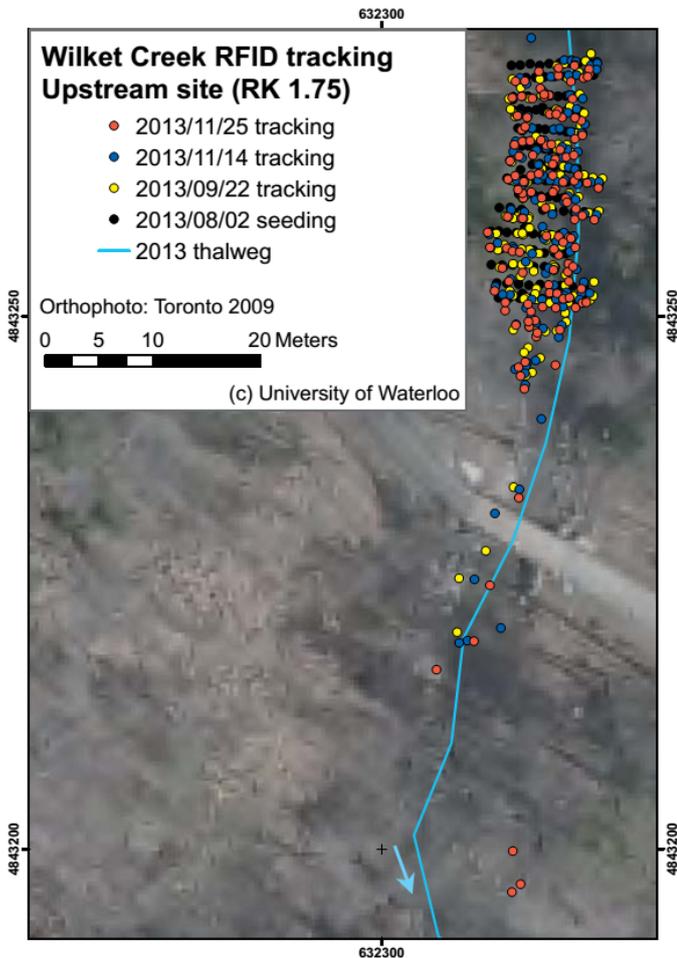


Figure 7. RFID tracking on the Upstream site (RK 1.75). The seeding locations of tracers are indicated. Tracers were naturally reworked between the seeding and the first tracking (2013/09/22) because of four flood events (maximum estimated discharge:  $1.7 \text{ m}^3/\text{s}$  on 2013/08/26). Blue arrow indicates flow direction.

#### 4 SYNTHESIS AND DISCUSSION

In both unrestored and restored reaches, the two over bankfull events flushed the relatively thin alluvial layer exposing the underlying glacial till, thus potentially leading to irreversible bed incision. The till seems to have a variable resistance to erosion: in some locations, bank retreat is much less marked than in other sections where erosion was important.

Particle tracking indicates that gravel fluxes through unrestored reaches are significant. Sand fluxes through the restored reach are significant too, while gravel fluxes might not be of the same time-scale. After completion of the restoration works, no significant gravel material was available in the Wilket Creek Park restored reach (RK 1.60) until the major flood events occurred. Gravel flux through the restored reach thus depends on upstream gravel in-

put. As we observed a gravel layer prograding at the upstream end of the reach and gravel mobility within the upstream unrestored site (RK 1.75), it is likely that this will supply gravel to the restored reach. It is doubtful that the volume of this bedload sheet will be sufficient to compensate the flushing of the sand fraction from the pools and contribute to cover and thus protect the glacial till.

As the watershed does not have significant sources of gravel, this highlights the more general problem of gravel supply throughout the creek. Some eroding banks are composed of a mix of clay, sand and gravel, but the amount of potential gravel input is very limited. Before urbanization of the watershed, the limited sediment supply was probably not an issue as the alluvial layer was thick enough to allow for bar formation and migration while bank erosion could also supply more gravel. As the bed incised due to changes in the hydrological regime caused by urbanization, the floodplain became disconnected from the channel, thus accelerating the imbalance between increased flow input and the limited gravel supply.

