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Sedimentary characteristics and morphologic change of till-bedded semi-alluvial streams: Medway Creek, Southern Ontario, Canada

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Abstract
We describe the first detailed reach-scale study of an incisional till-bed river. Our analysis focusses on boundary till characteristics, bare till patch features, annual erosion rates, bedform dimensions and spacing, and grain size distributions of bedforms. Results show that till exposures constitute a relatively small portion of the bed and that till erosion rates are relatively high compared to bedrock rivers, although highly variable between till patches and within patches. The bedforms are not well organized in terms of spacing and show high morphologic variability. The sediment forming the bed is poorly sorted, and grain sizes of the bedforms show high variability ranging from fines to large boulders, although gravel contribution from the till to the alluvium is relatively small. We found evidence of some in situ and transport rounding of till clasts. As expected, riffles and steps are coarser while glides and pools are finer-grained. Sedimentary stability metrics show that riffles are unstable, while pools and glides are more stable. These results indicate that the bedform morphology and sedimentology till-bedded rivers differ substantially from their alluvial and bedrock counterparts in a variety of ways. Consequently, we recommend that semi-alluvial rivers be differentiated from their alluvial and bedrock counterparts in future channel classifications. Such a practice will be useful for the river research and practitioners' community to gain the appropriate research tools needed for assessment, management, and restoration practices for these rivers.

Key words: till-bed channel; bedforms, boulders; channel stability; channel classification

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Highlights

- First detailed reach-scale study of an incisional till-bed river.
- Till-bedded channels are often different from their alluvial and bedrock counterparts.

- Till properties are highly variable within site and between sites.
- The reach spatial bedform arrangement is irregular, with highly variable spacing.
- The first natural erosion rates for bed lowering in a till channel are presented.
- Bed structure does not contain the armor layer typical to perennial streams.

1. Introduction

Compared to the vast literature on alluvial and bedrock rivers, understanding is limited of how semi-alluvial channels that are incised into till function and evolve. This lack of attention to till-bedded rivers is surprising as vast areas of North America were glaciated by the Laurentide and Cordilleran Ice Sheets (Ehlers and Gibbard, 2004a; Palacios et al., 2020), and it is also relevant to Europe (Trenter, 1999; Ehlers and Gibbard, 2004b; Prasicek, 2015), South America (Ehlers and Gibbard, 2004c; Palacios et al., 2020), New Zealand (Rainsley et al., 2019), Australia (Browne, 1957) and Asia (Prasicek et al., 2015). Furthermore, as climate warms, more areas will be deglaciated and more glacial deposits will be exposed (Marren and Toomath, 2014).

In North America, the melting of the continental Laurentide Ice Sheet (LIS) following the last Wisconsinan glaciation (Clark et al., 1993) exposed glacial sediments in many Atlantic watersheds (Brakenridge et al., 1988; Marchand et al., 2014), Hudson Bay rivers (Nielsen et al., 1986), and northern Mississippi-Missouri drainage watercourses (Bhowmik, 1979; Gran et al., 2009, Stout et al., 2014; Faulkner et al., 2016). Hence, channels incised into till are common in southern Ontario (Campo and Desloges, 1994; Foster, 1998; Thayer, 2010; Hrytsak, 2012; Phillips and Desloges, 2014 2015a, b: Thayer and Ashmore, 2016; Thayer et al., 2016) and in the wider Great Lakes (Hack, 1965; Arbogast et al., 2008).

These till-bedded rivers, if not pre-designed on pre-glaciation preserved channels (Emery et al., 2020), initially evolved after the retreat of the LIS following the end of the last glaciation and are still responding to base-level fall (and sometimes rise) of the Great Lakes (Thornbush and Desloges, 2011), the Mississippi River (Belmont, 2011; Shen et al., 2012; Gran et al., 2013; Wickert et al., 2013; Faulkner et al., 2016), Hudson Bay (Fraser et al., 2005) and the Atlantic Ocean (Clark and Fitzhugh, 1992), as well as to glacial-isostatic rebound (Lewis et al., 2005) and water deformation (Clark et al., 2007). Many of these channels do not function according to common geomorphic principles, such as formative discharge and bankfull discharge that link morphology to process (Powell, 2006). Furthermore, modern human-induced climate change (Ashmore and Church, 2001; Kling et al., 2003; Novotny and Stefan, 2007) and drastic land modification (Annable et al., 2011; 2012; Woltemade, 1994; Campo and Desloges, 1994; Miller and Nudds, 1996; Fitzpatrick et al., 1999; Belmont et al., 2011) have made these streams much more erosive than in the past because of increasingly flashy discharge from urban land surfaces and quick agricultural drainage with minimal water retention (Knox, 1989; Schottler et al., 2013). Similarly, anthropogenic change has also altered the hydrology, which leads to more frequent extreme flood events (Trudeau and Richardson, 2015; 2016) and changes in sediment delivery rates (Syvitski and Milliman, 2007; Belmont et al. 2011). In many cases, these till-bedded streams no longer resemble natural watercourses, and have altered geometries, low water quality, no floodplain, and high sediment loads (Dickinson and Green, 1988; Papangelakis et al., 2019). Commonly, the expected fluvial outcome when the hydrology, climate and sediment delivery ratios are altered is geomorphic instability, often expressed as extensive channel widening (i.e., bank collapse) and/or deep incision of the beds (Bevan et al., 2018). However, the geomorphic instability is not always conclusive in southern Ontario (Campo and Desloges, 1994; Annable et al., 2012) and the American Midwest (Doyle et al., 2000; Stout et al., 2014), as sediment sources of these channels are highly variable and site-specific (Wilkin and Hebel, 1982; Wilcock et al., 2009; Papangelakis et al., 2019).

The relative lack of scientific understanding of how these streams operate negatively affects management, modern conservation practices and river restoration techniques (Buchanan et al., 2010; Hassan et al., 2014). In North America, the vast application of the controversial Natural Channel Design (NCD; Rosgen, 1996) to semi-alluvial till channels may yield limited benefits or disastrous results that do not reflect natural form and process of these streams (Ness and Joy, 2002; Geomorphic Solutions, 2009; Baldigo et al., 2010). These results include unnatural stability as a result of using very large boulders to stabilize the channel bed and banks (i.e., boulder bed armoring and bank riprap), erroneous use of bankfull discharge values, and a mismatch between design (form) and hydrological and sedimentary processes (Ness and Joy, 2002). Champoux et al. (2003) investigated long-term restoration of a small stream in Wisconsin and found that the morainic section of the channel was highly unstable (i.e., rapid bank collapses and bed incision), further highlighting that restoration schemes should be based on local geomorphic context or process-based restoration (Beechie et al., 2010) rather than on an unsuitable restoration design (Juracek and Fitzpatrick, 2003; Pasternack, 2020).

In contrast to North American riverscapes, in Europe and Australia, different channel classifications schemes emerged for management (Rinaldi et al., 2015) and restoration (Brierley and Fryirs, 2005). In addition to morphology, these frameworks are also process-based (i.e., physical habitat and fluvial hydromorphology combined; Belletti et al., 2017) and have a wider context than only looking at channel morphology. For example, Gurnell et al. (2016) divided channel assessment procedure into three separate stages: First, the functionality of the river reach based on natural and anthropogenic processes in relation to stream type. Second, whether the segment in question fits into the whole catchment, specifically relating to sediment production and fluxes. This part of the assessment has an historical overview of human pressures over various timescales. Third, historical reach and geomorphic unit scale indicators are used to find the rates of change, at different scales with consideration of anthropogenic and natural changes. This wide holistic approach to restoration and management of rivers incorporates the complexities of form and processes methodology, leading to successful restoration and overcoming the challenges of its implementation (Wilcock, 2012). Hence, there is a need to establish a systematic, scientific understanding of semi-alluvial rivers (Phillips et al., 2015a; Papangelakis et al., 2019), similar to our understanding of alluvial (Bridge, 2003) and bedrock channels (Tinkler and Wohl, 1998a, b) and within a defined framework similar to the channel classification proposed by Montgomery and Buffington (1997) for mountain streams, by Turowski et al. (2008) for bedrock channels and by Sutfin et al. (2014) for ephemeral rivers.

However, compared to the vast literature on alluvial and bedrock rivers, the understanding of how semi-alluvial channels incised into till (or other glacial deposits) function and evolve is quite limited. Previous studies on till-bedded rivers either were done on a basin-scale (Hack, 1965; Campo and Desloges, 1994; Phillips and Robert, 2005; Arbogast et al., 2008; Wilcock et al., 2009; Gran et al., 2009; 2011; 2013; Belmont, 2011; Belmont et al., 2011; Stout et al., 2014; Phillips and Desloges, 2014; Hassan et al., 2014; Phillips and Desloges, 2015a,b; Thayer et al., 2016; Thayer and Ashmore, 2016; Faulkner et al., 2016), or were conducted for a different purpose, such as channelization (Landwehr and Rhoads, 2003; Ward et al., 2008), habitat quality (Wang et al., 1997; Blann et al., 2009; Ernst et al., 2010; Marchildon et al., 2011), archeology (Crawford et al., 1998; Stewart and Desloges, 2014), cohesive sediment strength (Shugar et al., 2007; Dasenbrock et al., 2010; Khan and Kostachuk, 2011) or sediment contamination (Rhoads and Cahill, 1999; Wilcock et al., 2009). Broader work focusing on the subject of glacial legacy on river/valley form was mainly done in mountainous terrains (Brardinoni and Hassan, 2006; 2007; Amerson et al., 2008; Addy et al., 2011; Gomez and Livingstone, 2012; Prasicek et al., 2014; Addy et al., 2014; Hassan et al., 2014), and occasionally in lowland semi-alluvial settings (Fola and Rennie, 2010; Collins and Montgomery, 2011; Phillips and Desloges, 2014, 2015a, 2015b; Thayer et al., 2016; Thayer and Ashmore, 2016; Papangelakis et al., 2019). Small-scale laboratory flume experiments were used in isolating specific processes of interest in semi-alluvial channels (Kamphuis, 1983; Kamphuis et al., 1990; Mier and Garcia, 2011; Pike et al., 2018; Papangelakis et al., 2021; Peirce et al., 2021).

Analogous to semi-alluvial bedrock rivers (e.g., Turowski et al., 2008; Meshkova et al., 2012), a semi-alluvial channel incised into till can be defined as “a channel that cannot substantially widen, lower or shift its bed without eroding till”. Once alluvium enters a till channel it becomes a mixed channel setting (Thayer and Ashmore, 2016), i.e., a till-alluvial system, if the channel is either till-constrained (the bed is till), till-confined (the banks are till), or both. The two main research questions we address in this work are: (i) what are the reach-scale sedimentary characteristics and short-term (single hydrological years) morphological changes of a till-bedded river? (ii) How do these sedimentary and morphologic characteristics compare to semi-alluvial, alluvial and bedrock channels? These short-term spatial details and temporal changes are often overlooked or cannot be identified when working on a much larger basin-scale.

2. Study area

2.1. Regional setting

Medway Creek (Fig. 1a, b) drains 205 km^2, flowing into the North Thames River, the larger tributary of the Thames River that flows across southern Ontario into Lake St. Clair. The channel has two main headwater branches: West Fork and East Fork. At their headwaters, the two channel forks resemble shallow ditches, with extensive tile drainage from the surrounding agricultural land. The watershed is confined to the west and northwest by the Lucan Moraine and the channels flow southward through a vast till plain. The East and West Forks converge just north of the village of Arva, after which the main stem flows south along the western toe of the Arva Moraine and enters a millpond at Arva Dam. Below Arva Dam the channel starts to incise and meander in a distinct glacial valley. About 3 km south of Arva, Medway Creek crosses the Arva Moraine into the basin in which the city of London is located. Presently, Medway Creek meanders 12 km from the Arva Dam to its confluence with the North Thames (Dreimanis et al., 1998).

Medway Creek below Arva Dam has incised into several stratigraphic sedimentary units. The oldest unit is Devonian bedrock of limestone and shale, above which six glacial till units can be described (Dreimanis et al., 1998). These sedimentary units thin, thicken or disappear upstream or downstream through the valley because of the competing Huron and Erie Lobes of the LIS (Hicock and Dreimanis, 1992). In addition, lacustrine sediments from Glacial Lake London can be identified on top of the four bluffs of Medway Valley (Bergman et al., 2021a).

Soils in the London area are moderately to poorly drained with a tendency to gley when wet. These include Luvisolic, Brunisolic, Gleysolic, Regosolic and organic soils (O.A.C., 1931; Hagerty and Kingston, 1992), with Gleysolic (poorly drained and prolonged saturation) and Luvisolic (under forested canopy) soils dominating the river and stream corridors. Hillsides along stream courses are frequently eroded, releasing numerous cobbles and boulders contained in the soils.

The climate of the Medway Creek basin is affected by the Great Lakes (Fig. 1a). Climate is temperate, with warm summers, cool winters, and reliable precipitation. Mean annual precipitation ranges from 800 to 1000 mm (Peck et al., 2012). Mean annual runoff ranges from less than 200 mm to greater than 450 mm. Streams carry about a third of the total precipitation (Chapman and Putnam, 1984). Medway Creek is located in the Great Lakes snow belt, and snowfall occurs from October until April with strong lake-effect snowstorms (Niziol et al., 1995).

During the European-American settlement, the natural forests were removed and replaced by agricultural land and urban development. Current land use of Medway Creek watershed is 83% agricultural (all types of crops; seasonal, permanent and livestock), 11% natural and 6% urban (Upper Thames Conservation Authority, 2018). Nonetheless, the main vegetative cover along Medway Creek is deciduous forest, followed by meadow.

Forest cover surrounds the river valley from Arva all the way to the confluence with the North Thames River. Sugar maple (*Acer saccharum*) and American beech (*Fagus grandifolia*) are the main tree species, with silver maple (*Acer saccharinum*) and white elm hardwood (*Ulmus americana*) in swamps and several species of hickory (*Carya*) on well drained sites (City of London Corporate Services Department, 2000).

2.2. Hydrology

The 5-yr mean annual flow of Medway Creek is 2.9 m^3/s (Upper Thames Conservation Authority, 2018), and the largest peak flow recorded was 147 m^3/s in 1977. The natural hydrologic regime follows strong seasonal trends associated with local climate and inherent geologic controls. Small streams in the London area are hydrologically variable (Richards, 1990), referring to their rapid response times to rainstorms or snowmelt events. Land use and soil type appear to be more important than watershed size in determining the runoff characteristics of a given stream or river in southwestern Ontario (Richards, 1990).

As precipitation is fairly evenly spread over the year and periodic thaws occur throughout winter at many locations, classic snowmelt hydrographs are rare (Allan and Hinz, 2004). The rain-on-snow events in late winter decrease the magnitude of the following spring flood. As temperatures warm during April-May, the (remaining) snow begins to melt and the spring flood ensues. Spring flood duration and magnitude depend on the amount of snow on the ground and the rate of increase in temperature. A gradual increase yields a moderate peak discharge and long duration rising limb, while a sharp increase in temperatures may yield a high peak flow and short duration rising limb. If temperatures fluctuate, the flow may contain many sub-peaks, piggy-back bores and the major peak discharge is relatively subdued (Fig. 2). Additionally, the river can convey large ice slabs in winter or early spring, which can create massive ice jams. Rainfall generally increases during summer, but river discharge decreases because of the high evaporative losses and the drying of soils in the watershed. During this time, the entire river discharge is based on groundwater outflow (baseflow) with occasional urban floods. No significant overland flow is generated from the catchment, and the upper parts of the basin become disconnected after the spring flood until late September or October when the basin's soils become saturated again. Flow is only sustained year-round in the lower incised reach below Arva Dam. In rare cases, antecedent high moisture ground conditions coupled with high rainfall may generate a large summer flood (Fitzpatrick et al., 2008). The Arva Mill occasionally uses the millpond water during the summer low flows and pulses the downstream channel for a few hours, but it is almost insignificant to the concurrent discharge. As temperatures drop during late summer into fall, autumn rains wet the catchment's bare soils and reconnect the upper basin to the river, generating flash floods after almost every significant rainfall. Peak discharges during the four-year study period ranged from 26 to 64 m^3/s, discharges that are sub-bankfull to bankfull (see Bergman et al., 2021b).

2.3. Medway Creek study site

The study site is a 1.5 km long, full meander of Medway Creek (~7th meander of the main stem, with a drainage area of 200 km^2) (Fig. 1b, c), which runs through the Medway Heritage Forest and is located just upstream of the confluence with the North Thames River. Medway Creek has been gauged since the 1940s by Environment Canada. The gauging station (# 02GD008) is currently operated by the Upper Thames River Conservation Authority (UTRCA). Where the channel cuts through the Arva Moraine, two near-vertical bluffs (one along the right bank in the center of the meander, and one along the left bank next to the upstream part of the reach) contribute large quantities of sediment to the channel during precipitation events and after the snowmelt. Elevations range between 242 m (riverbed) to 265.4 m (top of the right bank Arva Moraine bluff). The top of the valley is 272.8 m. Medway Creek's bed is about 5 m above Devonian limestone and shale bedrock and separated from it by Catfish Creek Till (Dreimanis et al., 1998).

Bedforms along the reach include pools, riffles, and glides (Figs. 1c and 3), point bars, one braid bar and two steps that are surprising for a reach with such a low slope (0.003%). The main channel does not preserve any bed knickpoints or waterfalls within the erodible till, although till ledges usually exist next to bank toes. However, small tributaries and gullies without sufficient stream power to scour the till do have exposed till waterfalls that imply channel evolution. Scattered coarse boulders (>1024 mm) are found along the reach that are beyond the channel's competence. Large woody debris (LWD) plays a key role in channel morphology as it protects the banks from erosion when logs are parallel to the flow below the bank's toe, but also causes complex flow patterns when they are perpendicular or diagonal to the flow direction, causing localized scour or aggradation of sediments.

3. Methods

A comprehensive survey of channel morphologies (mapping and bedforms) and sedimentology (of alluvium and till) was performed on the full 1.5 km meander of the Lower Medway Valley (Fig. 1b, c). Analyses include:

a. Description of till was characterized by randomly collecting 44 till clasts of various sizes from the riverbed. These included: Munsell color, sediment bulk properties, particle size properties, sediment cohesion properties to determine its erodibility, sphericity, clast volume and visual description of morphology (cracks, borings of aquatic insects leading to bioturbation and roundness). Material strength was obtained from four borehole drillings, which included SPT (Standard Penetration Test) in the field and Atterberg limits for plasticity index in the laboratory.

b. Morphologic mapping and bedform analysis of the 1.5 km reach of Medway Creek determined bed, bank and floodplain elevations using a differential GPS during low flow. The resulting topographic DEM was used to extract the reach's longitudinal profile. The dominant bedforms were identified according to slope and curvature, verified in the field and exposed large patches of till (≥1m in width or length) were added.

c. Both bank heights were measured in the field at 5-m intervals using a stadia rod. These bank elevations were later corrected relative to the thalweg datum (i.e., the height between bank toe and thalweg elevation were added) and imposed on it to create two additional long profiles of the reach. These data aided in developing the channel morphometry parameters, especially downstream hydraulic geometry, width-depth ratios and determining bankfull discharge.

d. Mapping of till patches was done in a separate GPS survey of the channel. This survey gave information about how many patches exist, their size, their areal percentage of the total bed, spacing between patches and relationship to other bedforms and large boulders.

e. Grain size distribution (GSD) analysis of all bedforms and alluvium character were surveyed. Each bedform's GSD included at least three cross sections of Wolman (1954) pebble counts and joined to finer samples ≤32 mm, which were bagged, dried and sieved in the laboratory. Grain size distributions were related to the bedform map (see **b**) using statistical sedimentary attributes and deploying bed stability indices (Kaufmann et al., 2008; 2009; Kappesser, 2002; Lisle and Hilton, 1992; 1999).

f. Monitoring of annual till erosion rates were done using 30 cm long steel erosion pins carefully inserted into two to six exposed till patches (12-53 pins per site). The results were compared to the longer term (geologic) incision rate from a topographic map (valley-scale) with the top of the valley serving as reference level divided by the time since the end of the last ice age. Results from the erosion analysis were compared to short-term channel incision rates for bedrock channels (Tinkler and Wohl, 1998a and references within; Stock et al., 2005).

g. Geomorphic stability analysis was performed on bedforms by deploying four bed stability indices from the literature: the Log Relative Bed Stability ($LRBS^*$) index of Kaufmann et al. (2008; 2009); Kappesser's (2002) Riffle Stability Index (RSI); the fine sediment abundance index, V*, of Lisle and Hilton (1992, 1999) and the bed modality index (Wilcock, 1993). A short explanation for each index appears below.

