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In situ jet-testing of the erosional resistance of cohesive streambeds

Daniel Shugar, Ray Kostaschuk, Peter Ashmore, Joe Desloges, and Leif Burge

Abstract: Fletcher's Creek is located in an urbanizing basin near Toronto and has a bed and banks composed primarily of cohesive Halton Till. Critical shear stress and an erodibility coefficient for the till were determined using an in situ jet-tester that directs a submerged jet of water perpendicular to the sediment surface. The results from 10 jet-tests indicate that the till has a relatively low critical shear stress and relatively high erodibility coefficient and could be susceptible to bed scour during flood events. Many other streams in southern Ontario have urbanizing watersheds with cohesive till beds that may also be susceptible to erosion.

Key words: critical stress, submerged jet, erodibility, cohesive soils.

Résumé : Le ruisseau Fletcher est situé dans un bassin en voie d'urbanisation près de Toronto; son lit et ses berges sont principalement composés de till cohérent Halton. Les contraintes critiques de cisaillement et un coefficient d'érodabilité du till ont été déterminés en utilisant une lance in situ qui dirige un jet d'eau submergé perpendiculairement à la surface des sédiments. Les résultats provenant de dix essais avec la lance indiquent que le till possède une résistance au cisaillement critique relativement faible et un coefficient d'érodabilité relativement élevée et qu'il pourrait subir de l'affouillement du lit durant les crues. Plusieurs autres ruisseaux du sud de l'Ontario présentent des bassins en voie d'urbanisation comportant des lits de till cohérent qui pourraient aussi être susceptibles à l'érosion.

Mots-clés : contrainte critique, lance submergée, érodabilité, sols cohérents.

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Introduction

The consequences of urban development in small urbanized basins include a tendency for intense local summer rainstorms to become the dominant flood-generation event instead of snowmelt. These hydrological changes, along with artificial realignment and straightening of channels, contribute to rapid channel incision, bank erosion, and channel widening (Finkenbine et al. 2000; Ashmore and Church 2001). Stream erosion problems in southern Ontario also arise because these streams are semi-alluvial in character (Campo and Desloges 1994; Ashmore and Church 2001), and locally heterogeneous bedrock or cohesive glacial deposits make up channel beds and lower banks. Halton Till (Karrow 1991) underlies much of the Credit River watershed near Toronto (Fig. 1) and forms the bed and lower banks for many of the stream channels. The erosional resistance of the till is thus a primary control of the behavior of these channels, but little is known about the erosion mechanisms and resistance of this material.

It is generally assumed, however, that the rate of erosion, ε (cm·s^{-1}), of cohesive sediment such as till can be described by (Hanson 1990a)

$$[1] \qquad \varepsilon = k_d (\tau - \tau_c)^a$$

where k_d is the erodibility coefficient (cm^3·N^{-1}·s^{-1}), τ is the effective boundary hydraulic shear stress (Pa) causing detachment at the bed, τ_c is the critical shear stress (Pa), and the exponent a is often assumed to be one and is absent from the equation (Hanson 1990a, 1990b; Stein and Nett 1997). The purpose of this study is to use an in situ jet-testing method developed by Hanson (1991) to determine the critical shear stress and erodibility of exposures of Halton Till in Fletcher's Creek, a tributary of the Credit River (Fig. 1).