The Windfields Park restored site (RK 4.80) is failing because of its cut-off but the downstream Wilket Creek Park restored reach (RK 0.55) is fairly stable after the two bankfull events. Our observations also suggest that the lateral planform of the Wilket Creek Park restored reach (RK 1.60) may not remain stable over the long term. This triggers the question about the relevance of the restoration works in relation to their cost and longevity. Efficiency of the ‘vertical’ restoration seems able to protect the sewage system underneath, even if the downstream end of the restoration seems to be weakened by these two bankfull events.

To date, it might be too early to assess whether the overall channel design of the Wilket Creek Park restored reach (RK 1.60) is stable or not and thus if the restoration was ‘successful’. To assess the time scale associated with channel stability, a decision matrix can be developed that would include ‘acceptable’ adjustments vs. ‘non-acceptable’ (Table 1). Acceptable adjustments would be defined as those who do not threaten essential infrastructures or who do not correspond to irreversible change on the river system. We propose here that the sewage system and habitations are essential infrastructures (but not the channel path) and that incision of the glacial till is irreversible. We propose not to consider that bank erosion is an irreversible process, except when it directly threatens a habitation. The frequency of floods leading to each adjustment type could then be assessed to estimate the time scale stability of the design. Even if the channel is stable, managers should not forget that the creek is lacking gravel input and that catchment scale solutions should be sought.

Table 1. Decision matrix of ‘acceptable’ vs. ‘non-acceptable’ adjustments in Wilket Creek. Bold Y corresponds to change current TRCA policy. The proposed discharge corresponds to the estimated WCrk2 gauge discharge. The presented values might be refined later when additional hydrologic data is available.

Adjustment description	Acceptable (Y/N)	Proposed corresponding discharge (m <sup>3</sup> /s)
Bank erosion with no direct threatening of sewer or manhole	Y	< 5
Bank erosion with direct threatening of sewer or manhole	N	> 5
Bank erosion with no direct threatening of path	Y	< 2
Bank erosion with direct threatening of path	<b>Y</b>	> 2
Bank erosion with no direct threatening of bridge pier	Y	< 5
Bank erosion with direct threatening of bridge pier	<b>Y</b>	> 5
Bank erosion with direct threatening of valley wall	<b>Y**</b>	> 2
Channel incision within alluvial material	Y	> 2
Channel incision with uncovering/incision of glacial till	N	> 1
Channel incision with threatening of sewer	N	> 5
Channel incision with no destructuration of restored riffles	Y	< 12
Channel incision with destructuration of restored riffles	N	>> 12
Channel incision with destructuration of natural riffles	Y	> 8-12
Overbank sand deposition, even on the path	<b>Y</b>	> 5
Overbank gravel deposition	n/a*	>> 12
In-channel sand deposition associated with potential increase of flooding risk	Y	> 2
In-channel gravel deposition associated with potential increase of flooding risk	Y	> 5

\*not likely to happen since overbank gravel deposition did not happen during the two over bankfull events studied and limited gravel supply within the whole catchment.

\*\*not acceptable if threatening habitation.

## 5 CONCLUSIONS

Wilket Creek is a dynamic and steep river whose hydrology and morphodynamics are heavily impacted by human activities. Because of watershed urbanization, the flashier hydrological regime strongly stresses river banks and bed. Present management efforts consist of sinuous riffle-pool designs that vertically and laterally constrain the channel. Because the channel design was established *a priori* as the most stable, the effectiveness of the restoration works was investigated and stability of the riffle-pool design assessed. For comparison, unrestored reaches were also monitored. Topographic surveys showed that 18 months after restoration, the vertical design is fairly stable but concerns exist about the medium/short term (5 years) stability of the channel planform after two over bankfull flood events. In addition to strong mobility of the sandy fraction, RFID tracking highlighted gravel mobility over the streambed for both restored and unrestored reaches. However this bedload mobility involves only a thin layer that travels over a glacial till that has been largely exposed by the two floods. Bedload mobility is less on restored reaches compared to unrestored ones, but as no significant gravel source is available

within the watershed, the imbalance between bedload flushing and gravel input highlights the need of mitigation measures to supplement the restoration works.

## ACKNOWLEDGEMENTS

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