The $LRBS^*$ method describes the tendency of the bed particles to resist erosion relative to the reference bankfull discharge and is calculated as (Kaufmann et al, 2009):

$$LRBS^* = \log[1.66\theta d_{gm}/(RS)] \qquad (1)$$

where d_{gm} is the geometric mean bed surface particle diameter (m), R is the hydraulic radius (m), S is the bed slope (an approximation of the water surface slope, and θ is the critical dimensionless Shields number. Higher values of $LRBS^*$ indicate higher stability, and values close to zero or even negative indicate that the bed is unstable and prone to scour and induce high rates of sediment transport.

The Riffle Stability Index (RSI) is the geometric mean's (d_g) percentile value on the cumulative GSD y-axis (Kappesser, 2002). The RSI is thus a unitless value between 0 and 100, where higher values indicate higher loading of fine sediments. The main assumption behind this index is that the amount of fines reflects the degree of landscape disturbance in the basin (Lamba et al., 2015), the stability of the bed (Curran and Wilcock, 2005) or alternatively the amount of fines in the depositional riffles affecting the aquatic biota (Mathers and Wood, 2016). Unlike scour pools that are pre-designed to contain large amounts of fines (Lisle and Hilton, 1992; 1999; Rathburn and Wohl, 2003), riffles GSDs contain much coarser sediments. An abnormally eroding landscape, whether natural or human-related, would choke the fluvial system with large influxes of fine sediments that it cannot evacuate on short timescales (Hayes et al., 2002; Benda et al., 2005; Gran and Montgomery, 2005; Bergman et al., 2010), while a functioning river would not significantly scour/aggrade its bed, or change its width (Mackin, 1948; Parker, 1978).

Dimensionless relative volume of bed material V^* is represented by:

$$V^* = V_f/(V_f + V_r) \qquad (2)$$

where V_f and V_r, respectively, are the fine sediment pool volume and residual pool volume for each pool. The scoured pool volume ($V_f + V_r$) equals the residual volume of a pool if the fine sediment were removed (Lisle and Hilton, 1992).

Wilcock (1993) suggested a bimodality parameter, *B*, to quantify the effect of bimodality on critical shear stress of the bed:

$$B = (d_c/d_f)^{0.5} \sum P_m \qquad (3)$$

where d_c is the coarse mode, d_f is the fine mode and $\sum P_m$ is the sum of the two modes, which can take a maximum value of unity for a purely bimodal mixture. If the *B* ratio presents low values ($B < 1.0$), modality is weak, whereas high values ($B > 1.0$) indicate strong modality. We used d_{16} and d_{84} for d_c and d_f, respectively.

h. Alluvial cover thickness and stratigraphy was exposed in 26 random locations along the channel thalweg. The alluvium (or its lack thereof) was characterized by measuring its depth to the boundary till by picking up clasts. In locations where alluvium was thick enough, pits were dug by hand. These pits revealed the vertical sedimentary structure of the alluvium (e.g., armor existence, framework, or censored gravel stratigraphy).

More details of the methods are provided in the Supplementary Materials. The results are compared to other semi-alluvial rivers of the region, as well as to alluvial and bedrock channels to give a broader context to similarities and differences.

4. Results

4.1 Till sediment characteristics

Forty-four till clasts were collected (Table 1). Clasts over ~200 mm (a-axis) were found to be very unstable; either cracking and breaking when exposed to air, or crumbling and breaking down into a slurry when kept in water. This size limit biases our sample collection as it cannot contain large stones that occasionally occur in the till banks and in the bed of Medway Creek. Sphericity of the clasts (median = 0.16) falls into the bladed shape category. The roundness values of the till clasts (median = 0.3) imply some rounding in place or actual transport of the entire till clasts as bedload during floods. The clasts collected from the riverbed alluvium are light grey (10YR7/1 Munsell color) when dry and grey (10YR5/1) when saturated. Fines (silt and clay; <0.063 mm) are the dominant size fraction, with smaller but highly variable amounts of sand and gravel (Fig. 4a; Table 1).

Twenty-three of the till clasts were bioturbated (Fig. 4b), while 21 showed no macro-biological activity (Fig. 4c). Some clasts showed burrowing chironomids (blood worms) when removed from the water (Fig. 4d). The diameter of the holes range from 2 to 8 mm in the bioturbated clasts and up 10 mm deep. The bioturbation of the chironomids holes is the first step in the breakdown of the clast into smaller fractions and removal of the exposed outer layer. Despite the external bioturbation, the till is massive and does not show apparent lamination or bedding. Till clasts that were not bioturbated had an average wet-to-dry-mass ratio of 1.02, suggesting the till was heavily consolidated with no significant voids or cracks that allow water penetration into the material. However, bioturbated clasts had a lower average wet-to-dry-mass ratio (0.97), indicating that some bioturbated till clasts endured breakdown and erosion.

Borehole drillings done during July 2013 for a proposed development included SPT (Standard Penetration Test) (Fig. 5) in the field and Atterberg limits in the laboratory, with seventeen tests conducted in the Medway Valley till (Tridon Properties Limited, 2014).

The till contained intermittent wet sand layers. The Atterberg limits or plasticity index indicate the till is slightly plastic to medium plastic (Table 1), suggesting high clay content. The till properties did not change with elevation. SPT blow count and plasticity index values can be combined to calculate the undrained shear strength of the tested till (Wroth and Wood, 1978) (median = 280 kN/m^2; Table 1).

4.2 Till exposures, boulders, and erosion of the boundary till

We detected and measured 24 patches of till that have at least ≥1 m of exposure as one of their dimensions (width or length) (Fig. 1c). Such exposures are visible while walking along the channel at almost all flow conditions as their pale color is quite distinct from neighboring gravels (Figs. 6c, d and 7a-c). Till patches of this size constitute 598 m^2 of the bed, 0.03% of the study reach. However, converging the numerous smaller till patches that are sometimes one or several clasts in size and did not pass the dimensional criteria, we visually estimate that the true number is two to three orders of magnitude higher and 5-10% of the bed is devoid of alluvium. These low values of till exposures bring us back to the definition of a till-bedded stream, that it must erode its till boundary (bed, banks, or both) to change (widen or incise) its geometry. In our case study, the thin alluvial bed cover is not sufficient to make the channel an alluvial river, but it is a transitional channel. Under the occurrence of a significant large, basin-scale runaway alluviation process, it is possible that a semi-alluvial till channel will shift to an alluvial river if production of sediment and surficial deposits (and consequent alluvium river cover) will override the till boundary. The opposite condition is that the till boundary is completely removed and the channel behaves as an ordinary alluvial channel (Martini, 1977) or bedrock channel (Hack, 1965). It seems that the assertion of early glaciologists such as Ruhe (1952), Ruhe and Scholtes (1956), Goldthwait (1959) and Dreimanis (1962), that time is crucial in a deglaciated landscape evolution and development (i.e., ice retreat, soils, fauna and flora), also applies today to young riverscapes flowing over and incised into these glacial sediments (Brakenridge et al., 1988; Knox, 1989; Campo and Desloges, 1994; Phillips and Robert, 2005; Arbogast et al., 2008; Gran et al., 2009, 2011, 2013; Wilcock et al., 2009; Belmont, 2011; Belmont et al., 2011; Gomez and Livingstone, 2012; Marchand et al., 2014; Phillips and Desloges, 2014; 2015a, b; Papangelakis et al., 2019, 2021).

Analysis of 26 random locations along the study reach thalweg revealed that alluvium thickness ranges from 0 (i.e., no alluvium at all and exposure of the boundary till) to 62 cm at riffle tails (average depth = 20 cm, median = 10 cm). In the same creek, Hrytsak (2012) found in two reaches an average alluvium depth of 24 cm, which is quite similar to our results. In many pools, glides, and riffle heads the alluvium has a thin cover, where beneath a single clast lies the till substrate. This suggests that the till boundary is highly prone to abrasion and impact erosion if the protecting alluvium is removed during sediment transport - the tools and cover effect (Kamphuis, 1983; Johnson and Whipple, 2007; Chatanantavet and Parker, 2009; Turowski and Rickenmann, 2009; Johnson and Whipple, 2010). In contrast, in the riffles' centers and tails the alluvium thickens and the cobbles are highly interlocked with sandy fines filling the matrices. These sedimentary structures are, therefore, much more difficult to break.

Exposed till patches appear in pools, riffles, and glides, but not in steps (Fig. 6a) and bars. In many cases, the till patch is a continuation of the almost vertical bank till and forms a ledge and complex cross section with an inner terrace-like shape (Figs. 6b, c and 7a, b).

Where there is a steep gradient between the ledge and bed below, the exposed till ledge cannot alluviate from incoming bedload transport as it is topographically disconnected (i.e., higher) from the nearby deeper active bed (Figs. 6b, c and 7a, b). However, the till ledge might be partially alluviated (i.e., it has some gravel on top) from *in situ* gravel that is embedded within the till matrix (Fig. 8a) or eroded out of it, as was also found by Mier and Garcia (2011) when they eroded a till slab in a flume. The exposed submerged till might be smooth and surrounded by alluvium (Fig. 8b) or with cracks and topographic irregularities (Fig. 8c). Occasionally, loose coarse material covering the till surface can originate from collapsed bank (Fig. 6d) or bluff (Fig. 7a) material. It is worth noting that besides bank ledges, the till itself does not preserve the abundant sculpted forms described for bedrock channels (Richardson and Carling, 2005).

We identified 275 boulders (≥500 mm) along the study reach. Correlation of boulder location to the 24 till patch exposures nearby shows that boulders are not the direct cause for the boundary exposures, neither in terms of distance nor in size. This finding negates the alluviation hypotheses proposed by Chatanantavet and Parker (2008), that under low sediment volume conditions in the channel, boulders serve as large roughness elements that generate local alluviation. When there is greater volume of sediment in the channel, different bedforms develop, but bed exposures might be present as the thickness and roughness of the alluvium coupled with shear stress, determine the local entrainment, translation, and deposition (Hodge et al., 2011; Hodge and Hoy, 2012; Inoue et al., 2014). Furthermore, only when the sediment supply to the channel is abundant will the bed exposures completely disappear, i.e., the bed will be experiencing runaway alluviation (Chatanantavet and Parker, 2008; Johnson, 2014).

Recovery rates of the erosion pins during four years were 57-100%, with an average of 65%. During two of the hydrological years (HY 2011-2012 and HY 2012-2013), the largest erosion pin patch (53 pins) next to the right bank was buried by a massive collapse of the till bank (estimated initially at 15 m^3) that merged into the bed so that recovery of pins by the end of the hydrologic year was calculated as zero. The patch was re-exposed during HY 2013-2014 after the removal of the reworked till. There are two to six different patches per year and a total of eleven patches (Table 2). Bed-lowering erosion rates are highly variable, both spatially and temporally (Table 1). Spatial autocorrelations using Moran *i* reveal that there is no dependence of neighboring erosion pins within each patch, nor between the patches. The extreme erosion of one of the pins (260 mm in one year) seems unusually high compared to the other pins but also to bedrock incision rates (Tinkler and Parish, 1998; Wohl and Ikeda, 1998; Whipple et al., 2000a, b; Stock et al., 2005). This could possibly be caused by the removal of a large chunk of till around the erosion pin. Alternatively, it could be caused by the erosion pin protruding into the flow and being continuously and preferentially impacted by moving grains, thereby further increasing the erosion of the till. This preferential path of moving particles drawn into a local topographic low in the bed has a positive transport feedback mechanism as it lowers the more sediment passes above it (Johnson and Whipple, 2007).

4.3 Bedform dimensions and spacing

Following the detailed bedform classification of Montgomery and Buffington (1997), we identified 43 bedforms in the study reach (Fig. 1c). Five of these are bars, which were excluded from the bedform analysis because they lack low-flow connectivity to the upstream and downstream bedforms and are only activated during exceptionally high flows. This identification is designed to test whether the typical bedform coupling (i.e., pools and riffles, stepped-bed morphology and glides and riffles), appearing in alluvial rivers (Bowman, 1977; Keller and Melhorn, 1978; Platts et al., 1983) and in alluviated bedrock channels (Martini, 1977; O'Connor et al., 1986), also exist in this semi-alluvial setting. Their grain size distributions are discussed below. The remaining 38 continuous bedforms consist of 15 riffles, 13 pools, 8 glides and 2 cobble-boulder steps (Table 1; Fig. 9).

The spatial bedform arrangement is irregular, with highly variable spacing (Table 1). In addition, the typical bedform coupling of alluvial rivers does not apply to the study reach, as in many instances there are intervening bedforms that disrupt this organization (Fig. 1c). Thus, nine of the bedforms in between riffles are pools, three are glides and two are a variety of bedforms. For pools, eight of the intervening bedforms are riffles, one is a glide and three are a variety of bedforms, while for glides the intervening bedforms are two riffles, one step, one pool and three are a variety of bedforms.

The two boulder steps span the whole channel width: the upstream step is 10.4 m wide and the downstream step 13.3 m wide (Fig. 6a). The steps separate steep reaches into a series of riffles and pools. The upstream step separates two glides and the one downstream is between a pool and glide. The existence of these steps can be assumed to be related to the contrasting internal lithology of the eroding till; predominantly contributing fines to the alluvium but also contributing cobbles and boulders, as found in other headwater streams (Hattanji et al., 2012).

4.4 Grain size distributions and alluvium structure

The two steps were stationary during the study period, i.e., they did not change location or migrate, somewhat like a steady local base level (Bowman, 1977). Despite their coarse size, the steps are not a stagnant sedimentary body, and they break down and re-form during high flows. Comparing their annual GSDs reflects the behavior of the mobile coarse fraction of the entire channel, similar to higher elevation point bars in alluvial channels (Nunally, 1967). Sedimentary changes occurred in the GSDs of the steps over the four-year study period. The d_{50} of the upstream and downstream steps fined (from 159 mm down to 118 mm and from 182 mm down to 178 mm, respectively). On the other hand, the coarser tails of the GSDs, from d_{84} and larger, show that the upstream step coarsened while the downstream one fined (d_{max} of 770 mm went up to 920 mm and 840 mm declined to 700 mm, respectively). The margin of error of these step surveys is assumed to be relatively small for three reasons: (1) the same veteran operator repeatedly conducted the GSDs sampling (Wohl et al., 1996), (2) the same exact method was used, and it is highly reliable for gravel-boulder bed channels (margin of error 6-12% according to Wohl et al., 1996), and (3) the step bedform sampled was not mixed with other nearby upstream/downstream bedform populations (Bowman, 1977; Kondolf, 1997). Hence, we conclude that boulders of certain sizes were mobile on Medway Creek because step stability is dependent on the mobility of framework particles (largest grains in the channel bed; Tribe and Church, 1999), and these are reflected in the d_{84} and larger particles in coarse channels (Chin, 1998). Warburton (1992) described the destruction of step morphology in a proglacial mountain stream as the upper phase of a flood by a three-phase bedload transport model. Furthermore, there is evidence of step-forming boulder mobility even during relatively frequent floods with return intervals of 5 yr (Billi and Preciso, 2003; Lenzi et al, 2004).

Ledges (Figs. 6b, c, 7 and 8a) are the only sculpted forms that are preserved within the till geometry. We did observe a boulder lag at the toe of the right bank bluff, almost bar-like in shape (Fig. 6d). Because this bluff is an outer meander cut bank, we believe the boulder lag reflects the inability of the channel to transport these boulders during most flows, especially because nearby till exposures suggest high shear stress during floods (Fig. 6d).

The GSDs of all 43 bedforms (pools, riffles, glides, bars, and steps) are mostly bimodal (65%), especially for the riffles (73%), pools (77%), and bars (60%), and less so for the glides (37%). By bedform, most of the bed is poorly sorted (84%) while the remaining bedforms are moderately sorted. By bed area, 77% of the bed is poorly sorted while the rest is moderately sorted. However, it is difficult to discern any trends as the grain sizes of the bedforms overlap both in the fine and coarse tails, except for Point bar 3, which is much finer than the rest. This bar is more typical of braided glacial sediments where there is abundance of fine sediment production and transport (Williams and Rust, 1969). To overcome this difficulty, we average the GSDs of all bedforms by their type. This shows that pools are finest (d_{50}=43 mm), followed by bars (d_{50}=52 mm). Glides are intermediate (d_{50}=72 mm), and riffles and steps are coarsest (d_{50}=110 mm and 140 mm, respectively). The pools and glides are almost identical in their coarse tail (d_{70} and larger). The steps show a much coarser distribution than all other bedforms, but considering that this GSD is based only on two bedforms and their limited total area of the bed, it would be wrong to draw any major conclusions about the whole bed from them. However, the GSDs of the steps changes with time, which are a good indicator of the behavior of the coarse bedload fractions and whether boulders of certain sizes are mobile or not (see below).

Two types of bars exist along the reach: four point bars and one braid bar just below the downstream step. The sedimentary importance of the bars lies in the fact that they are slightly elevated above the immediate channel and dry most of the time, i.e., they represent the sediment composition that is transported as bedload during high flows (Leopold, 1994), although the sand fraction can also be entrained in suspension (Nunally, 1967). They constitute <1.0% of the total area of the reach. Looking at their coarse tails shows that they contain few large cobbles and small boulders (256-512 mm). Point bar 3 is significantly finer than its counterparts and is entirely composed of sand.

The sorting index (SI) of all bedforms conforms to poorly sorted to very poorly sorted gravels (Table 1). If partitioned into bedform types, riffles, glides and point bars are better sorted than the pools. The two steps, containing mainly cobbles and boulders, and the braid bar are the best sorted bedforms (Table 1).

The sand fraction of the distributions (≤2 mm) shows that the predominantly fine-grained composition of the till is not directly reflected in the bedforms. As expected, pools have the highest sand representation (median = 11.1%; Table 1), followed by glides (5.3%) and riffles (4.5%), while the steps have the lowest sand fractions (2.7%). The bars were devoid of any sand during the sampling survey, apart from Point bar 3, which was entirely made of sand.

4.5 Channel stability

Geomorphic stability is defined as a channel that is adjusted to its hydrology and sedimentology, meaning that bank and bed erosion rates are within natural variability for that area and the river has the capability to transport incoming sediments from hillslopes and upstream without going through major deposition or scour. Pools, which would be expected to scour during high flows, are the most stable bedforms according to the LRBS*, followed closely by glides (Table 1; Fig. 10a). The depositional riffles are the least stable bedform in the reach (Table 1; Fig. 10a). The LRBS* of the whole reach equals 0.8, which is higher than the Carson River, Virginia Rivers and Pacific NW rivers (Fig. 10a).

The RSI for Medway Creek's riffles are relatively low (average and median = 38) (Table 1; Fig. 10b), suggesting that the riffles are stable too – an observation that might be discordant with the LRBS* findings that riffles are the least stable bedform (Fig. 10a). The narrow range of RSI values (31-48) also indicates that all riffles possess similar attributes, with relatively low textural variability.

Fine-sediment abundance can indicate a reduction in transport capacity without a compensating decrease in sediment supply. Pools are usually the best indicator sites for fine sediment abundance. To test an abundance of fines metric on Medway Creek we implemented the technique proposed by Lisle and Hilton (1992, 1999) on the 13 pools of the study reach. Because we conducted the GSD sampling with a 32 mm truncation between Wolman pebble counts and sieved fractions (coarse gravel to very coarse gravel transition), we used this clear boundary to define the finer material (V_f). This truncation point for fines is coarser than the traditional sand-gravel transition (2 mm). However, on a channel like Medway Creek that has a wide GSD from silt-clay till patches up to medium boulders, the coarser transition is fitting to reduce the sampling bias of the fine tail of the distribution. The relative volume of fine sediment in pools is low (median = 0.03; Table 1; Fig. 10c), indicating that the pools are stable, similar to the results for LRBS*. Only the value for the fifth pool is unusually high ($V^* = 0.15$) compared to other pools. This pool is just downstream of the right bank bluff, which might be the cause for fines loading, although the first pool downstream of the left bank bluff does not show the same fines loading.