D. Shugar[1,2] **and R. Kostaschuk.** Department of Geography, University of Guelph, Guelph, ON N1G 2W1, Canada.
P. Ashmore. Department of Geography, The University of Western Ontario, London, ON N6A 5C2, Canada.
J. Desloges and L. Burge.[3] Department of Geography, University of Toronto, 100 St. George Street, Toronto, ON M5S 3G3, Canada.
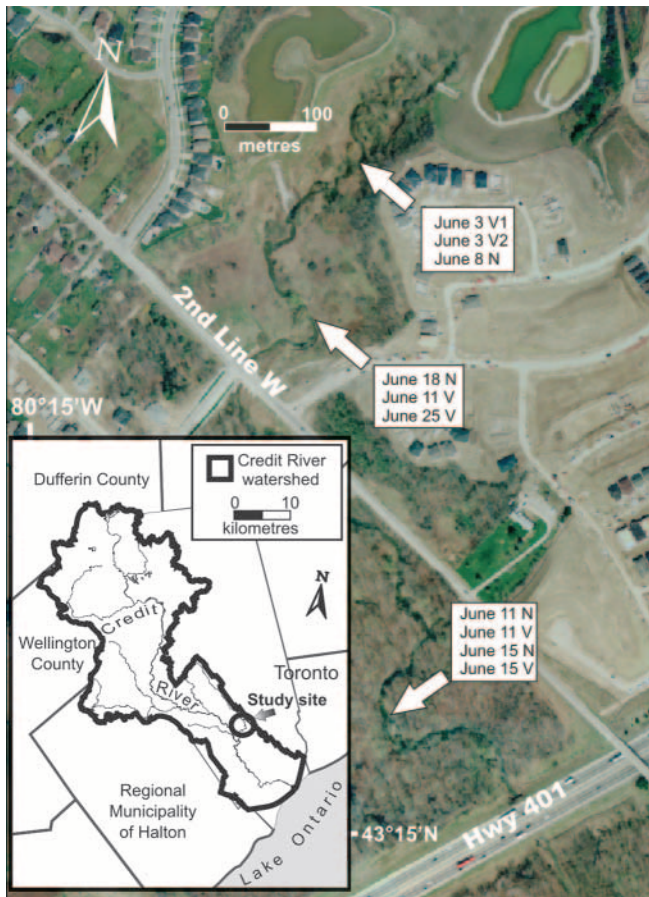
[1]Corresponding author (e-mail: dshugar@sfu.ca).
[2]Present address: Centre for Natural Hazard Research, Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada.
[3]Present address: Department of Geography, Okanagan College, 1000 KLO Road, Kelowna, BC V1Y 4X8, Canada.
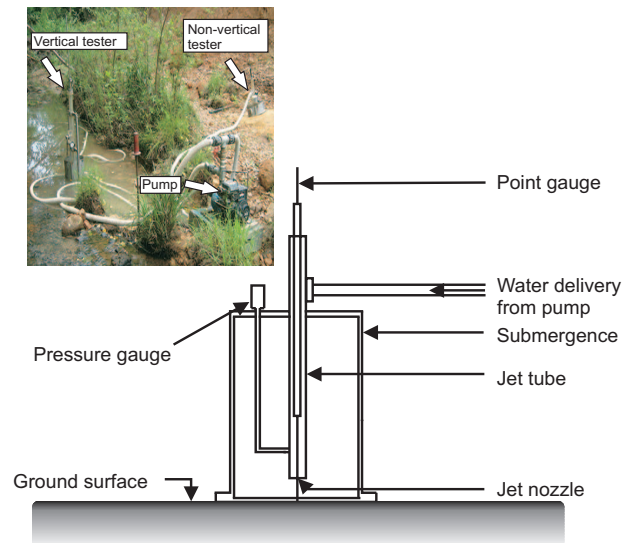
Fig. 1. Orthorectified aerial photograph of lower Fletcher's Creek (photograph 40603 reproduced with permission from Triathlon Ltd.), with locations of jet-testing sites highlighted. Dates followed by a V indicate a vertical jet test, and those followed by an N indicate a nonvertical test. The inset shows the regional location of the study site on Fletcher's Creek in the Credit River watershed.

Fig. 2. Schematic of the in situ vertical jet apparatus. The inset shows a typical field deployment of vertical and nonvertical jet-testers.

Methods

Two types of jet-tests, as defined by the orientation of the sediment bed, were used in this study (Fig. 2). Ten jet-tests, ranging from 50 min to just over 3 h in duration, were conducted on subaerially exposed till in Fletcher's Creek between 3 and 25 June 2004 (Fig. 1). A brief description of field procedures is provided here; a detailed description of jet-testing theory and field and analytical procedures can be found in Hanson and Cook (2004) and Annandale (2006). The submergence tank is first pounded into the bank or bed material until a watertight seal is formed. The point gauge is then inserted into the jet tube and locked in place, and the pressure gauge and deflector plate are attached. A gasoline-powered pump is used to draw creek water for the tests. Initial readings are made with the point gauge by lowering it to the bed before the tank is filled with water. The point gauge is then raised to a base level at which the tip does not interfere with the jet but can easily pass through the nozzle. A valve to the jet is then opened, filling the tank with water and submerging the jet nozzle. Measurements of depth of

scour are made every 2 min in this study. At each 2 min mark the point gauge is lowered through the jet orifice, effectively shutting off the jet flow, until it reaches the bed. After making the depth measurement, the jet operator gently removes, by hand, any large particles that have been dislodged into the scour hole. Depth of scour is recorded on a field sheet, and the point gauge is then raised to allow the jet to impinge for the next time interval. Readings are continued until scour depth no longer increases or increases by only very small amounts. The data are then used to calculate k_d and τ_c using a spreadsheet routine developed by Hanson and Cook. Although the jet was perpendicular to the surface in all tests, Hanson and Cook point out that the tractive stress distribution beneath an impinging jet is not uniformly distributed but theoretically is zero at the centre of the impingement zone, increasing to a peak value at a given radial distance from the centre and then decreasing at radial distances farther from the centre.