Sediment modality is another indicator of bed stability, as bimodal sediment is less stable than unimodal sediment and consequently results in higher transport rates and sediment yields (Wang et al., 2015). Furthermore, bimodal beds may represent a distinct threshold between gravel-bed and sand-bed states (Sambrook Smith, 1996). This could reflect the parent material composition as each peak represents a distinct population of different material supplied to the stream, or material of the sizes between the peaks could be structurally unstable and quickly break down into sand-size particles (Wolcott, 1988). If the sediment mixture is weakly bimodal, the critical shear stress of individual fractions will show little variation in grain size and will depend only on the mean grain size of the mixture (i.e., d_{50}). For strongly bimodal sediments, fractional critical shear stress increases with grain size, an apparent result of lateral segregation of the finer and coarser fractions on the bed surface that causes fractional critical shear stress to deviate from size independence in the direction of unimodal (Shields) values (Wilcock, 1993). The till from Medway Creek presents a high modality parameter value of 5.9.

5. Discussion

5.1 Till sediments, till exposure and till erosion

While a comparison of till properties between different sites and types of tills is difficult because of different techniques used by researchers, grain sizes and bulk density in Medway Creek are comparable to those of selected tills of the Great Lakes area (Fig. 11a-c). Critical shear stress for Medway till slabs is comparable to that of other southern Ontario streams (Fig. 12).

Turbid water is more erosive on exposed till than clear water (Mier and Garcia, 2011), mainly because of direct particle impacts on till (Kamphuis, 1983; Kamphuis et al., 1990; Pike et al., 2018). Medway's till is dominated by mass erosion, which occurs around natural planes of weakness and irregularities, like gravel particles, within till (Pike et al., 2018), which can lead to spatially variable erodibility. Tools and cover effect (Turowski and Rickenmann, 2009) depend on sediment supply from upstream, but complete cover effect of alluvium protecting till can only occur when sediment is thick enough to prevent till coming into contact with moving alluvium or the shearing action of the flow, which is not the case for all of the bed of Medway Creek.

In bedrock channels coarse stationary material that creates high roughness and turbulence is assumed responsible for alluviation and protection of the boundary from incision (Chatanantavet and Parker, 2008). However, that appears not to be true for till-bedded Medway Creek, as there is no apparent relation between till patch and boulder size or positioning. Over the study period we observed that the top 1-2 cm of the till bed became soft while the underlying till remained consolidated. This corroborates the proposal by Chatanantavet and Parker (2009) of a bedrock "battering layer" overlying an aging layer. However, we did not observe plucking (Whipple et al., 2000a) or sculpted forms (Richardson and Carling, 2005) that appear in bedrock channels, besides ledges next to banks (Figs. 6b, c and 7).

There are currently no published natural erosion rates for bed lowering in till channels to compare. Erosion rates of till banks in two Irish rivers ranged between 30-60 mm/yr, with high variability within site and between sites (Hill, 1973). Comparison of Medway Creek to erosion of bedrock channels indicates that Medway's maximum erosion rates are of the same order as reported rates for bedrock channels (Stock and Montgomery, 1999). These short-term values are very high relative to geologic erosion rates for till, which is similar to results for bedrock channels (Stock et al., 2005; Kent et al., 2021). This may be caused by: (i) periods of rapid valley incision and of relaxation when the channel reaches hard substrate; (ii) climate-induced flow variability (i.e., less precipitation and flows); or (iii) spatially and temporally variable incision, depending on local hydraulic/sedimentary/tectonic conditions.

Spatial heterogeneity in erosion within patches and between patches is probably related to till consolidation and tensile strength. Alternatively, at this patch-scale, the local bed relates to microtopography (Fig. 7): a low-lying exposed till patch constantly draws moving grains toward it, i.e., once thin alluvium is in motion gravel particles accelerate over till because of the sudden change in boundary roughness (Finnegan et al., 2007), damaging it by rolling impacts and sliding friction (Kamphuis, 1983; Pike et al., 2018). A positive feedback mechanism occurs in which the till patch continuously erodes by moving particles.

5.2. Bedforms and alluvium

Typical alluvial rivers' bedform coupling of pools-riffles, glides-riffles and steps-pools does not apply to our study reach, as there are intervening bedforms that disrupt this sequence (Fig. 1c). Boulder steps were coined by Martini (1977) as "small scale riffle bars" or "large scale transverse ribs". While they are distinct and unusual for a low gradient channel, these unusual bedforms also appear in other nearby semi-alluvial channels incised into till (authors' personal observations). However, boulder steps are located >1 km apart in our study reach, so we cannot relate them to the boulder steps in other studies. We cannot say that any of the boulders moved during our study and conclude this is an immobile part of the bed, originating from till in the bed and banks rather than being fluvially transported. Fine tails of gravel and sand in both steps were non-existent in early sampling and not caused by sampling truncation or error. Thus, steps can trap finer bed fractions in large voids between cobbles and boulders.

A key sedimentary feature of sediment availability from banks and hillslopes, and the extent of mobility of alluvium during floods, is armoring of the bed (Parker and Klingeman 1982; Dietrich et al., 1989) or its absence (Laronne et al., 1994). Armoring suggests low sediment supply from upstream or lateral inputs, leaving a coarse lag at the surface when fines are winnowed, so that minimal bed mobility occurs (Parker, 1990). Conversely, thick non-graded alluvium implies high sediment supply and mobility (Powell, 1998), although moving along the stream can yield variations in armoring even if sediment supply is high (Lisle and Madej, 1992) or when the riverbed is patchy with a wide grain size distribution (Paola and Seal, 1995). For a bed structure to form, a minimum thickness of alluvium is needed – the active layer, associated with scour and fill processes, was found in a flume to be up to 10 grain diameters (d_{50}) below the surface (Church and Haschenburger, 2017). However, in some instances, such as desert streams, there is abundance of sediment supply and the active alluvium can be several meters thick (Lekach et al., 1998).

Based on 26 sites in the alluvium of Medway Creek where depth to till was measured, a relatively homogenous vertical structure was found from the surface down to the till. This also occurs in other southern Ontario streams, which have a low armor-ratio ($d_{50Surface}/d_{50Subsurface} < 2$) (Annable, 1996). If armor-ratio metric is valid for streams like

Medway, as for alluvial streams, this indicates that there is much sediment supplied from upstream till banks and bed. This implies that till exposures are not the result of a sediment shortage (i.e., enough within-reach sediment blankets the bed), but of local hydraulics.

5.3. Channel stability

Geomorphic channel impairment is generally defined as a constant imbalance between a river's hydrology and sedimentology (process and form), indicating that the river is not functioning properly. This negative state contrasts with natural variability as the river's channel form and process maintain quasi-equilibrium (Mackin, 1948; Parker, 1978).

The LRBS* values indicate that bedforms in Medway Creek are more stable than alluvial rivers (Fig. 10a), whereas results for alluvial streams indicate higher RSI values (Fig. 10b). Lack of research on till channels makes it hard to conclude whether Medway's low RSI's are normal, indicate control by till texture, or reflect disturbance from land use.

Large amounts of fine sediment in our pools, V^*, support LRBS*: pools are the most stable bedform of our reach (Fig. 10a, c). Compared to alluvial rivers, values of V* in Medway Creek are low (Fig. 10c). In alluvial rivers, V^* can indicate reduced transport capacity without decreasing sediment supply. If the bed is sediment-starved, a coarse surface layer of armor will develop once fines are winnowed (Dietrich et al., 1989). If sediment supply exceeds transport capacity, fines will dominate the surface layer (Laronne et al., 1994; Hayes et al., 2002; Gran and Montgomery, 2005; Bergman et al., 2010). Excess fines in a riverbed can be a negative component of GSD: they block gravel pores, smooth the surface, reduce roughness, and affect fish habitat quality and spawning (Everest et al., 1987). Fines increase bed instability by reducing the shear stress needed to entrain coarser grains (Wilcock et al., 2001). It is unclear if the abundance of fines is a reliable stability metric in a river where the boundary material produces large amounts of fines.

Lisle and Hilton (1999) distinguished river channels with fines from poor parent materials, and fines from rich ones. The latter show that V* varies from 0.01-0.50, with an average of 0.2 and a median 0.19 (n =22). Sediments in Middlefork River, Illinois that, like Medway, incised into glacial sediments, are eroding from in-channel sources (bed, banks, farmed floodplains) rather than farmed uplands (Wilkin and Hebel, 1982).

Three of the channel stability metrics we applied (LRBS*, RSI, V*) were developed for alluvial rivers and have not yet been applied on till-bedded rivers. If they are robust measures of till channel stability, as they are for alluvial channels (Rathburn and Wohl, 2003; Pahl, 2006), they suggest that the bed is stable.

In a wider context, we compare bed of Medway Creek to three rivers where local geology produces rapid breakdown and a high supply of fines: Nahal Eshtemoa of the Negev Desert in Israel (Powell et al., 1999), a semi-alluvial, semiarid, gravel-bed channel incised into loess; Nahal Me'arot of Israel (Greenbaum and Bergman, 2006), eroding tuffs and limestone; and the West Walker River of California that flows into a rain shadow desert and eroding granites (Bergman et al., 2010). Medway Creek and the West Walker River are perennial rivers dominated by spring snowmelt, whereas Nahal Me'arot and Nahal Eshtemoa are flashflood-prone ephemeral wadis. While bed structure and composition are mainly controlled by sediment supply (Parker and Klingeman, 1982; Dietrich et al., 1989; Laronne et al., 1994), hydrograph shape and duration effects on bed stability produce similar sediment stability outcomes (Hassan et al., 2006).

Medway Creek falls between ephemeral and perennial desert rivers, with the GSD of Medway finer than the West Walker River but coarser than Mediterranean volcanic and semiarid GSDs (Fig. 13). There is not an unusual amount of fines (<2 mm), although if truncation of fines is increased to 32 mm (medium gravels), as we calculated V^*, it is one third of the bed. This value suggests that the shear stress needed to entrain much of the bed is not high, indicating bed instability. All four riverbeds are bimodal, trimodal and polymodal, and consequently unstable (Table 3; Fig. 13). Thus, the loading of fines in Medway Creek is not abnormal. When studying rivers with a unique geology, sediment metrics should be used in context: with background bed fine levels or as part of a long-term monitoring program in which changes can be detected and cause and effect distinguished (Lisle et al., 2015). More sedimentary datasets are needed from fine-rich channels to isolate non-alluvial/geologic controls or signatures from normal fluvial process variability typical of alluvial channels free of non-fluvial constraints (Wolcott, 1988; Sklar et al., 2006).

Although Medway Creek is an incised channel, and its stability results are higher than values for alluvial rivers, it would be incorrect to assume in-stream habitat quality based on sedimentary/hydraulic criteria alone without taking biological inventory (Duncan et al., 2011). From an ecologic viewpoint, with 44 species, Medway Creek has the highest fish biodiversity in any southern Ontario stream (John Schwindt, Upper Thames River Conservation Authority biologist, personal communication). High fish biodiversity implies a healthy and stable stream system, suggesting geomorphic-sedimentary stability metrics are adequate at this stage to assess channel state.

6. A case for a new channel classification category

In all historic channel classifications in humid-climate environments (e.g., Leopold and Wolman, 1957; Kellerhals et al., 1976; Rust, 1977; Rosgen; 1994b; Kondolf, 1995; Montgomery and Buffington, 1997; Newson and Newson, 2000; Church, 2002), semi-alluvial channels in general, and till-bedded channels in particular, do not receive specific treatment. The river researcher or practitioner thus needs to assume they are a hybrid between bedrock channels and alluvial channels, often just treated as low gradient, sinuous gravel-bed rivers (Hartley, 1999; MacVicar and Roy, 2011; Marchildon et al., 2011).

Under certain circumstances, when bed alluviation is sufficient, semi-alluvial channels may indeed behave as regular alluvial rivers – as was shown in Irvine Creek, a bedrock tributary of the Grand River, southern Ontario (Martini, 1977). However, our results, and anecdotal research from other studies on till-bedded rivers, show that semi-alluvial till-bedded channels are fundamentally different from both alluvial channels and bedrock channels in many aspects: (1) high variability in till erodibility, both within the same till and between tills; (2) inconsistent bedform arrangement; (3) lack of one dominant discharge such as the bankfull or effective discharge; (4) anomalous grain sorting processes that are a mix of fluvial and non-fluvial controls; (5) large spatial variation in alluvium thickness; and (6) alluvium structure that does not resemble the 2-layered armor structure typical of perennial alluvial rivers.

We therefore argue that all semi-alluvial channels deserve a category of their own between bedrock channels and alluvial channels in all future channel classifications. The differentiation of a new category has three main implications:

1. The geologic constraint, conditioning or legacy of semi-alluvial rivers should be explicitly considered rather than merely an overlooked background detail. The

historical context may better explain form and processes and reveal the non-fluvial component of the landscape. Such a legacy exerting some control on river evolution is not necessarily restricted to tills or other glacial deposits, but could also relate to incised loess channels (Seginer, 1966; Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1994; Rozin and Schick, 1996; Hanson and Simon, 2001; Craddock et al., 2010; Bergman et al., 2014) or channels loaded with eroded volcanic materials such as tuff, pumice, tephra and ash (Collins et al., 1983; Major et al., 2000; Hayes et al., 2002; Greenbaum and Bergman, 2006).

2. The degree of control that non-alluvial material exerts might be associated with time scale and changing climate – if the material was completely exhumed, the channels may behave as ordinary alluvial or bedrock channels. For example, in the Great Lakes region, both Hack (1965) and Martini (1977) describe channels that incise into bedrock, i.e., the glacial deposits were completely removed since the end of the last ice age. Elsewhere, rivers encounter tills or other glacial deposits. The early work of Ruhe (1952) identified age as a crucial factor in drainage density and drift exhumation – the younger moraine tills of the Des Moines Lobe are less eroded than those that were uncovered earlier, thus creating distinct topographic surfaces with various degrees of incision, even though they are all from the last Wisconsinan glaciation. On a shorter time scale in a tropical climate, Hayes et al. (2002) described extreme fine sediment loading following the eruption of Mount Pinatubo in 1991 on the Pasig-Potrero River (Philippines) that was covered by 33% of pyroclastic flows. In the same river, Gran and Montgomery (2005) showed the rapid evacuation of those volcanic sediments and

the change from braided pattern with massive sediment transport to single-thread armored channel, with clear water indicating the recovery and return to geomorphic stability.

3. Once semi-alluvial channels become their own category, it will be possible to implement appropriate management and restoration schemes instead of using practices borrowed from alluvial rivers, such as Rosgen's NCD that proved to be inadequate (Ness and Joy, 2002), or from river ecology such as fish habitat enhancement using installation of in-stream structures that also failed to improve habitat (Champoux et al., 2003). Specifically, it will be possible to reconstruct an official archetypal river model or to design a handbook that managers and practitioners will be able to use and focus their actions based on sound river science.

Such a classification not only places semi-alluvial channels within a defined river framework but also allows us to distinguish between form and process, a highly debated topic in stream restoration and management (Kasprak et al., 2016). Once there is sufficient data collected, it will enable us to develop specific metrics suitable for these streams with the historic or management context of an ultimate or optimal morphological form rather than just using a rapid assessment protocol to describe healthy/impaired river condition (Lisle et al., 2015).

The establishment of a theoretical framework coupled with real case studies that identify the uniqueness of semi-alluvial till-bedded rivers needs to be supported by appropriate metrics as used in this work. However, rapid assessment protocols are not enough to judge the immediate state of a river (Lisle et al., 2015) and deeper understanding based on long-term monitoring of a variety of effective variables is needed to supplement such a program done every few years. Presently, the sources of till within channels are poorly understood and it would be beneficial to understand these sources by fingerprinting (Belmont et al., 2011), as was also done for mountainous bedrock channels (Riebe et al., 2015). Understanding where the sediments originate from, whether from the watershed (ultimate source) or simply the till lining the channel bed and banks (local source), is a crucial step in any management program that allows river personnel to understand what are normal levels of sedimentation (within natural variability) and what rates indicate degradation and impairment that might need artificial intervention to restore the channel back to a healthy state.

7. Conclusions and recommendations

A comprehensive dataset is presented of a glacially-conditioned 1.5 km long meander on Medway Creek, London, southern Ontario, Canada. The dataset includes till characteristics, natural setting till erosion rates (annual bed lowering), bedform features and bed stability analysis using a variety of sedimentary metrics and a comparison to other rivers with abundant fines. Bed till exposures constitute a relatively small portion of the total bed area. Nearby upstream boulders of various sizes do not seem to be directly related to till patch area regardless of their position. Erosion rates are comparable to channels incising into soft bedrock and are very high compared to the local incision rate. Bedforms are highly disorganized and show no regular spacing that is typically found in stable autogenic bedrock and alluvial rivers. The channel does not show typical alluvial sorting processes implying some non-fluvial control. Alluvium thickness is also highly variable from non-existent (exposed till substrate) or one grain thick up to 60 cm deep at riffle tails where they plunge into a subsequent pool or glide. The typical two-layered armor structure ordinarily seen in perennial alluvial rivers is completely missing. The sand fraction that is a known destabilizing fraction of the bed in alluvial channels is not as dominant along the various bedforms as one would expect. Channel stability analysis, using four different sedimentary attributes from the literature, shows that Medway Creek is stable in the investigated study reach. Furthermore, it does not seem anomalous compared to other rivers in which the geology generates large quantities of sediment.

We recommend that till rivers receive more attention from the fluvial scientific and practitioners' communities as knowledge about them is currently lacking. While till rivers cover vast extents of formerly glaciated areas around the world, they are completely ignored in present river classifications. Based on our study and other investigations of similar channels within glacial deposits, semi-alluvial channels deserve to be a category on their own. This is not only relevant for river classification, but this knowledge gap also has implications for everyday management and restoration practices and whether current indices such as channel geometry and stability metrics are suitable and adequate to determine impairment and river health.

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References

Aberle, J., Nikora, V., Walters, R., 2004. Effects of bed material properties on cohesive sediment erosion. Marine Geology 207, 83-93.

Addy, S., Soulsby, C., Hartley, A.J., Tetzlaff, D., 2011. Characterisation of channel reach morphology and associated controls in deglaciated montane catchments in the Cairngorms, Scotland. Geomorphology 132, 176-186.

Addy, S., Soulsby, C., Hartley, A.J., 2014. Controls on the distribution of channel reach morphology in selectively glaciated catchments. Geomorphology 211, 121-133.

Allan, J., Hinz, L., 2004. An Assessment of Flows for Rivers of the Great Lakes Basin. School of Natural Resources & Environment, The University of Michigan, Ann Arbor, Michigan, Final Report to the Great Lakes Protection Fund, October, 2004, Available from: http://www-personal.umich.edu/~dallan/pdfs/GLPF_Report.pdf. Last accessed on June 5th, 2013.

Amerson, B.E., Montgomery, D.R., Meyer, G., 2008. Relative size of fluvial and glaciated valleys in central Idaho. Geomorphology 93, 537-547.

Annable, W.K., 1996. Morphologic relationship of rural watercourses in southern Ontario and selected field methods in fluvial geomorphology. Credit Valley Conservation Authority, Ontario Ministry of Natural Resources, Peterborough, ON, 92 pp.

Annable, W.K., 1999. On the design of natural channels: decisions, directions and design. In: Stream Corridors, Adaptive Management and Design: Proceedings of the Second International Conference on Natural Channel Systems. Niagara Falls, Ontario.

Annable, W.K., 2003. Short comings in applying regional hydraulic and morphologic databases in Natural Channel Design projects. Hydrology Days.

Annable, W.K., Lounder, V.G., Watson, C.C., 2011. Estimating channel-forming discharge in urban watercourses. River Research and Applications 27, 738-753.

Annable, W.K., Watson, C.C. Thompson, P.J., 2012. Quasi-equilibrium conditions of urban gravel-bed stream channels in southern Ontario, Canada. River Research and Application 28, 302-325.

Arbogast, A.F., Bookout, J.R., Schrotenboer, B.R., Lansdale, A., Rust, G.L., Bato, V.A., 2008. Post-glacial fluvial response and landform development in the upper Muskegon River valley in North-central Lower Michigan, U.S.A. Geomorphology 102, 615-623.

Ashmore, P., 1999. What would we do without Rosgen?: rational regime relations and natural channels. In: Stream Corridors, Adaptive Management and Design: Proceedings of the Second International Conference on Natural Channel Systems. Niagara Falls, Ontario.

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

Baldigo, B.P., Ernst, A.G., Warren, D.R., Miller, S.J., 2010. Variable responses of fish assemblages, habitat, and stability to Natural-Channel-Design restoration in Catskill Mountain streams. Transactions of the American Fisheries Society 139, 449-467.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. Bioscience 60, 209-222.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P., 2017. Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. Geomorphology 283, 143-157.

Belmont, P. 2011. Floodplain width adjustments in response to rapid baselevel fall and knickpoint migration. Geomorphology 128, 92-102.

Belmont, P., Gran, K.B., Schottler, S.P., Wilcock, P.R., Day, S.S., Jennings, C., Lauer, J.W., Viparelli, E., Willenbring, J.K., Engstrom, D.R., Parker, G., 2011. Large shift in source of fine sediment in the Upper Mississippi River. Environmental Science and Technology 45, 8804–8810.

Benda, L., Hassan, M.A., Church, M. May, C.L., 2005. Geomorphology of steepland headwaters: The transition from hillslopes to channels. Journal of the American Water Resources Association (JAWRA) 41, 835-851.

Bergman, N., Schmidt, J. Wilcock, P.R., 2010. The sedimentary characteristics of a coarse gravel-bed river choked with fine sediment, West Walker River, California. Poster presented in the Spring Runoff Conference, Utah State University, Logan, Utah. Available at: https://works.bepress.com/peter_wilcock/269/

Bergman, N., Sholker, O., Roskin, Y., Greenbaum, N., 2014. The Nahal Oz Reservoir dam-break flood: Geomorphic impact on a small ephemeral loess-channel, Negev Desert, Israel. Geomorphology, 210, 83-97.

Bergman, N., Van De Wiel, M.J., Hicock, S.R., Rousseau, Y.R., 2021a. The drainage of the last Glacial Lake London, Ontario: Mapping and hydraulic modeling. In review.

Bergman, N., Van De Wiel, M.J., Hicock, S.R., Moser, K., 2021b. Semi-alluvial till-bedded stream channel crossing an interlobate moraine in Southern Ontario, Canada: Morphometry, hydrology and hydraulics of Medway Creek. In review.

Bevan, V., MacVicar, B., Chapuis, M., Ghunowa, K., Papangelakis, E., Parish, J., Snodgrass, W., 2018. Enlargement and evolution of a semi-alluvial creek in response to urbanization. Earth Surface Processes and Landforms 43, 2295-2312.

Bhowmik, N.G., 1979. Hydraulics of Flow in the Kaskaskia River, Illinois. Illinois State Water Survey, Report of Investigations 91, Urbana, 116 pp.

Billi, P., Preciso, E., 2003. Le strutture agradinata come eleementi naturali di stabilizzazione dei torrenti montani. Sopra Livello Mare 10, 61-65.

Blann, K.L., Anderson, J.L. Sands, G.R., Vondracek, B., 2009. Effects of agricultural drainage on aquatic ecosystems: A Review. Critical Reviews in Environmental Science and Technology 39, 909-1001.

Bowman, D., 1977. Stepped-bed morphology in arid gravelly channels. Geological Society of America Bulletin 88, 291-298.
Brakenridge, G.R., Thomas, P.A., Conkey. L.E., Schiferle, J.C., 1988. Fluvial sedimentation in response to postglacial uplift and environmental change, Missisquoi River, Vermont. Quaternary Research 30, 190-203.
Brardinoni, F., Hassan, M. A., 2006. Glacial erosion, evolution of river long profiles, and the organization of process domains in mountain drainage basins of coastal British Columbia. Journal of Geophysical Research 111, F01013.
Brardinoni, F., Hassan, M.A., 2007. Glacially-induced organization of channel-reach morphology in mountain streams. Journal of Geophysical Research 112, F03013.
Bridge, J.S., 2003. Rivers and Floodplains: Forms, Processes, and Sedimentary Record. Wiley-Blackwell, Malden, MA, 504 pp.
Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Style Framework. Blackwell, Oxford, UK, 398 pp.
Browne, W., 1957. Pleistocene glaciation in the Commonwealth of Australia. Journal of Glaciology 3, 111-115.
Buchanan, B.P., Walter, M.T., Nagle, G.N., Schneider, R.L., 2010. Monitoring and assessment of a river restoration project in central New York. River Research and Applications 28, 216-233.
Campo, S.H., Desloges, J.R., 1994. Sediment yield conditioned by glaciation in a rural agricultural basin of southern Ontario, Canada. Physical Geography 15, 495-515.
Champoux, O., Biron, P.M., Roy, A.G., 2003. The long-term effectiveness of fish habitat restoration practices: Lawrence Creek, Wisconsin. Annals of the Association of American Geographers 93, 42-54.
Chapman, L.J., Putnam, D.F., 1984. Physiography of Southern Ontario. University of Toronto Press, Toronto, Ontario, Canada.
Chatanantavet, P., Parker, G., 2008. Experimental study of bedrock channel alluviation under varied sediment supply and hydraulic conditions. Water Resources Research 44, W12446.
Chatanantavet, P., Parker, G., 2009. Physically based modeling of bedrock incision by abrasion, plucking, and macroabrasion. Journal of Geophysical Research 114, F04018.
Chin, A. 1989. Step-pools in stream channels. Progress in Physical Geography 13, 391-408.
Chin, A. 1998. On the stability of step-pool mountain streams. The Journal of Geology 106, 59-70.
Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology 47, 541-557.
Church, M. Jones, D. 1982. Channel bars in gravel bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-Bed Rivers: Fluvial Processes, Engineering and Management. Wiley, Chichester, 291-338.
Church, M.A., McLean, D.G., Wolcott, J.F., 1987. River bed gravels: sampling and analysis. In: Thorne, C. R. Bathurst, J. C. Hey, R.D. (Eds.) Sediment transport in gravel-bed rivers. Chichester, Wiley, 43-88.
Church, M., Haschenburger, J. K., 2017. What is the "active layer"?. Water Resources Research 53, 5-10.

City of London Corporate Services Department. 2000. Guidelines document for the evaluation of ecologically significant woodlands, 1-7.
Clark, J.A., Zylstra, D.J., Befus, K.M., 2007. Effects of Great Lakes water loading upon glacial isostatic adjustment and lake history. Journal of Great Lakes Research 33, 627-641.
Clark, P.U., Clague, J.J., Curry, B.B., Dreimanis, A., Hicock, S.R., Miller, G.H., Berger, G.W., Eyles, N., Lamothe, M., Miller, B.B., Mott, R.J., Oldales, R.N., Stea, R.R., Szabo, J.P., Thorleifson, L.H., Voncent, J.-S., 1993. Initiation and development of the Laurentide and Cordilleran ice sheets following the last interglaciation. Quaternary Science Reviews 12, 79-114.
Clark, P.U., Fitzhugh, W.W., 1992. Postglacial relative sea level history of the Labrador Coast and interpretation of the archaeological record. In: Johnson, L.L. (Ed.) Paleoshorelines and Prehistory: an Investigation of Method. CRC Press, London, 189-213.
Collins, B.D., Montgomery, D.R., 2011. The legacy of Pleistocene glaciation and the organization of lowland alluvial process domains in the Puget Sound region. Geomorphology 126, 174-185.
Collins, B.D., Dunne, T., Lehre, A.K., 1983. Erosion of tephra-covered hillslopes north of Mount St. Helens, Washington: May 1980-May 1981, Zeitschrift für Geomorphologie 46, 103-121.
Coulthard, T.J. Van De Wiel, M.J., 2007. Quantifying fluvial non-linearity and finding self-organized criticality? Insights from simulations of river basin evolution. Geomorphology 91, 216-235.
Craddock, W.H., Kirby, E., Harkins, N.H., Zhang, H., Shi, X., Liu, J., 2010. Rapid fluvial incision along the Yellow River during headward basin integration. Nature Geoscience 3, 209-213.
Crawford, G.W., Smith, D.G., Desloges, J.R., Davies, A.M., 1998. Floodplains and agricultural origins: A case study in South-Central Ontario, Canada. Journal of Field Archaeology 25, 123-137.
Culley, R.W., 1971. Effect of freeze-thaw cycling on stress-strain characteristics and volume change of till subjected to repetitive loading. Canadian Geotechnical Journal 8, 359-371.
Curran, J.C., Wilcock, P.R., 2005. Effect of sand supply on transport rates in a gravel-bed channel. Journal of Hydraulic Engineering 131, 961-967.
Dasenbrock, D.D., Schneider, J.A., Mergen, E.M., 2010. Cone penetration testing experience in glacial geological conditions of Minnesota, USA. Minnesota Department of Transportation, 8 pp.
Dickinson, W.T., Green, D.R., 1988. Characteristics of sediment loads in Ontario streams. Canadian Journal of Civil Engineering 15, 1067-1079.
Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340, 215-217.
Doyle, M.W., Harbor, J.M., Rich, C.R., Spacie, A., 2000. Examining the effects of urbanization on streams using indicators of geomorphic stability. Physical Geography 21, 155-181.

Dreimanis, A., Winder, C.G., Aaltonen, R.A., 1998. London Ontario: Geology, geomorphology, geodata. In: Karrow, P.F. and White, O.L. (eds.) Urban Geology of Canadian Cities. Geological Society of Canada Special Paper 42, 237-260.

Duncan, W.W., Goodloe, R.B., Meyer, J.L. Prowell, E.S., 2011. Does channel incision affect in-stream habitat? Examining the effects of multiple geomorphic variables on fish habitat. Restoration Ecology 19, 64-73.

Ehlers, J., Gibbard, P.L., (Eds.) 2004a. Quaternary Glaciations Extent and Chronology: Part II: North America. Developments in Quaternary Science 2, Elsevier, Amsterdam.

Ehlers, J., Gibbard, P.L., (Eds.) 2004b. Quaternary Glaciations Extent and Chronology: Part I: Europe. Developments in Quaternary Science 2, Elsevier, Amsterdam.

Ehlers, J., Gibbard, P.L., (Eds.) 2004c. Quaternary Glaciations Extent and Chronology: Part III: South America, Asia, Africa, Australasia, Antarctica. Developments in Quaternary Science 2, Elsevier, Amsterdam.

Elliot, K.A. 1998. The forests of southern Ontario. The Forestry Chronicle 74, 850-854.

Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Carrivick, J.L., Cotterill, C.J., Richardson, J.C., Ivanovic, R.F., Mellett, C.L., 2020. Ice sheet and palaeoclimate controls on drainage network evolution: an example from Dogger Bank, North Sea. Earth Surface Dynamics 8, 869-891.

Ernst, A.G., Baldigo, B.P., Mulvihill, C.I., 2010. Effects of Natural-Channel-Design restoration on habitat quality in Catskill Mountain streams, New York. Transactions of the American Fisheries Society 139:468–482.

ESRI., 2012. ArcGIS for Desktop. Release 10.1. Redlands, CA.

Everest, F.H., Beschta, R.L., Scrivener, J.C., Koski, K.V., Sedell, J.R., Cederholm, C.J., 1987. Fine sediment and salmonid production: A paradox. In: Salo, E., Cundy, T., (Eds.) Streamside Management: Forestry and Fishery Interactions, University of Washington, Seattle, 98-142.

Faulkner, D.J., Larson, P.H., Jol, H.M., Running, G.L., Loope, H.M., Ronald J. Goble, R.J., 2016. Autogenic incision and terrace formation resulting from abrupt late-glacial base-level fall, lower Chippewa River, Wisconsin, USA. Geomorphology 266, 75-95.

Fausey, N.R., Hall, G.F., Bigham, J.M., Allred, B.J., Christy, A.D., 2000. Properties of the fractured glacial till at the Madison County, Ohio, Field Workshop Pit Site. The Ohio Journal of Science 100, 107-112.

Finnegan, N.J., Sklar, L.S., Fuller, T.K., 2007. Interplay of sediment supply, river incision, and channel morphology revealed by the transient evolution of an experimental bedrock channel. Journal of Geophysical Research Earth Surface 112, F03S11.

Fitzpatrick, F.A., Peterson, E.M., Stewart, J.S., 1996. Habitat Characteristics of Benchmark Streams in Agricultural Areas of Eastern Wisconsin. U.S. Geological Survey Water-Resources Investigations Report 96-4038-B, 35 p.

Fitzpatrick, F.A., Knox, J.C., and Whitman, H.E., 1999. Effects of historical land-cover changes on flooding and sedimentation, North Fish Creek, Wisconsin. U.S. Geological Survey Water-Resources Investigations Report 99-4083, 12 p.

Fitzpatrick, F.A., Peppler, M.C., Walker, J.F., Rose, W.J., Waschbusch, R.J., Kennedy, J.L., 2008. Flood of June 2008, southern Wisconsin. U.S. Geological Survey Scienific Investigations Report 2008-5235, 24 p.

Fola, M.E., Rennie, C.D., 2010. Downstream hydraulic geometry of clay-dominated cohesive bed rivers. Journal of Hydraulic Engineering 136, 524-527.
Foster, G.E., 1998. Morphology of three semi-alluvial stream channels in southern Ontario. Unpublished Master's Thesis. The University of Western Ontario, 215 pp.
Fraser, C., Hill, P.R., Allard, M., 2005. Morphology and facies architecture of a falling sea level strandplain, Umiujaq, Hudson Bay, Canada. Sedimentology, 52, 141-160.
Fripp, J.B., Diplas, P., 1993. Surface sampling in gravel streams. Journal of Hydraulic Engineering 119, 473-490.
Geomorphic Solutions., 2009. Evaluating the effectiveness of 'Natural' Channel Design projects: An introduction and preliminary assessment of sites in TRCA's jurisdiction. Prepared by: Geomorphic Solutions, Sernas Group Inc., The Toronto and Region Conservation Authority, LGL Limited, February 2009, 116 p.
Goldthwait, R.P., 1959. Scenes in Ohio during the last ice age. The Ohio Journal of Science 59, 193-216.
Gomez, B., Livingstone, D.M., 2012. The river it goes right on: Post-glacial landscape evolution in the upper Waipaoa River basin, eastern North Island, New Zealand. Geomorphology 159-160, 73-83.
Grabowski, R.C., Droppo, I.G., Wharton, G., 2011. Erodibility of cohesive sediment: The importance of sediment properties. Earth Science Reviews 105, 101-120.
Gran, K.B., Montgomery, D.R., 2005. Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines. GSA Bulletin 117, 195-211.
Gran, K.B., Belmont, P., Day, S.S., Jennings, C., Johnson, A., Perg, L., Wilcock, P.R., 2009. Geomorphic evolution of the Le Sueur River, Minnesota, USA and implications for current sediment loading. In: James, L.A., Rathburn, S.L., Whittecar, G.R., (Eds.) Restoration of fluvial systems with broad historical changes and human impacts. GSA Special paper 451, 119-130.
Gran, K.B., Belmont, P., Day, S.S., Finnegan, N., Jennings, C., Lauer, W.J., Wilcock, P.R., 2011. Landscape evolution in south-central Minnesota and the role of geomorphic history on modern erosional processes. GSA Today 21, 7-9.
Gran, K.B., Finnegan, N., Johnson, A.L., Belmont, P., Wittkop, C., Rittenour, T., 2013. Landscape evolution, valley excavation, and terrace development following abrupt postglacial base-level fall. Geological Society of America Bulletin 125, 1851-1864.
Greenbaum, N., Bergman, N., 2006. Formation and evacuation of a large gravel-bar deposited during a major flood in a Mediterranean ephemeral stream, Nahal Me'arot, NW Israel. Geomorphology 77, 169-186.
Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., Garcı´a de Jalo´n, G., Gonza´lez del Ta´nago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendricks, D., Henshaw, A.J., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences 78, 1-16.
Hack, J.T., 1965. Postglacial drainage evolution and stream geometry in the Ontonagon area, Michigan. USGS Professional Paper 504-B.

Hagerty, T.P., Kingston, M.S., 1992. The soils of Middlesex County. Report no. 56 of the Ontario Centre for Soil Resource Evaluation, Resources Management Branch, Ontario Ministry of Agriculture and Food, Guelph, Ontario, volume 1, 213 pp.

Hattanji, T., Wasklewicz, T.A., Hayakawa, Y.S., Wester, T., Hegi, Y., 2012. Hydrogeomorphic effects of basin lithology on development of channel steps in first-order basins of the Ashio Mountains, Japan. Physical Geography 33, 536-560.

Hanson, G.J. Simon, A., 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. Hydrological Processes 15, 23-38.

Hartley, A.M., 1999. The pool-riffle sequence as the principal design component of low-gradient, meandering, gravel-bed channels. M.Sc. Thesis, School of Engineering, University of Guelph, Guelph, Ontario, Canada, 158 pp.

Haschenburger, J.K., Rice, S.P., Voyde, E., 2007. Evaluation of bulk sediment sampling criteria for gravel-bed rivers. Journal of Sedimentary Research 77, 415-423.

Hassan, M.A., Egozi, R., Parker, G., 2006. Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers. Water Resources Research 42, W09408.

Hassan, M.A., Brayshaw, D., Alila, Y., Andrews, E., 2014. Effective discharge in small formerly glaciated mountain streams of British Columbia: Limitations and implications. Water Resources Research 50, 4440-4458.

Hayes, S.K., Montgomery, D.R., Newhall, C.G., 2002. Fluvial sediment transport and deposition following the 1991 eruption of Mount Pinatubo. Geomorphology 45, 211-224.

Hicock, S.R. Dreimanis, A. 1992. Deformation till in the Great Lakes region: implications for rapid flow along the south-central margin of the Laurentide Ice Sheet. Canadian Journal of Earth Sciences 29, 1565-1579.

Hill, A.R. 1973. Erosion of river banks composed of glacial till near Belfast, Northern Ireland. Zeitschrift für Geomorphologie 17, 428-442.

Hodge, R.A., Hoey, T.B., Sklar, S.L., 2011. Bed load transport in bedrock rivers: The role of sediment cover in grain entrainment, translation, and deposition. Journal of Geophysical Research 116, F04028.

Hodge, R.A., Hoey, T.B., 2012. Upscaling from grain-scale processes to alluviation in bedrock channels using a cellular automaton model. Journal of Geophysical Research 117, F01017.

Hrytsak, T.N., 2012. Alluvial cover dynamics in a semi-alluvial channel. MSc Thesis, Department of Geography, Western University, 156 pp.

Inoue, T., Izumi, N., Shimizu, Y., Parker, G., 2014. Interaction among alluvial cover, bed roughness, and incision rate in purely bedrock and alluvial-bedrock channel, Journal of Geophysical Research Earth Surface 119, 2123-2146.

Johnson, J.P.L., 2014. A surface roughness model for predicting alluvial cover and bed load transport rate in bedrock channels. Journal of Geophysical Research 119, 2147-2173.

Johnson, J.P.L., Whipple, K.X., 2007. Feedbacks between erosion and sediment transport in experimental bedrock channels. Earth Surface Processes and Landforms 32, 1048-1062.

Johnson, J.P.L., Whipple, K.X., 2010. Evaluating the controls of shear stress, sediment supply, alluvial cover, and channel morphology on experimental bedrock incision rate. Journal of Geophysical Research 115, F02018.

Jordan, B.A., Annable, W.K., Watson, C.C., Sen, D., 2010. Contrasting stream stability characteristics in adjacent urban watersheds: Santa Clara Valley, California. River Research and Applications 26, 1281-1297.

Juracek, K. E., Fitzpatrick, F.A., 2003. Limitations and implications of stream classification. Journal of the American Water Resources Association 39, 659-670.

Kamphuis, J.W., 1983. On the erosion of consolidated clay material by a fluid containing sand. Canadian Journal of Civil Engineering 10, 223-231.

Kamphuis, J.W., Gaskin, P.N., Hoogendoorn, E., 1990. Erosion tests on four intact Ontario clays. Canadian Geotechnical Journal 27, 692-696.