Samples of till were collected in the field from four jet pump test locations. Sand and gravel content were determined using standard sieve analysis. The grain-size distribution of silt and clay (<63 μm) was determined using a Micromeritics SediGraph 5100. Organic matter and carbonate content were determined using the loss-on-ignition (LOI) technique (1 h at 550 and 1000 °C, respectively). Bulk density and moisture content were measured for four samples using standard procedures.

Results and discussion

The Halton Till is poorly sorted, with an average of 17% gravel, 29% sand, 27% silt, and 26% clay for the four samples tested (Table 1). The till contains very little organic matter. Bulk density varies from 1787 to 2051 kg·m^{-3}, and moisture content from 6% to 14%.

Table 1. Sediment characteristics of the Halton Till bed in Fletcher's Creek from vertical (V) and nonvertical (N) tests conducted between 3 and 25 June 2004.

	3 June (V)	11 June (N)	15 June (N)	25 June (N)
Organic C (%)	1.99	2.42	1.90	2.32
Calcium carbonate (%)	12.14	10.12	10.90	13.21
Gravel (>2 mm)(%)	8.96	23.82	16.92	21.23
Sand (63 µm – 2 mm) (%)	31.45	25.98	32.60	27.14
Silt (4–63 µm) (%)	28.60	27.61	27.26	24.27
Clay (<4 µm) (%)	30.99	22.59	23.22	27.36

Hanson and Simon (2001) developed a chart displaying the susceptibility to erosion based on τ_c and k_d for loess beds in the Midwestern US. The 10 jet-test results from Fletcher's Creek were plotted in their diagram (Fig. 3), resulting in a classification from very erodible to moderately resistant for the Halton Till. No obvious spatial or temporal patterns were observed in susceptibility to erosion or in τ_c and k_d at the 10 field test sites. Similarly, no significant difference was observed between vertical and non-vertical tests for τ_c or k_d (probability $p = 0.33$ and 0.16, respectively, using t tests), indicating that the banks and bed are similarly susceptible to erosion. For Fletcher's Creek, τ_c varies by six orders of magnitude and k_d varies by only one (Fig. 3), which is similar to the results of Hanson and Simon. Kamphuis et al. (1990) tested cohesive material from southern Ontario streambeds in a laboratory flume and found similar critical shear stress values (0–6 Pa), providing independent support for the values presented here.

The testing apparatus and methods of jet-testing developed by Hanson and coworkers and used in this study are recognized by the American Society for Testing and Materials (ASTM) standard D5852-95 (ASTM 1995), but there are several important limitations to the method that must be considered. The ASTM (1995) suggests that the jet-tester is not suited for determining erodibility of soils that have structure characteristics larger than the scale of the jet-testing device. For example, the erodibility of soil that has a dominant soil structure (aggregate or particle size) of 7–8 cm or larger which might play a key role in the detachment process should not be estimated with the jet index test. Dislodged gravel particles and till were removed by hand from scour holes at each 2 min test interval in this study, so this effect should not be significant. The ASTM also notes that the precision and bias for measuring soil erodibility by the jet index method have not been determined. However, there are no available methods that provide absolute values for the soil erodibility coefficient against which this test method or any other can be compared. Annandale (2006) also questions the assumption of linearity between fluid shear stress and erosion rates (eq. [1], $a = 1$), although he notes that it is valid as a first approximation.

We expect that jet-test results will be affected by abrasion caused by sand particles trapped in the scour hole during the test. Examination of scour holes during tests in Fletcher's Creek indicated the presence of some sand particles, which is expected given that sand is an important component of the particle-size distribution of the Halton Till (Table 1). The presence of the sand and associated abrasion is likely representative of conditions during floods, so we believe the jet-

Fig. 3. Erodibility coefficient and critical shear stress for sites at Fletcher's Creek.
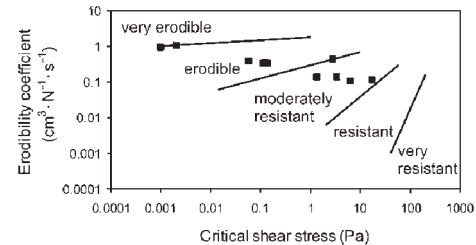
test method used here for Fletcher's Creek may be representative of actual erosion processes, resulting in increased scour and therefore a lower τ_c value (Kamphuis et al. 1990).

It is likely that the large variation in k_d and τ_c values in this study is mainly related to varying degrees of subaerial exposure and erosion by flood flows (cf. Hanson and Simon 2001). For example, subaerial exposure of the bed and bank materials during a low stage will result in expansion and cracking of the sediment, making it more susceptible to erosion during the next high-flow event. Removal of this easily eroded surface material during higher stages and flow velocities will in turn expose underlying sediment that is potentially more resistant to erosion. Groundwater seeps and high-flow events prior to testing could also result in excess pore pressures in the bed that would affect test results (e.g., Simon and Collison 2001). All of the tests in this study were conducted on subaerially exposed samples close to the water level, but the exposure and seepage history of the bed sediment are unknown. Regardless of the reasons, it is clear that the Halton Till bed in Fletcher's Creek has large ranges of k_d and τ_c values, especially for such a small geographical area. This variability must be taken into consideration in the assessment and modeling of erosion in Fletcher's Creek and other semi-alluvial streams in southern Ontario.