Kappesser, G., 2002. A riffle stability index to evaluate sediment loading to streams. Journal of the American Water Resources Association 38, 1069-1081.

Kasprak, A., Hough-Snee, N., Beechie, T., Bouwes, N., Brierly, G., Camp, R., Fryirs, K., Imaki, H., Jensen, M., O'Brien, G., Rosgen, D., Wheaton, J., 2016. The blurred line between form and process: A comparison of stream channel classification frameworks. PLOS One 11, 1-31.

Kaufmann, P.R., Faustini, J.M. Larsen, D.P. Shirazi, M.A., 2008. A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99, 150-170.

Kaufmann, P.R., Larsen, D.P., Faustini, J.M., 2009. Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams. Journal of American Water Resources Association 45, 434-459.

Keller, E.A., Melhorn, W.N., 1978. Rhythmic spacing and origins of pools and riffles. Geological Society of America Bulletin 89, 723-730.

Kellerhals, R. Bray, D.I. 1971. Sampling procedures for coarse fluvial sediments. Journal of the Hydraulics Division, ASCE, 97, 1165-1179.

Kellerhals, R., Church., M. Bray, D.I., 1976. Classification and analysis of river processes. Journal of the Hydraulics Division, 102, 813-829.

Kent, E., Whittaker, A.C., Boulton, S.J., Alçiçek, M.C, 2021. Quantifying the competing influences of lithology and throw rate on bedrock river incision. Geological Society of America Bulletin 133, 1649-1664.

Khan, I., Kostaschuk, R., 2011. Erodibility of cohesive glacial till bed sediments in urban stream channel systems. Canadian Journal of Civil Engineering 38, 1363-1372.

Kling, G.W., Hayhoe, K., Johnson, L.B., Magnuson, J.J., Polasky, S., Robinson, S.K., Shuter, B.J., Wander, M.M., Wuebbles, D.J., Zak, D.R., Lindroth, R.L., Moser, S.C., Wilson, M.L., 2003. Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C.

Knox, J.C., 1989. Long and short-term episodic storage and removal of sediment in watersheds of southwestern Wisconsin and northwestern Illinois. In: Hadley, R.F., Ongley, E.D., (Eds.), Sediment and the Environment. International Association of Hydrological Sciences, Wallingford, UK, 157-164.

Knox, J.C., 2006. Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. Geomorphology 79, 286-310.

Kondolf, M.G., 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. Aquatic Conservation: Marine and Freshwater Ecosystems 5, 127-141.

Kondolf, M.G., 1997. Applications of the pebble count notes on purpose, method and variants. Journal of the American Water Resources Association 33, 79-87.

Lamba, J., Thompson, A.M., Karthikeyan, K.G., Fitzpatrick, F.A., 2015. Sources of fine sediment stored in agricultural lowland streams, Midwest, USA. Geomorphology, Volume 236, 44-53.

Landwehr, K., Rhoads, B.L., 2003. Depositional response of headwater stream to channelization, east central Illinois, USA. River Research and Application 19, 77-100.

Laronne, J.B., Reid, I., Yitshack, Y., Frostick, L.E., 1994. The non-layering of gravel streambeds under ephemeral flood regimes. Journal of Hydrology 159, 353-363.

Lekach, J., Amit, R., Grodek, T., Schick, A.P., 1998. Fluvio-pedogenic processes in an ephemeral stream channel, Nahal Yael, Southern Negev, Israel. Geomorphology 23, 353-369.

Lenzi, M.A., Mao, L., Comiti, F., 2004. Magnitude-frequency analysis of bed load data in an Alpine boulder bed stream. Water Resources Research 40. W07201.

Leopold, L.B. 1994. A view of the river. Harvard University Press, Cambridge MA, 298 pp.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. Geological Survey Professional Paper 282-B, 85 pp.

Lewis, C.F.M., Blasco, S.M., Gareau, P.L., 2005. Glacial isostatic adjustment of the Laurentian Great Lakes basin: using the empirical record of strandline deformation for reconstruction of early Holocene paleo-lakes and discovery of a hydrologically closed phase. Géographie physique et Quaternaire 59, 187-210.

Lisle, T.E. Hilton, S., 1992. The volume of fine sediment in pools: An index of the supply of mobile sediment in stream channels. Water Resources Bulletin 28, 371-383.

Lisle, T.E., Hilton, S., 1999. Fine bed material in pools of natural gravel-bed channels. Water Resources Research 35, 1291-1304.

Lisle, T.E., Madej, M.A., 1992. Spatial variation in armouring in a channel with high sediment supply. In: Billi, P., Hey, R.D. Thorne, C.R., Tacconi, P. (Eds.) Dynamics of Gravel-Bed Rivers. John Wiley & Sons, New York, 277-293.

Lisle, T.E., Buffington, J.M., Wilcock, P.R., Bunte, K., 2015. Can rapid assessment protocols be used to judge sediment impairment in gravel-bed streams? A commentary. Journal of the American Water Resources Association 51, 373-387.

Mackin, J.H., 1948. Concept of the graded river. Geological Society of America Bulletin 48, 463-512.

MacVicar, B.J., Roy, A.G., 2011. Sediment mobility in a forced riffle-pool. Geomorphology 125, 445-456.

Major, J.J., Pierson, T.C., Dinehart, R.L., Costa, J.E., 2000. Sediment yield following severe volcanic disturbance - a two-decade perspective from Mount St. Helens. Geology 28, 819-822.

Marchand, J-P., Buffin-Bélanger, T., Hétu, B., St-Onge, G., 2014. Stratigraphy and infill history of the glacially eroded Matane River Valley, eastern Quebec, Canada. Canadian Journal of Earth Sciences 51, 105-124.

Marchildon, M.A., Annable, W.K., Imhof, J.G., Power, M., 2011. A high-resolution hydrodynamic investigation of brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) redds. River Research and Application 27, 345-359.

Marren, P.M., Toomath, S.C., 2014. Channel pattern of proglacial rivers: topographic forcing due to glacier retreat. Earth Surface Processes and Landforms 39, 943-951.

Martini, I.P., 1977. Gravelly flood deposits of Irvine Creek, Ontario, Canada. Sedimentology 24, 603-622.

Mathers, K.L., Wood, P.J., 2016. Fine sediment deposition and interstitial flow effects on macroinvertebrate community composition within riffle heads and tails. Hydrobiologia 776, 147–160.

McNeil, J., Lick, W., 2001. Effects of sediment bulk properties on erosion rates. The Science of the Total Environment 266, 41-48.

Meshkova, L.V., Carling, P.A., Buffin-Be´langer, T., 2012. Nomenclature, complexity, semi-alluvial channels and sediment-flux-driven bedrock erosion. In: Church, M., Biron, P.M., Roy, A.G., (Eds.) Gravel-bed Rivers: Processes, Tools, Environments. John Wiley & Sons, Ltd., Chapter 31, 424-431.

Michigan Department of Natural Resources., 1991, Qualitative biological and habitat survey protocols for wadable streams and rivers. Michigan Department of Natural Resources, Surface Water Quality Division, Great Lakes and Environmental Assessment Section, GLEAS Procedure 51, 40 p.

Mier, J.M., Garcia, M.H., 2011. Erosion of glacial till from the St. Clair River (Great Lakes basin). Journal of Great Lakes Research 37, 399-410.

Miller, M.W., Nudds, T.D., 1996. Prairie landscape change and flooding in the Mississippi River Valley. Conservation Biology 10, 847-853.

Montgomery, D.R., Buffington, J.M., 1997. Channel reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596-611.

Myers, T.J., Swanson, S., 1996. Temporal and geomorphic variations of stream stability and morphology: Mahogany Creek, Nevada. Water Resources Bulletin 32, 253-265.

Ness, R., Joy, D.M., 2002. Performance of Natural Channel Designs in southwestern Ontario. Canadian Water Resources Journal 27, 293-315.

Newson, M.D., Newson, C.L., 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24, 195-217.

Nielsen, E., Morgan, A.V., Morgan, A., Mott, R.J., Rutter, N.W., Causse, C., 1986. Stratigraphy, paleoecology, and glacial history of the Gillam area, Manitoba. Canadian Journal of Earth Sciences 23, 1641-1661.

Niziol, T.A., Snyder, W.R., Waldstreicher, J.S., 1995. Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. Weather Forecasting 10, 61-77.

Novotny, E.V., Stefan, H.G., 2007. Stream flow in Minnesota: Indicator of climate change. Journal of Hydrology 334, 319-333.

Nunally, N.R. 1967. Definition and identification of channel and over-bank deposits and their respective role in floodplain formation. Professional Geographer 19, 1-4.

O.A.C., 1931. Soil survey of the county of Middlesex, province of Ontario. Soil Survey Report, Department of Chemistry, O.A.C., Guelph.

O'Connor, J.E., Webb, R.H., Baker, V.R., 1986. Paleohydrology of pool-and-riffle pattern development: Boulder Creek, Utah. Geological Society of America Bulletin 97, 410-420.

O'Neill, M.P., Abrahams, A.D., 1984., Objective identification of pools and riffles. Water Resources Research 20, 921-926.

Pahl, R., 2006. Carson River relative bed stability investigation. Nevada Division of Environmental Protection, Bureau of Water Quality Planning, 15 pp.

Palacios, D., Stokes, C.R., Phillips, F.M., Clague, J.J., Alcalá-Reygosa, J., Andrés, N., Angel, I., Blard, P-H., Briner, J.P., Hall, B.L., Dahms, D., Hein, A.S., Jomelli, V., Mark, B.G., Martini, M.A., Moreno, P., Riedel, J., Sagredo, E., Stansell, N.D., Vázquez-Selem, L., Vuille, M., Ward, D.J., 2020. The deglaciation of the Americas during the Last Glacial Termination. Earth Science Reviews 203, 103113.

Paola, C., Seal, R., 1995. Grain size patchiness as a cause of selective deposition and downstream fining. Water Resources Research 31, 1395-1407.

Papangelakis, E., MacVicar, B., Ashmore, P., 2019. Bedload sediment transport regimes of semi-alluvial rivers conditioned by urbanization and stormwater management. Water Resources Research 55, 10,565–10,587.

Papangelakis, E., Welber, M., Ashmore, P., MacVicar, B., 2021. Controls of alluvial cover formation, morphology and bedload transport in a sinuous channel with a non-alluvial boundary. Earth Surface Processes and Landforms 46, 399-416.

Parker, G., 1978. Self-formed straight rivers with equilibrium banks and mobile bed. Part 2. The gravel river. Journal of Fluid Mechanics 89, 127-146.

Parker, G., 1990. Surface-based bedload transport relation for gravel rivers. Journal of Hydraulic Research 28, 417-436.

Parker, G., Klingeman, P.C., 1982. On why gravel bed streams are paved. Water Resources Research 18, 1409-1423.

Pasternack, G.B., 2020. River restoration: Disappointing, nascent, yet desperately needed. Reference Module in Earth Systems and Environmental Sciences. Treatise on Geomorphology, Elsevier, ISBN 9780124095489.

Peck, A., Prodanovic, P., Simonovic, S.P.P., 2012. Rainfall intensity duration frequency curves under climate change: City of London, Ontario, Canada. Canadian Water Resources Journal 37, 177-189.

Peirce, S., MacVicar, B.J., Papangelakis, E., Vervynck, L., Ashmore, P., 2021. Experiments on restoring alluvial cover using gravel augmentation in a variable width channel with irregular meanders. Geomorphology 379, in press.

Peterson, T.J., Western, A.W., Argent, R.M., 2012. Analytical methods for ecosystem resilience: A hydrological investigation. Water Resources Research 48, W10531.

Pfankuch, D.J., 1975. Stream reach inventory and channel stability evaluation. U.S. Department of Agriculture Forest Service. Region 1. Missoula, Montana, 25 pp.

Phillips, J.D., 2003. Sources of nonlinear complexity in geomorphic systems. Progress in Physical Geography 26, 339-361.

Phillips, J.D., 2014. Global tipping points: Some lessons from studies of thresholds in Geomorphology. Available in: https://geography.as.uky.edu/sites/default/files/Tipping%20Points.pdf. Last accessed October 5, 2014.

Phillips, R.T.J., Robert, A., 2005. River incision in relation to post-glacial events in the Humber River basin, Ontario. Géographie physique et Quaternaire 59, 17-30.
Phillips, R.T.J., Desloges, J.R., 2014. Glacially conditioned specific stream powers in low-relief river catchments of the southern Laurentian Great Lakes. Geomorphology 206, 271-287.
Phillips, R.T.J., Desloges, J.R., 2015a. Alluvial floodplain classification by multivariate clustering and discriminant analysis for low-relief glacially conditioned river catchments. Earth Surface Processes and Landforms 40, 756-770.
Phillips, R.T.J., Desloges, J.R., 2015b. Glacial legacy effects on river landforms of the southern Laurentian Great Lakes. Journal of Great Lakes Research 41, 951-964.
Pike, L., Gaskin, S., Ashmore, P., 2018. Flume tests on fluvial erosion mechanisms in till-bed channels. Earth Surface Processes and Landforms 43, 259-270.
Platts, W.S., Megahan, W.F., Minshall, G.W., 1983. Methods for evaluating stream, riparian, and biotic conditions. U.S. Forest Service, Intermountain Forest and Range Experimental Station, Ogden Utah, Department of Agriculture, General Technical Report INT-138, 70 p.
Powell, D.M., 1998. Patterns and processes of sediment sorting in gravel-bed rivers. Progress in Physical Geography 22, 1-32.
Powell, D.M., Reid, I., Laronne, J.B., 1999. Hydraulic interpretation of cross-stream variations in bed-load transport. Journal of Hydraulic Engineering 125, 1243-1252.
Powell, G., 2006. Examination, application, and evaluation of geomorphic principles and resulting water quality in Midwest agricultural streams and rivers. PhD dissertation, Food, Agricultural, and Biological Engineering, Ohio State University. Available from: https://etd.ohiolink.edu/
Prasicek, G., Otto, J-C., Montgomery, D.R., Schrott, L., 2014. Multi-scale curvature for automated identification of glaciated mountain landscapes. Geomorphology 209, 53-65.
Prasicek, G., Otto, J-C., Montgomery, D.R., Schrott, L., 2015. Glaciated valleys in Europe and western Asia. Journal of Maps 11, 361-370.
Rainsley, E., Turney, C. S. M., Golledge, N. R., Wilmshurst, J. M., McGlone, M. S., Hogg, A. G., Li, B., Thomas, Z. A., Roberts, R., Jones, R. T., Palmer, J. G., Flett, V., de Wet, G., Hutchinson, D. K., Lipson, M. J., Fenwick, P., Hines, B. R., Binetti, U., Fogwill, C.J., 2019. Pleistocene glacial history of the New Zealand subantarctic islands. Climate Past 15, 423-448.
Rathburn, S., Wohl, E., 2003. Predicting fine sediment dynamics along a pool-riffle mountain channel. Geomorphology 55, 111-124.
Rhoads, B.L., Cahill, R.A., 1999. Geomorphological assessment of sediment contamination in an urban stream system. Applied Geochemistry 14, 459-483.
Rice, S.P., Church, M., 1996. Sampling surficial fluvial gravels: The precision of size distribution percentile estimates. Journal of Sedimentary Research 66, 654-665.
Rice, S.P., Hascheburger, J.K., 2004. A hybrid method for size characterization of coarse subsurface fluvial sediments. Earth Surface Processes and Landforms 29, 373-389.
Richards, R.P., 1990. Measures of flow variability and a new flow based classification of Great Lakes tributaries. Journal of Great Lakes Research 16, 53-70.
Richardson, K., Carling, P.A., 2005. A typology of sculpted forms in open bedrock channels. Geological Society of America Special Papers 392, 108 pp.

Riebe, C.S., Sklar, L.S., Lukens, C.E., Shuster, D.L., 2015. Climate and topography control the size and flux of sediment produced on steep mountain slopes. Proceedings, National Academy of Sciences (PNAS) 112, 15574-15579.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122-136.

Roberts, J., Jepsen, R., Gotthard, D., Lick, W., 1998. Effects of particle size and bulk density on erosion of quartz particles. Journal of Hydraulic Engineering 124, 261-1267.

Rosgen, D.L. 1994a. River restoration utilizing natural stability concepts. Land and Water 38, 36-41.

Rosgen, D.L., 1994b. A classification of natural rivers. Catena 22, 169-199.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Rozin, U., Schick, A.P., 1996. Land use change, conservation measures and streamchannel response in theMediterranean/semiarid transition zone: Nahal Hoga, southern coastal plain, Israel. Erosion and Sediment Yield: Global and Regional Perspectives. IAHS Publ. 236, 427-444.

Ruhe, R.V., 1952. Topographic discontinuities of the Des Moines lobe. American Journal of Science 250, 46-56.

Ruhe, R.V., Scholtes, W.H., 1956. Ages and development of soil landscapes in relation to climatic and vegetational changes in Iowa. Soil Science Society of America Journal 20, 264-273.

Rust, B.R., 1977. A classification of alluvial channel systems. Fluvial Sedimentology Memoir 5, 187-198.

Sambrook Smith, G.H., 1996. Bimodal fluvial bed sediments: origin, spatial extent and processes. Progress in Physical Geography 20, 402-417.

Schottler, S.P., Ulrich, J., Belmont, P., Moore, R., Lauer, W.J., Engstrom, D.R., Almendinger, J.E., 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes 28, 1951-1961.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. In Morisawa, M. (Ed.) Fluvial geomorphology. Binghamton, NY, Publications in Geomorphology, 299-310.

Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised Channels: Morphology, Dynamics and Control. Water Resources Publication, Littleton, Co. 200 pp.

Seginer, I., 1966. Gully development and sediment yield. Journal of Hydrology 4, 236-253.

Shen, Z., Törnqvist, T.E., Autin, W.J., Mateo, Z.R.P., Straub, K.M., Mauz, B., 2012 Rapid and widespread response of the Lower Mississippi River to eustatic forcing during the last glacial-interglacial cycle. Geological Society of America Bulletin 124, 690-704.

Shugar, D., Kostaschuk, R., Ashmore, P., Desloges, J.R., Burge, L., 2007. In situ jet testing of the erosional resistance of cohesive streambeds. Canadian Journal of Civil Engineering, 34, 1192-1195.

Simon, A., 1994. Gradation processes and channel evolution in modified West Tennessee streams: Process, response and form. U.S. Geological Survey Professional Paper 1470, 63 pp.

Simon, A., Hupp, C.R., 1986. Chanel Evolution in Modified Tennessee channels. Proceedings, IV Federal Interagency Sedimentation Conference, Las Vegas, Nevada, March 24-27, volume 2, 5-71-5-82.

Simon, A., Doyle, M., Kondolf, M. Shields Jr., F.D., Rhoads, B., McPhillips, M., 2007. Critical evaluation of how the Rosgen classification and associated ‘‘natural channel design’’ methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43, 1-15.

Sklar, L.S., Dietrich, W.E., Foufoula-Georgiou, E. Lashermes, B., Bellugi, D., 2006. Do gravel bed river size distributions record channel network structure? Water Resources Research 42, W06D18.

Stewart, A.M., Desloges, J.R., 2014. A 9000-year record of vertical and lateral accretion on the floodplain of the lower Thames River, southwestern Ontario, Canada, and implications for archaeological research. Quaternary Research 342, 161-172.

Stock, J.D., Montgomery, D.R., 1999. Geologic constraints on bedrock river incision using the stream power law. Journal of Geophysical Research 104, 4983-4993.

Stock, J.D., Montgomery, D.R., Collins, B.D., Dietrich, W.E., Sklar, L., 2005. Field measurements of incision rates following bedrock exposure: Implications for process controls on the long profiles of valleys cut by rivers and debris flows. Geological Society of America Bulletin 117, 174-194.

Stout, J.C., Belmont, P., Schottler, S.P., Willenbring, J.K., 2014. Identifying sediment sources and sinks in the Root River, southeastern Minnesota. Annals of the Association of American Geographers 104, 20-39.

Sutfin, N.A., Shaw, J., Wohl, E.E., Cooper, D.A., 2014. A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA. Geomorphology 221, 164-175.

Syvitski, J.P.M., Milliman, J.D., 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. The Journal of Geology 115, 1-19.

Taylor, C.H., 1977. Seasonal variations in the impact of suburban development on runoff response: Peterborough, Ontario. Water Resources Research 13, 464-467.

Taylor, C.H. Roth, D.M. 1979. Effects of suburban construction on runoff contributing zones in a small southern Ontario drainage basin. Hydrological Sciences-Bulletin 24, 279-301.

Thayer, B.J., 2010. Floodplain development for a semi-alluvial river. Unpublished Honor Thesis, Department of Geography, Western University, 87 p.

Thayer, B.J., Ashmore, P., 2016. Floodplain morphology, sedimentology and development processes of a partial alluvial channel. Geomorphology 269, 160-174.

Thayer, B.J., Phillips, R.T.J., Desloges, J.R., 2016. Downstream channel adjustment in a low-relief, glacially conditioned watershed. Geomorphology 262, 101-111.

Thornbush, M.J., Desloges, J.R., 2011. Palaeoenvironmental reconstruction at an oxbow lake situated at the lower Nottawasaga River, southern Ontario, Canada. Environmental Archeology 16, 1-15.

Tinkler, J., Wohl, E.E., 1998a. (Eds.) Rivers Over Rock: Fluvial Processes in Bedrock Channels. Tinkler, K.J., and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union Geophysical Monograph 107, Washington, D.C., 323 p.

Tinkler, K., Wohl, E.E., 1998b. A primer on bedrock channels. In: Tinkler, K.J., and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union Geophysical Monograph 107, Washington, D.C., 1-18.

Tinkler, K.J., Parrish, J., 1998. Recent adjustments to the long profile of Cook Creek, an urbanized bedrock channel in Mississauga, Ontario. In: Tinkler, K.J., and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union Geophysical Monograph 107, Washington, D.C., 167-188.

Trenter, N.A., 1999. Engineering in Glacial Tills: CIRIA (Construction Industry Research and Information Association) Report C504, London, 259 pp.

Tribe, S., Church, M., 1999. Simulations of cobble structure on a gravel streambed. Water Resources Research 35, 311-318.

Tridon Properties Ltd., 2014. 161 Windermere Road Vacant Land Condominium Development Environmental Impact Study. AECOM, Kitchener, ON, Appendix B – Borehole Logs.

Trudeau, M. P., Richardson, M., 2015. Change in event-scale hydrologic response in two urbanizing watersheds of the Great Lakes St Lawrence Basin 1969 – 2010. Journal of Hydrology 523, 650-662.

Trudeau, M. P., Richardson, M., 2016. Empirical assessment of effects of urbanization on event flow hydrology in watersheds of Canada's Great Lakes-St Lawrence basin. Journal of Hydrology 541, 1456-1474.

Turowski, J.M., Hovius, N., Wilson, A., Horng, M., 2008. Hydraulic geometry, river sediment and the definition of bedrock channels. Geomorphology 99, 26-38.

Turowski, J.M., Rickenmann, D., 2009. Tools and cover effects in bedload transport observations in the Pitzbach, Austria. Earth Surface Processes and Landforms 34, 26-37.

Upper Thames Conservation Authority., 2018. Medway Creek 2017 Watershed Report Card. Available from: http://thamesriver.on.ca/wp-content/uploads//WatershedReportCards/RC_Medway.pdf. Last accessed: November 20, 2021.

Wang, L., Lyons, J., Kanehl, P., Gatti, R., 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. Fisheries 22, 6-12.

Wang, L., Cuthbertson, A., Pender, G., Cao, Z., 2015. Experimental investigations of graded sediment transport under unsteady flow hydrographs. International Journal of Sediment Research 30, 306-320.

Warburton, J., 1992. Observations of bed load transport and channel bed changes in a proglacial mountain stream. Arctic and Alpine Research 24, 195-203.

Ward, A.D., Mecklenburg, D., Powell, G.E., Jayakaran, A.D., D'Ambrosio, J., Draper, J., 2008. Creating ditches with floodplains. 16th National Nonpoint Source Monitoring Workshop September 14-18, 2008 Columbus, Ohio, 12 p.

Whipple, K.X., Hancock, G.S., Anderson, R.S., 2000a. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. Geological Society of America Bulletin 112, 490-503.

Whipple, K.X, Snyder, N.P., and Dollenmayer, K., 2000b. Rates and processes of bedrock incision by the Upper Ukak River since the 1912 Novarupta ash flow in the Valley of Ten Thousand Smokes, Alaska. Geology 28, 835-838.

Wickert, A.D., Mitrovica, J.X., Williams, C., Anderson, R.S., 2013. Gradual demise of a thin southern Laurentide ice sheet recorded by Mississippi drainage. Nature 502, 668-674.
Wilcock, P.R., 1993. Critical shear stress of natural sediments. Journal of Hydraulic Engineering 119, 491-505.
Wilcock, P.R., Kenworthy, S.T., Crowe, J.C., 2001. Experimental study of the transport of mixed sand and gravel. Water Resources Research 37, 3349-3358.
Wilcock, P.R., Baskfield, P., Belmont, P., Birr, A., Cooper, P., Engstrom, D., Jennings, C., Kiesling, R., Matteson, S., Mulla, D., Nieber, J., Regan, C., Schottler, S., 2009. Identifying sediment sources in the Minnesota River Basin. Minnesota River Sediment Colloquium June 30, 2009, Minnesota Pollution Control Agency, 16 p.
Wilcock, P.R., 2012. Stream restoration in gravel-bed rivers. In: Church, M., Biron, P.M., Roy, A.G., (Eds.) Gravel-bed Rivers: Processes, Tools, Environments. John Wiley & Sons, Ltd., Chapter 12, 137-146.
Wilkin, D.C., Hebel, S.J., 1982. Erosion, redeposition, and delivery of sediment to Midwestern streams. Water Resources Research 18, 1278-1282.
Williams, P.F., Rust, B.R., 1969. The sedimentology of a braided river. Journal of Sedimentary Petrology 39, 649-679.
Wohl, E.E., Anthony, D.J., Madsen, S.W., Thompson, D.M., 1996. A comparison of surface sampling methods for coarse fluvial sediments. Water Resources Research 32, 3219-3226.
Wohl, E.E., Ikeda, H., 1998. Patterns of bedrock channel erosion on the Boso Peninsula, Japan. The Journal of Geology 106, 331-345.
Wolcott, J., 1988. Nonfluvial control of bimodal grain-size distributions in river-bed gravels. Journal of Sedimentary Research 58, 979-984.
Wolman, M.G., 1954. A method of sampling coarse bed material. Eos Transactions, AGU 35, 951-956.
Woltemade, C.J., 1994. Form and process: Fluvial geomorphology and flood-flow interaction, Grant River, Wisconsin. Annals of the Association of American Geographers 84, 462-479.
Wroth, C.P., Wood, D.M., 1978. The correlation of index properties with some basic engineering properties of soils. Canadian Geotechnical Journal 15, 137-145.

Tables

Table 1. Till and bedform properties of Medway Creek.

Table 2. Erosion rates of till patches during the study period.

Table 3. Bed characteristics of streams with abundance of fines originating from the parent material.

Table 1.

		Minimum	Median	Average	Maximum
Till properties	a-axis (mm)	60	100	111	210
	b-axis (mm)	50	80	85	140
	c-axis (mm)	20	55	56	110
	silt/clay fraction (%)	56.9	77.4	75.8	89.4
	sand fraction (%)	7.9	16.9	17.8	31.8
	gravel fraction (%)	2.1	5.6	6.4	16.7
	volume (cm^3)	66	218	317	1020
	dry mass (g)	90	385	531	1575
	wet mass (g)	92	390	546	1576
	bulk density (g/cm^3)	1.32	1.54	1.64	2.54
	porosity (%)	0.06	1.28	2.40	11.75
	sphericity (-)	0.12	0.16	0.17	0.32
	roundness (-)	0.1	0.3	0.3	0.8
	plasticity index (-)	9	17	18	29
	shear strength (kN/m^2)	99	280	280	493
	erosion rate (mm/yr)	6	39	61	260
Bedform geometry	pool width (m)	12		16	20
	pool length (m)	13		70	279
	pool channel slope (-)	0.0001	0.0009	0.0021	0.0075
	pool spacing (m)	5.1	14.5	33.5	195.0
	riffle width (m)	12		15	21
	riffle length (m)	5		12	31
	riffle channel slope (-)	0.0031	0.0106	0.0142	0.0346
	riffle spacing (m)	12.0	47.3	84.1	321.5
	glide width (m)	12		15	18
	glide length (m)	19		62	186
	glide channel slope (-)	0.0003	0.0027	0.0029	0.0056
	glide spacing (m)	0.5	67.0	121.3	369.3
Bedform sediments	sorting index (-), all bedforms	1.7	2.8	2.9	4.4
	sorting index (-), pools	2.6	3.5	3.5	4.4
	sorting index (-), riffles	1.9	2.7	2.7	3.7
	sorting index (-), glides	1.7	2.7	2.7	3.6
	sorting index (-), steps	2.1	2.2	2.2	2.3
	sorting index (-), point bars	1.7	2.0	2.4	4.0
	sorting index (-), braid bar	1.9	1.9	1.9	1.9
	sand fraction (%), pools	4.2	11.1	15.5	39.4
	sand fraction (%), riffles	0.7	4.5	5.5	11.4
	sand fraction (%), glides	1.7	5.3	6.9	13.8
	sand fraction (%), steps	2.6	2.7	2.7	2.7
Bedform stability indices	LRBS* (-), pools	0.16	0.96	1.12	1.96
	LRBS* (-), riffles	-0.03	0.24	0.38	1.28
	LRBS* (-), glides	0.434	1.13	1.09	1.85
	RSI (-), riffles	31	38	38	48
	V* (-), pools	0.01	0.03	0.04	0.15

Table 2.

Hydrological year	Peak discharge m^3s^{-1}	Site	Location in channel	Erosion pins #	Configuration W*L	Recovered #	Recovery %	Average erosion rate mm	Median erosion rate mm	Minimum erosion rate mm	Maximum erosion rate mm	Inter-patch erosion spatial autocorrelation Moran I	Moran I P-value
2010-2011	84	1	Glide (center channel)	20	4*5	19	95	143	134	106	225	0.02	0.62
		2	Pool (next to right bank)	53	5*10+3	48	91	80	78	44	143	0.40	0.00
2011-2012	23	1	Glide (center channel)	20	4*5	19	95	70	66	19	125	-0.01	0.81
		2	Pool (next to right bank)	53	5*10+3	Buried	0	-	-	-	-		
2012-2013	68	1	Glide (center channel)	20	4*5	20	100	32	32	19	53	-0.07	0.91
		2	Pool (next to right bank)	53	5*10+3	Buried	0	-	-	-	-		
		3	Riffle (next to right bank)	24	6*4	24	100	48	39	13	111	0.20	0.10
2013-2014	33	1	Glide (center channel)	20	4*5	20	100	16	16	10	26	-0.04	0.94
		2	Pool (next to right bank)	53	5*10+3	30	57	125	114	44	260	0.41	0.00
		3	Riffle (next to right bank)	24	6*4	24	100	24	20	6	55	0.20	0.10
		4	Pool (center downstream	16	4*4	16	100	40	34	8	108	0.14	0.24
		5	Pool (next to left bank)	12	3*4	11	92	59	64	32	84	-0.06	0.85
		6	Riffle (next to left bank)	18	4*4+2	18	100	30	28	16	61	0.31	0.03
			Total	386		249	65	61	39	6	260		

* In Moran's I Values range from −1 (indicating perfect dispersion) to +1 (perfect correlation). A zero value indicates a random spatial pattern.

Table 3.

	Medway Creek	Nahal Me'arot	Nahal Eshtemoa	West Walker River
Bed type (d_{50})	Cobbles (67 mm)	Medium gravel (11 mm)	Coarse gravel (28 mm)	Cobbles (171 mm)
Modality	Bimodal	Trimodal	Polymodal	Bimodal
Sorting	Very poorly sorted (2.8)	Very poorly sorted (2.5)	Very poorly sorted (2.2)	Very poorly sorted (2.8)
Skewness	Very fine skewed (0.51)	Very fine skewed (0.33)	Fine skewed (0.16)	Very fine skewed (0.61)
Kurtosis	Mesokurtic (1.07)	Mesokurtic (1.07)	Mesokurtic (1.02)	Very leptokurtic (1.69)

Figures

Figure 1. (a) Great Lakes and Medway Creek study area (red square). (b) The watershed of Medway Creek (c) View of the study area with length along the thalweg profile, bedforms, till patches, contours and bed coloration according to elevation.

Figure 2. Average and median hydrographs for Medway Creek showing the flashy nature of the flows with a spring freshet peak discharge. Data is based on gauged data from 1945-2014.

Figure 3. The three most common bedforms on Medway Creek: pool (top), riffle (center) and glides (bottom).

Figure 4. Till clasts from Medway Creek bed. (a) Fractional breakdown of sediment sizes among all collected clasts (n = 44). The boxes indicate 25th and 75th percentiles as well as the median; the whiskers indicate 5th and 95th percentiles. (b) Sample dry clast showing bioturbation. (c) Sample dry clast showing protruding stones of the gravel fraction, covered by algae. (d) Sample wet clast, immediately following recovery from channel bed, showing burrowing chironomids (blood worms).

Figure 5. Penetration resistance (N blows) using Standard Penetration Test (SPT) into the local Medway Creek till conducted within four boreholes for a proposed development above the river valley. The topsoil and lacustrine layers are not included (Source: Tridon Properties Ltd., 2014).

Figure 6. Morphologic features along Medway Creek. (a) The downstream cobble-boulder step (view is upstream). Similar features were observed in other till rivers of the area. Note a giant 2 m boulder in the background. (b) Bed till ledge connected to the bank. During summer low flows the till is partially dry, cracks and breaks down into block-like clasts of various sizes that are incorporated into the channel bed alluvium (view is downstream). (c) Submerged bed till ledge during winter high flow. The ledge is smoothed, and a new layer of till is exposed (view is upstream). (d) A planar view from the top of the right bank bluff into the channel (flow direction is left to right.). The most apparent features are the bed till exposures and the coarse boulder lag in the center-right of the photo.

Figure 7. (a) Complex morphology showing a till ledge with some coarse alluvium connected to the vertical bank. (b) Schematic diagram of a partial cross section showing a till ledge connection to the bank and channel bed. This terrace-like feature is exposed at low flow and is topographically disconnected from the alluvial bed. This is the only sculpted form preserved in the boundary till.

Figure 8. Till exposures along Medway Creek. (a) Till exposure with *in situ* gravel-sized stones (flow direction is from left to right). Note the large differences in grain sizes from few cobbles and boulders down to numerous granules that dot the till. (b) Center-channel till patch surrounded by alluvium with distinct coloration differences during low flow

conditions (flow direction is from right to left). The boulders on the center right might be responsible for the boundary exposure which is located directly in their wake. (c) Submerged bed till exposure with cracks and irregularities that are potential weak spots for erosion by the flow and surrounding gravels (flow direction is from top to bottom).

Figure 9. Bedform characteristics: (a) Slope. (b) Length. (c) Channel widths along the study reach.

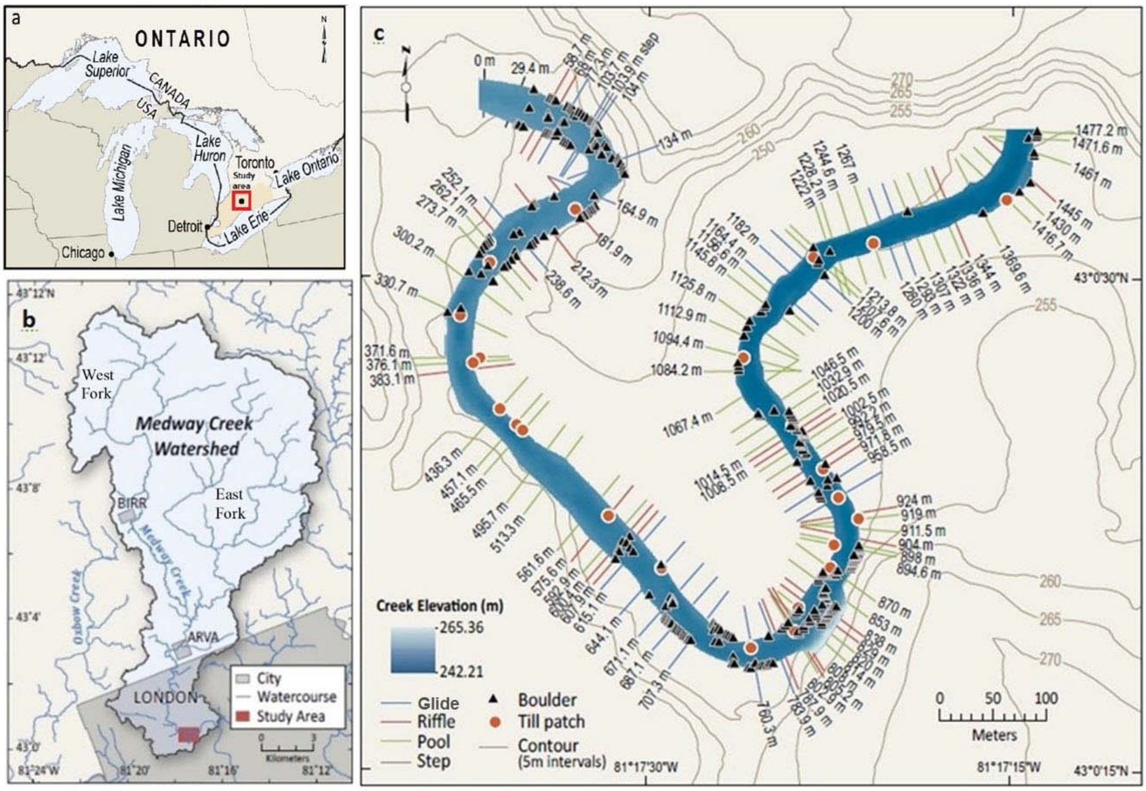
Figure 10. Three indices used to describe bed stability of the study reach. (a) The Kaufmann et al. (2008; 2009) LRBS* method per bedforms compared to other rivers. (b) Riffle Stability Index (RSI) according to Kappesser (2002) compared to three other rivers. (c) relative volume of fine sediment in pools (Lisle and Hilton, 1992; 1999). Data from Lisle and Hilton (1992) of disturbed and undisturbed pools on Bear Creek and other California rivers for comparison. The boxes indicate 25th and 75th percentiles as well as the median; the whiskers indicate 5th and 95th percentiles. *Notes: Pacific NW data are from Kaufmann et al (2009). Only data from sedimentary lithologies is included here, and only low disturbed rivers are incorporated in graph. Values are derived from Kaufmann et al's Fig 3A, interpreting whiskers as 5% and 95%. Carson River data in Pahl (2006) use Kaufmann (1999) method. Values here are converted from original Pahl data (col K) to LRBS* data (col F) using the regression formula in Kaufmann et al (2009). Same for original Virginia river data (Kappesser, 2002) (col L), which is also converted to LRBS* (col G) using the same regression formula.

Figure 11. Till properties of Medway Creek compared to selected tills of the Great Lakes area. (a) Percentage of fines (silt and clay) compared to Ohio tills (Fausey et al., 2000) and Halton and Fletcher creeks (Khan and Kostachuk, 2011). (b) Percentage of sand for the same channels. (c) Bulk density for these semi-alluvial channels with the Kalamazoo River added (McNeil and Lick, 2004). The large variability in the matrix of the tills determines their erodibility in space and time.

Figure 12. Critical shear stress needed to dislodge the till of Medway Creek (Pike et al., 2018) and selected other rivers of the Great Lakes (based on data from Kamphuis et al., 1990; Mier and Garcia, 2011; Khan and Kostachuk, 2011). It is evident that besides Highland Creek and to some extent Fletcher Creek, the shear stress values needed to erode the till are relatively low. It is noteworthy to mention that besides Highland Creek and Fletcher Creek where *in situ* jet testing was used in the field, all other values for other channels were attained in a laboratory flume.

Figure 13. Comparison of Medway Creek GSD to three other streams that have an abundance of fines originating from their parent material.