Despite the limitations of the jet-testing procedures used here, in situ testing in general is preferable for till streambeds because of problems of extracting small samples of stony till for laboratory analysis. The only other viable option is an in situ benthic flume (Aberle et al. 2006), but this procedure has its own set of problems.

Summary

An in situ jet-testing apparatus is used to determine the erosion resistance of cohesive Halton Till streambeds in Fletcher's Creek near Toronto. Jet-testing is based on the diffusion characteristics of a submerged circular jet and is used

to determine the critical shear stress and erodibility of the bed material. Values of critical shear stress and erodibility for the till are highly variable, probably because of their history of subaerial exposure and erosion. Halton Till streambeds are classified as very erodible to moderately resistant, with a relatively low critical shear stress and relatively high erodibility coefficient. The susceptibility of the Halton Till to erosion indicates that increased magnitude and frequency of flood events associated with urbanization will likely result in rapid scour of the bed and banks of Fletcher's Creek and similar streams in the Toronto region. The jet-testing routine outlined here provides a relatively inexpensive test recognized by the ASTM that could add to the assessment response of stream channels to extreme flows and altered hydrologic regime and should form part of the routine testing of till streambeds.

References

Aberle, J., Nikora, V., and Walters, R. 2006. Data interpretation for in situ measurements of cohesive sediment erosion. Journal of Hydraulic Engineering, **132**: 581–588.

Annandale, G.W. 2006. Scour technology: mechanics and practice. McGraw Hill, New York. 430 pp.

Ashmore, P., and Church, M. 2001. The impact of climate change on rivers and river processes in Canada. Bulletin 555, Geological Survey of Canada, Ottawa, Ont.

ASTM. 1995. Standard test method for erodibility determination of soil in the field or in the laboratory by the jet index method (D5852-95). *In* Annual Book of ASTM Standards, American Society for Testing and Materials (ASTM), West Conshohocken, Pa. Vol. 4, pp. 1–5.

Campo, S.H., and Desloges, J.R. 1994. Sediment yield conditioned by glaciation in a rural agricultural basin of southern Ontario, Canada. Physical Geography, **15**: 495–515.

Finkenbine, J.K., Atwater, J.W., and Mavinic, D.S. 2000. Stream health after urbanization. Journal of the American Water Resources Association, **36**: 1149–1160.

Hanson, G.J. 1990a. Surface erodibility of earthen channels at high stresses. Part I. Open channel testing. Transactions of the American Society of Agricultural Engineers, **33**: 127–131.

Hanson, G.J. 1990b. Surface erodibility of earthen channels at high stresses. Part II. Developing an in situ testing device. Transactions of the American Society of Agricultural Engineers, **33**: 132–137.

Hanson, G.J. 1991. Development of a jet index to characterize erosion resistance of soils in earthen spillways. Transactions of the American Society of Agricultural Engineers, **34**: 2015–2020.

Hanson, G.J., and Cook, K.R. 2004. Apparatus, test procedures and analytical methods to measure soil erodibility in situ. Applied Engineering in Agriculture, **20**: 455–462.

Hanson, G.J., and Simon, A. 2001. Erodibility of cohesive streambeds in the loess area of the Midwestern USA. Hydrological Processes, **20**: 23–38.

Kamphuis, J.W., Gaskin, P.N., and Hoogendoorn, E. 1990. Erosion tests on four intact Ontario clays. Canadian Geotechnical Journal, **27**(5): 692–696.

Karrow, P.F. 1991. Quaternary geology of the Brampton area. Open File Report 5819, Ontario Geological Survey, Ministry of Northern Development and Mines, Toronto, Ont.

Simon, A., and Collison, A.J. 2001. Pore-water pressure effects on the detachment of cohesive streambeds: seepage forces and matric suction. Earth Surface Processes and Landforms, **26**: 1421–1442.

Stein, O.R., and Nett, D.D. 1997. Impinging jet calibration of excess shear sediment detachment parameters. Transactions of the American Society of Agricultural Engineers, **40**: 1573–1580.

List of symbols

a exponent
k_d erodibility coefficient ($cm^3 \cdot N^{-1} \cdot s^{-1}$)
ε rate of erosion of cohesive sediment ($cm \cdot s^{-1}$)
τ effective boundary hydraulic shear stress (Pa)
τ_c critical shear stress (Pa)