Figures



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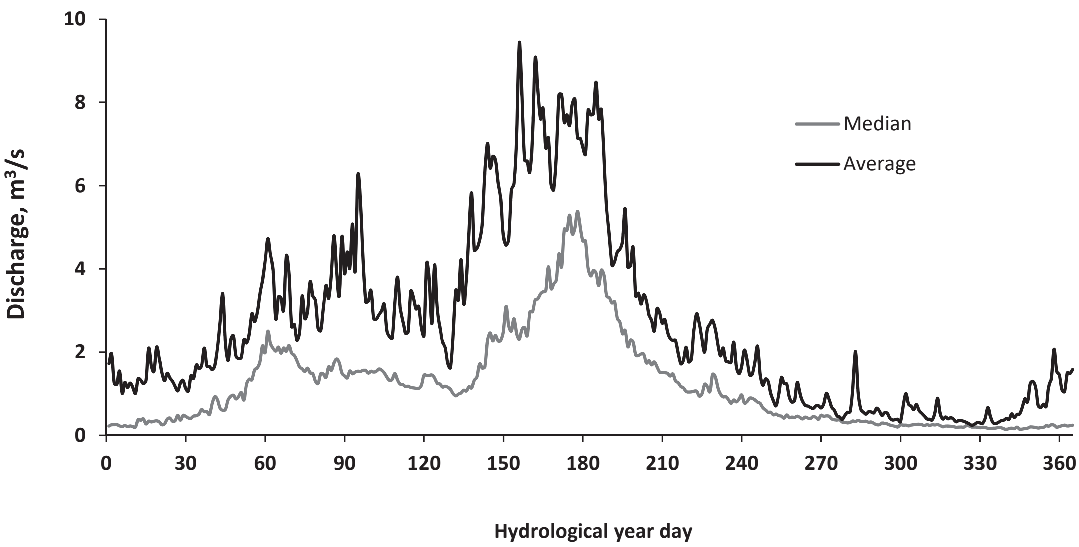

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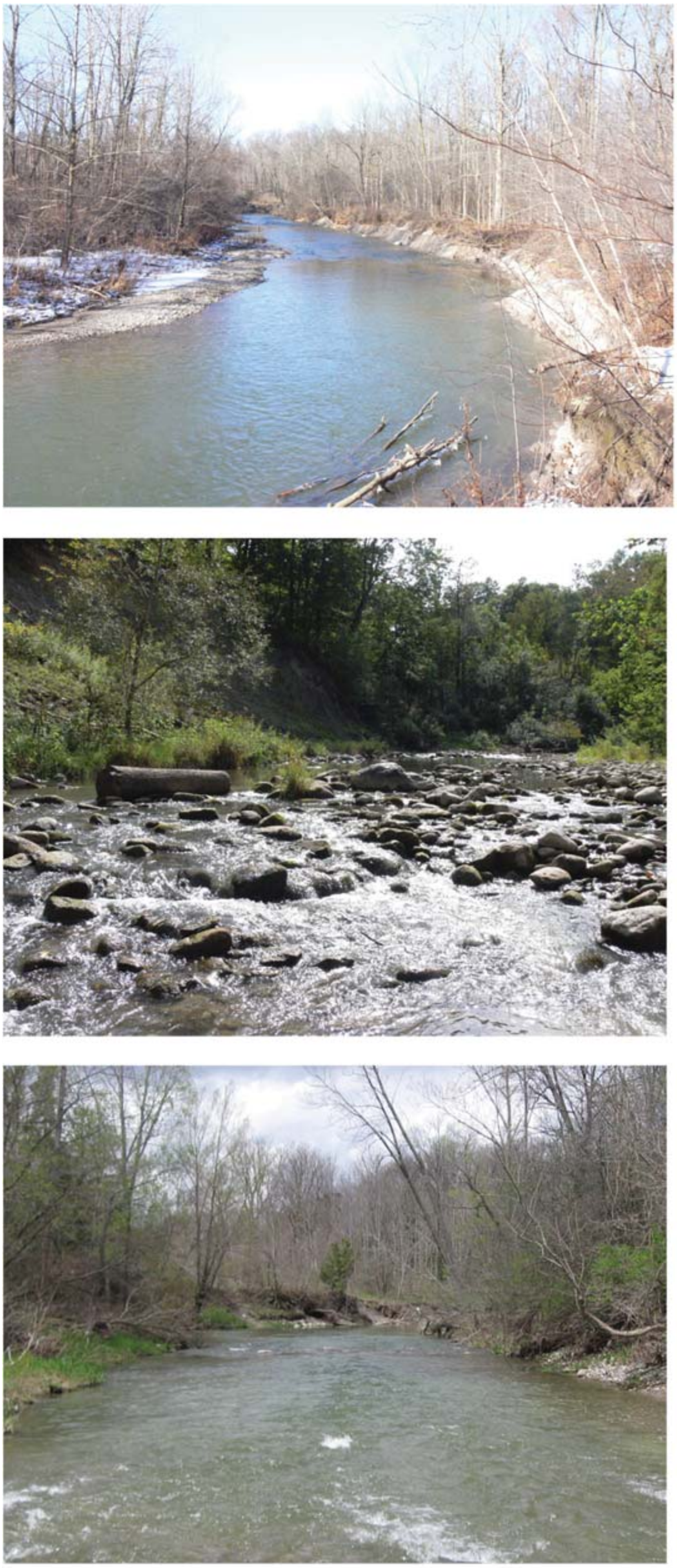

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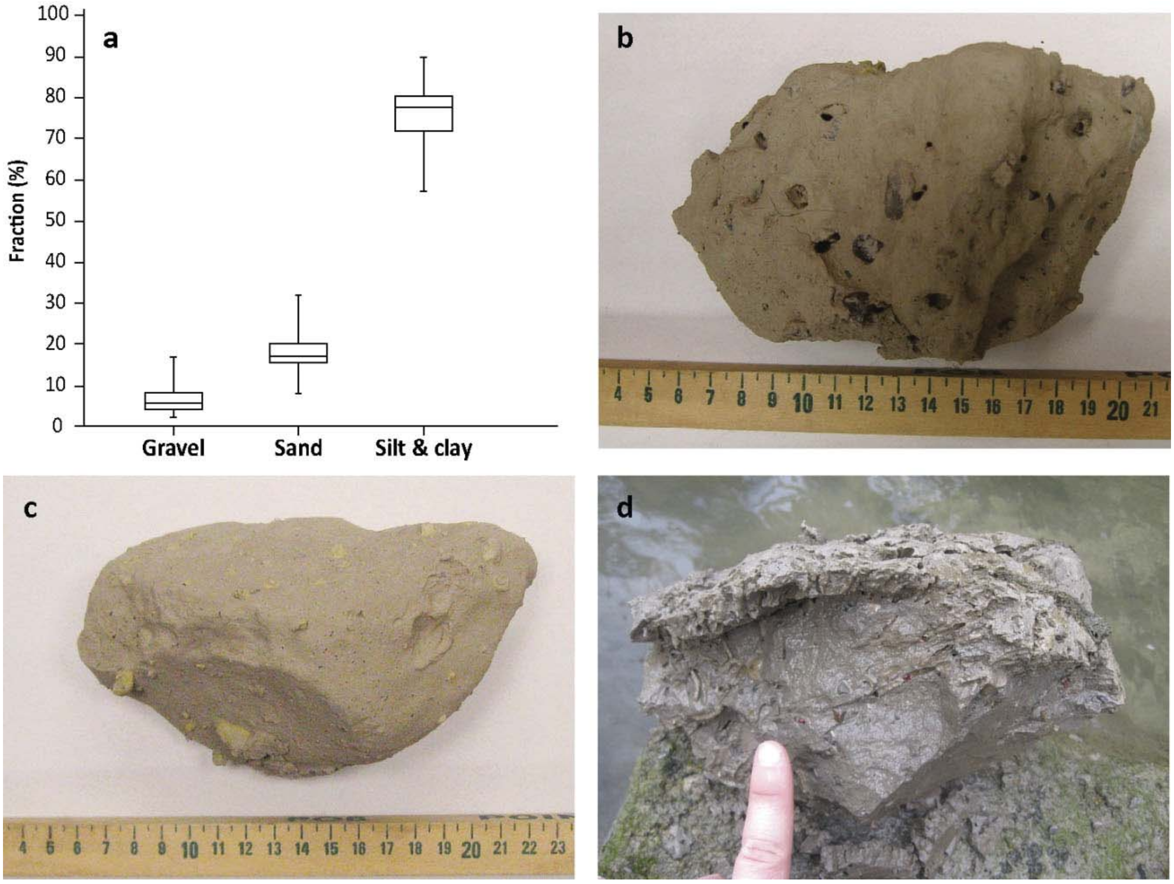
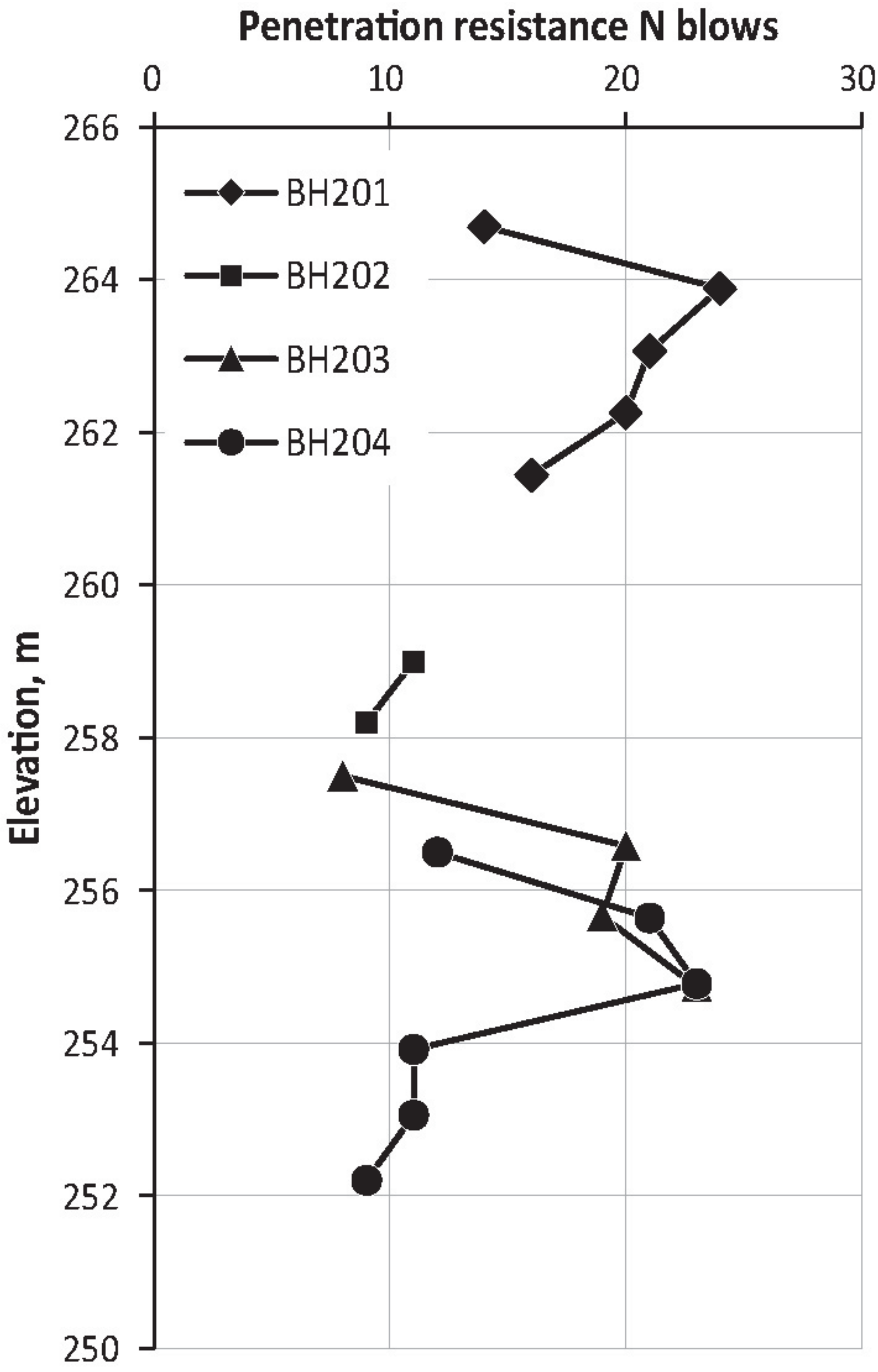
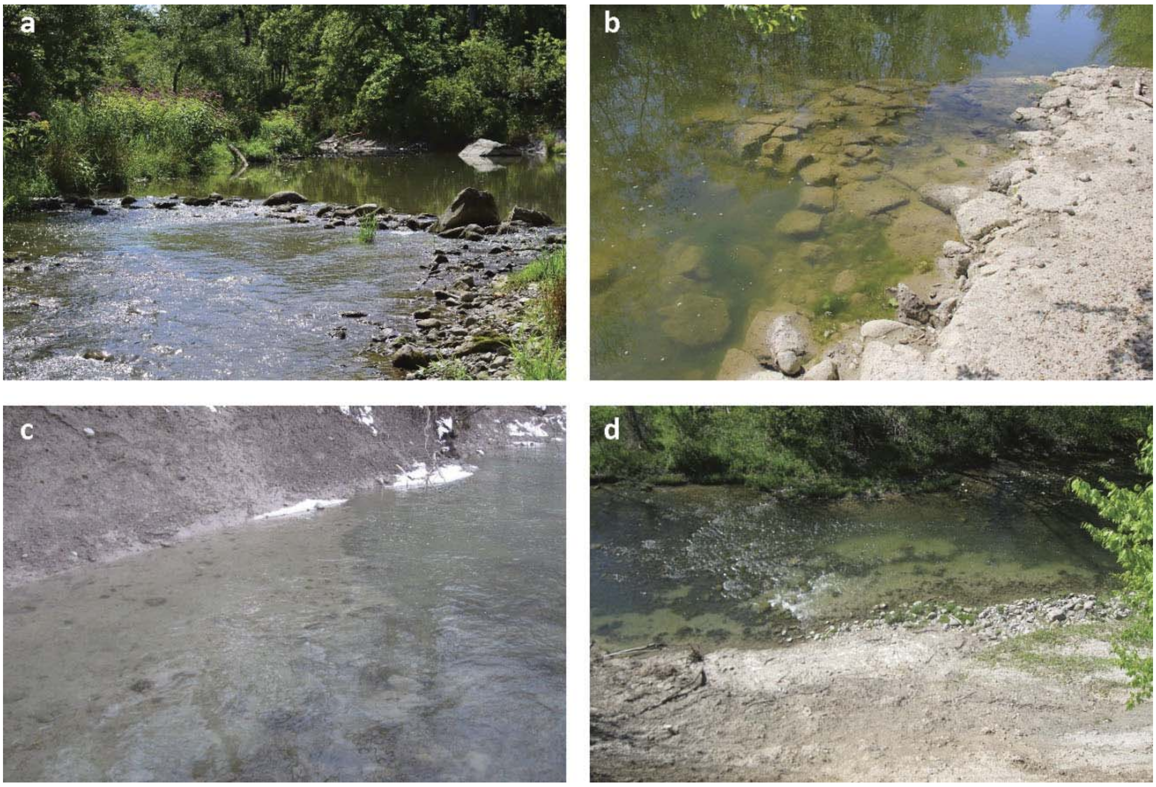

a
b
c
d
Fraction (%)
100
90
80
70
60
50
40
30
20
10
0
Gravel
Sand
Silt & clay

Figure 4.



Penetration resistance N blows
0
10
20
30
266
264
262
260
258
256
254
252
250
Elevation, m
BH201
BH202
BH203
BH204

Figure 5.



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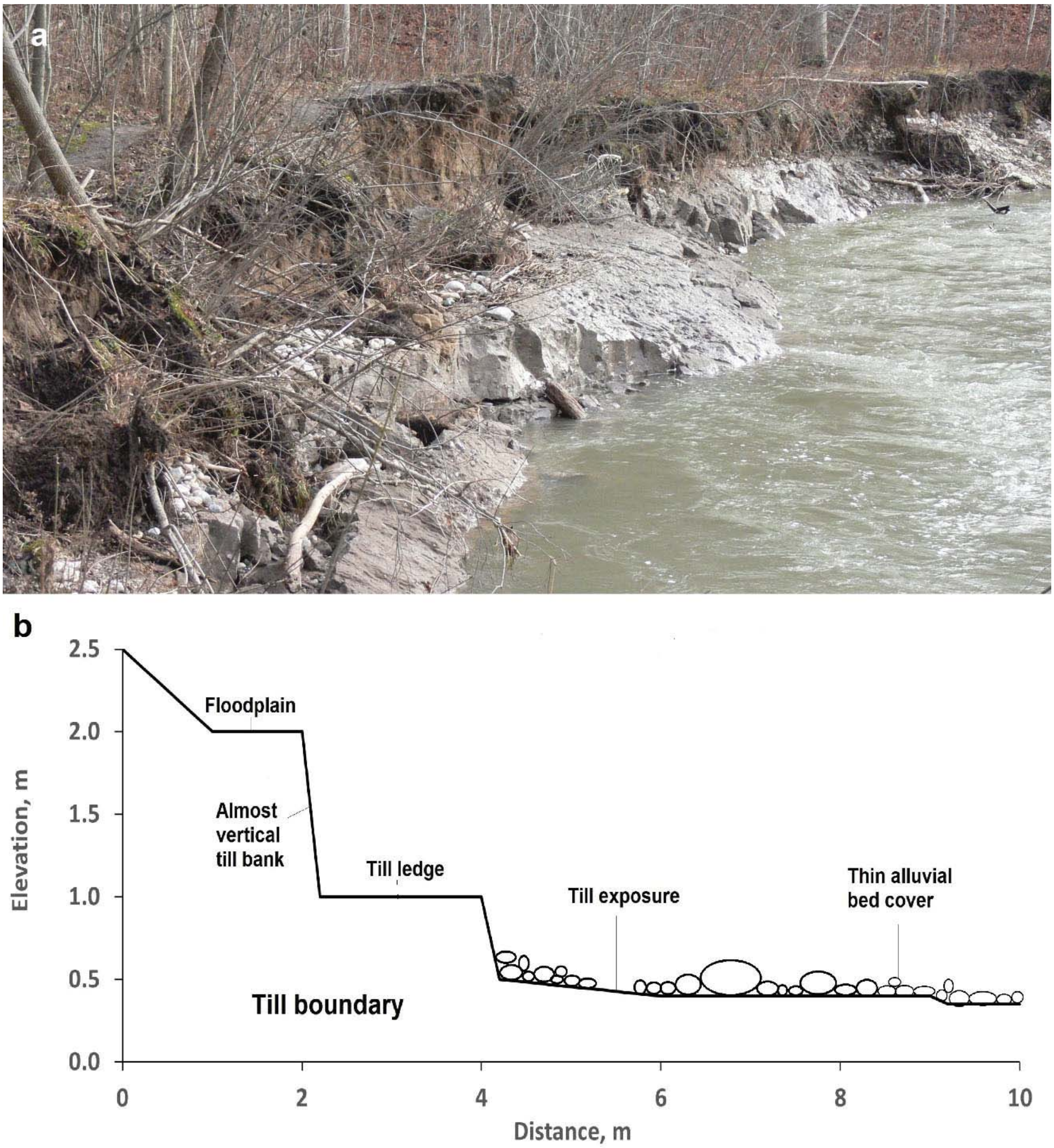
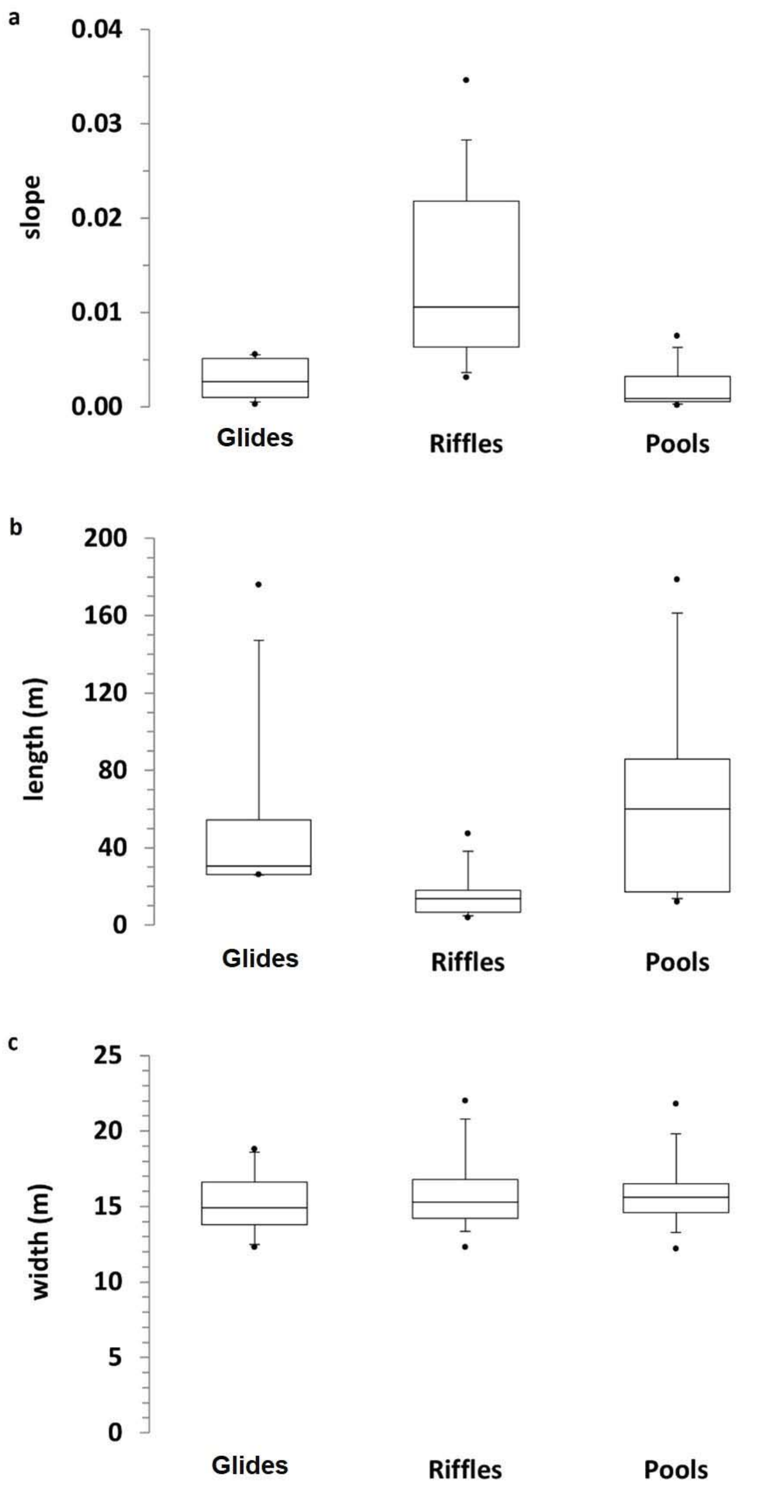

a
b
2.5
2.0
1.5
1.0
0.5
0.0
Elevation, m
Floodplain
Almost
vertical
till bank
Till ledge
Till exposure
Thin alluvial
bed cover
Till boundary
0
2
4
6
8
10
Distance, m

Figure 7.

Figure 8.



a
0.04
0.03
0.02
0.01
0.00
slope
Glides
Riffles
Pools
b
200
160
120
80
40
0
length (m)
Glides
Riffles
Pools
c
25
20
15
10
5
0
width (m)
Glides
Riffles
Pools

Figure 9.

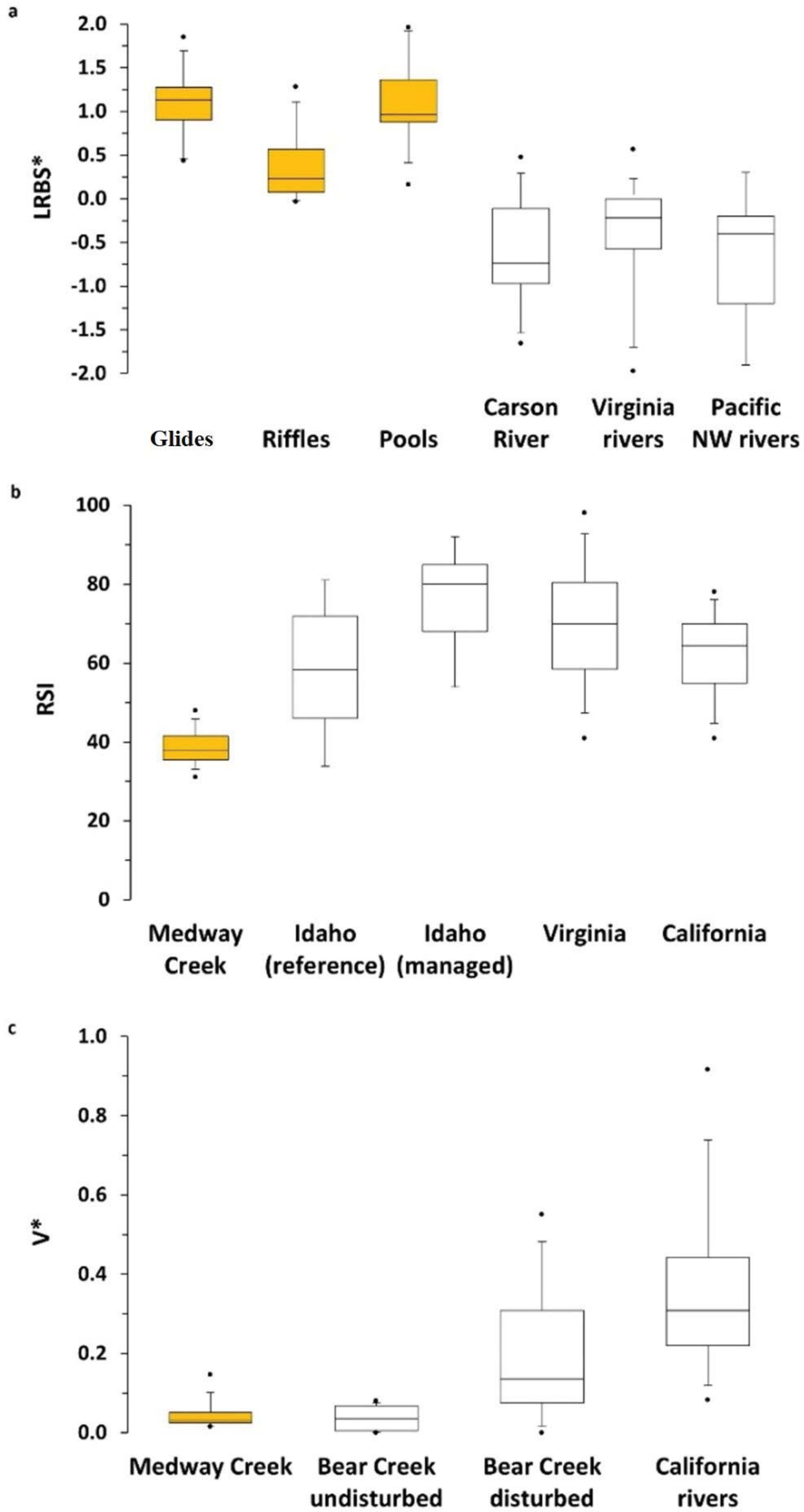

a
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
LRBS*
Glides
Riffles
Pools
Carson River
Virginia rivers
Pacific NW rivers
b
100
80
60
40
20
0
RSI
Medway Creek
Idaho (reference)
Idaho (managed)
Virginia
California
c
1.0
0.8
0.6
0.4
0.2
0.0
V*
Medway Creek
Bear Creek undisturbed
Bear Creek disturbed
California rivers

Figure 10.

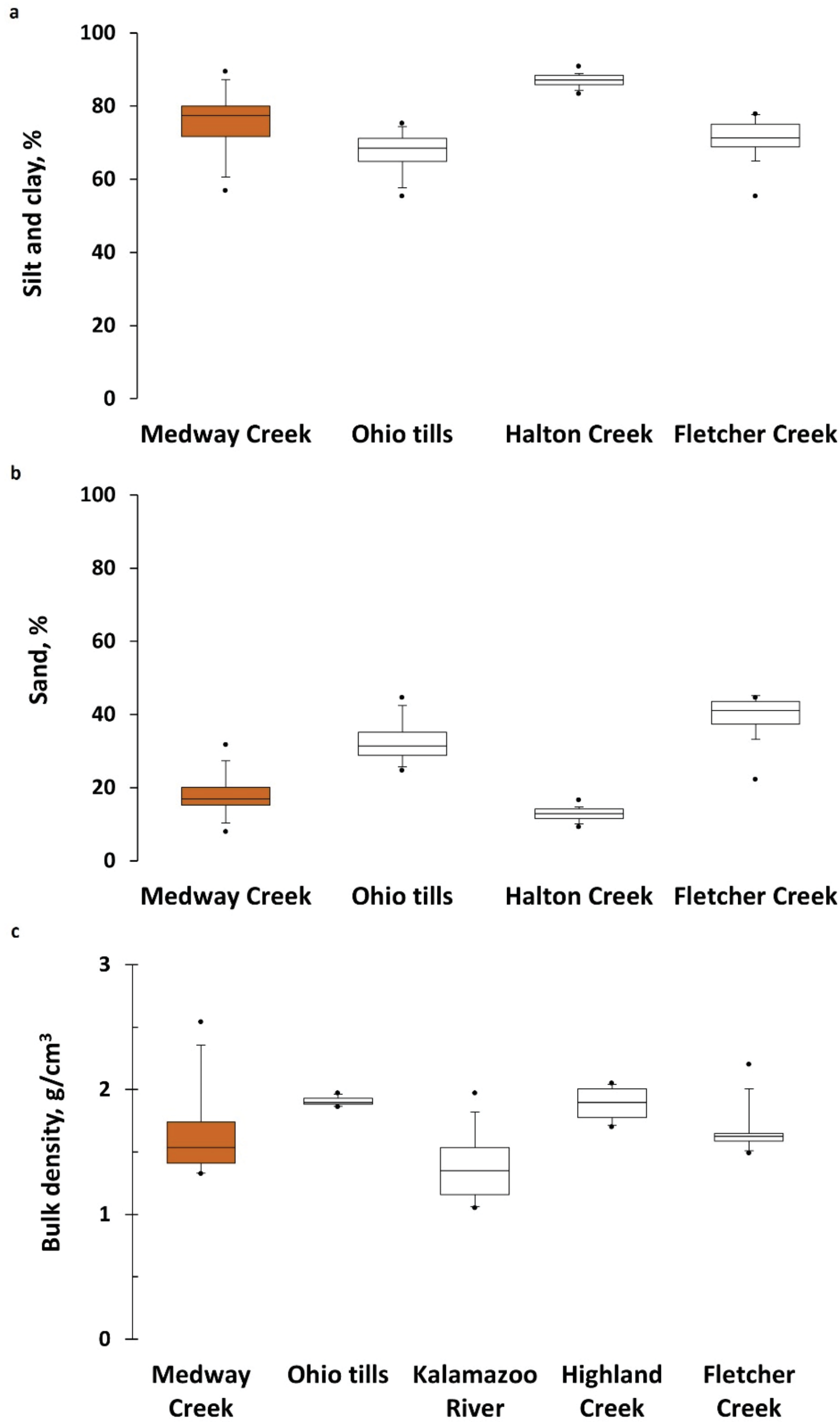
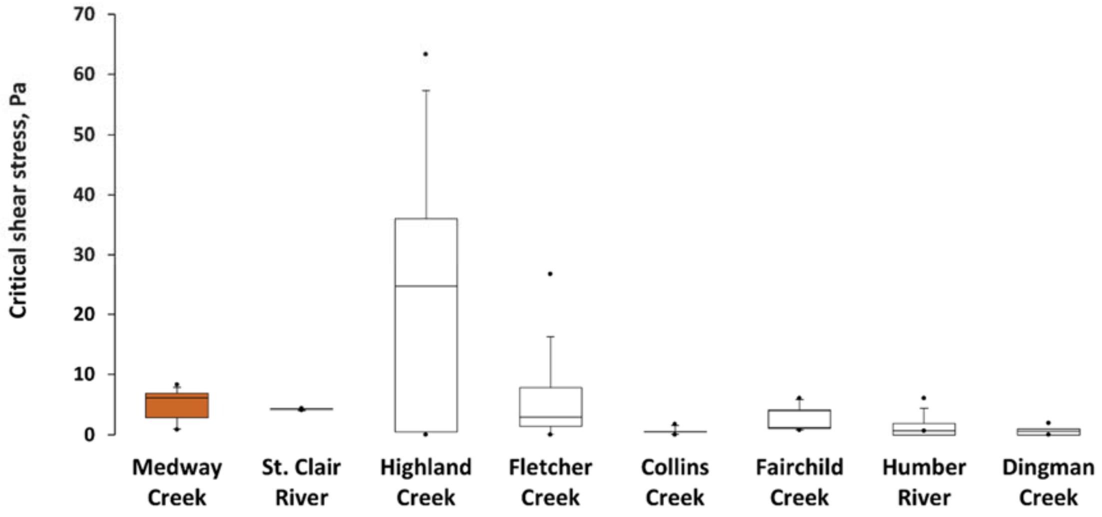

a
Silt and clay, %
100
80
60
40
20
0
Medway Creek
Ohio tills
Halton Creek
Fletcher Creek
b
Sand, %
100
80
60
40
20
0
Medway Creek
Ohio tills
Halton Creek
Fletcher Creek
c
Bulk density, g/cm3
3
2
1
0
Medway Creek
Ohio tills
Kalamazoo River
Highland Creek
Fletcher Creek

Figure 11.



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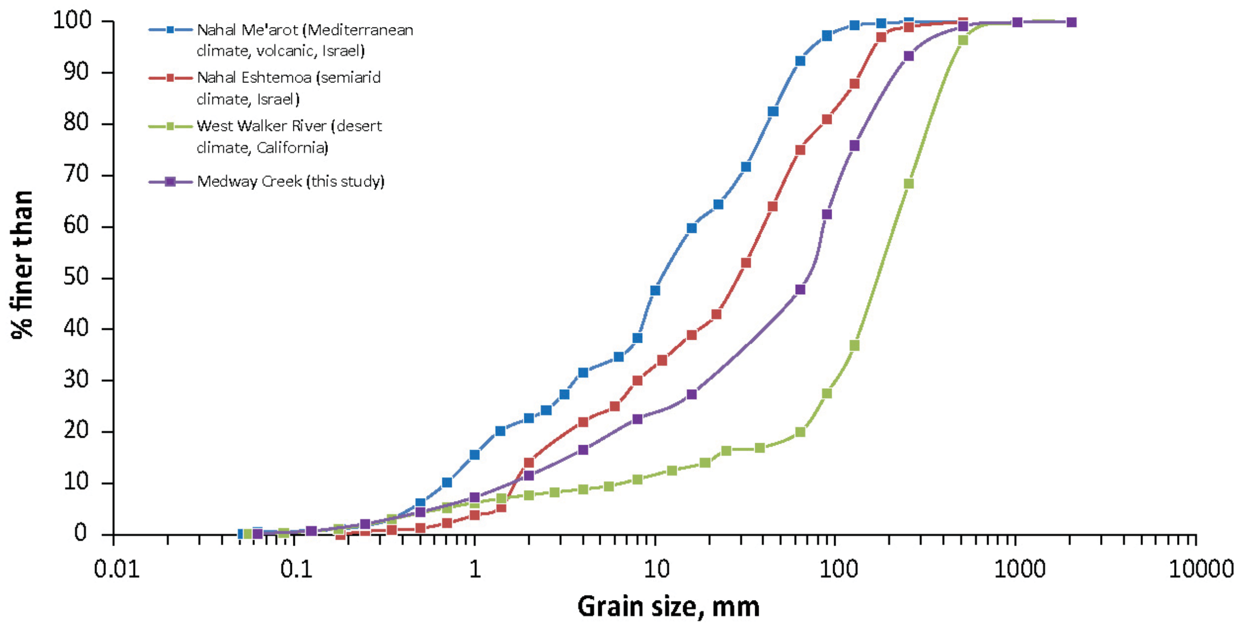

Figure 13.

Appendix 1: Supporting Materials

Methods

a. Till sediment characteristics: Sediment bulk properties (Roberts et al., 1998; McNeil and Lick, 2001), particle size properties (Aberle et al., 2004), sediment cohesion properties and biological activity (Grabowski et al., 2011) determine material erodibility, in addition to other factors that interact with them in traction or impact (e.g., sand and gravel as bedload or particle saltation hits, air/water temperature that causes freeze-thaw cycles, its desiccation and cracking; Culley, 1971; Hill, 1973; Pike et al., 2018). Till was characterized by randomly collecting 44 till clasts of various sizes from the riverbed. Each clast was air dried, color determined according to Munsell system, measured for size along its three axes (short, intermediate and long), sphericity calculated from the axes, precisely weighed with an analytical scale, volume determined (the sample within a nylon bag was inserted into a water container with known volume and the water displacement was recorded), as well as its submerged weight (clast weighed under water), bulk density (mass/volume) and porosity. Subsequently, each clast was disintegrated in water and when fully dispersed, passed through 2 mm and 63-µm sieves to separate the gravel, sand and fines and get their percentages after drying in an oven at 105°C. Each sample was photographed and described morphologically (cracks, borings of aquatic insects leading to bioturbation and roundness). Material strength was obtained from four borehole drillings, which were done at the top of the valley (above the left bank downstream for a proposed development), which included SPT (Standard Penetration Test) in the field and Atterberg limits for plasticity index in the laboratory (Tridon Properties Limited, 2014). This technique is similar to the CPT (Cone

Penetration Test) technique used by Dasenbrock et al. (2010) to characterise tills and other glacial deposits in Minnesota. Trenter (1999) suggested that the best use of this approach is site-specific when only SPT N-values are available in some boreholes. Furthermore, this SPT method can only be used in tills that contain gravels while many geotechnical tests require that the sample will be devoid of gravel.

b. Topographic and morphological mapping: The 1.5 km reach of Medway Creek was mapped for bed, bank and floodplain elevations using a differential GPS (5500 points) during low flow (~ $1m^3$/sec). The resulting topographic DEM (Digital Elevation Model) was used to extract a channel longitudinal profile. The profile was corrected for noise (Phillips and Desloges, 2014), after which precise subunits (~1 m resolution) were identified based on dominant bedforms (pools, riffles, glides, bars and steps) and exposed patches of till. Bedforms were identified from the DEM based on local slope and curvature of the long profile (Church and Jones, 1982 for bars; O'Neill and Abrahams, 1984 for pools and riffles; Chin, 1989 for step-pools and general bedform definition from Montgomery and Buffington, 1997). This bedform classification was visually verified in the field at low water level. Foster (1998) has shown this method is an effective procedure of bedform identification in three other semi-alluvial till-bedded streams of the area (Dingman Creek, Nissouri Creek and Oxbow Creek).

Both bank heights were measured in the field at 5-m intervals using a stadia rod (307 points for the left bank, 309 for the right bank). These bank elevations were later corrected relative to the thalweg datum (i.e., the height between bank toe and thalweg elevation were added) and imposed on it to create two additional long profiles of the reach. This approach proved more precise than extraction of bank elevations from the DEM (or LiDAR) as it allowed finding a precise break in the cross-sectional slope into the floodplain according to high flow marks, top of a bar or lack of vegetation when the exposed till/soil topography was highly complex (and bankfull discharge was hard to determine). Channel widths were determined with a measuring tape in the field at 25 m intervals (62 points) to account for the cross-sectional complexity that cannot be accurately extracted from a DEM for reasons mentioned above. These data aided in developing the channel morphometry parameters, especially downstream hydraulic geometry, width-depth ratios and determining bankfull discharge.

c. Till patch mapping: Unlike channel bedforms, for which identification protocols exist (see **b**), there is currently no established procedure to identify and extract till exposures from a topographic map. Consequently, a separate GPS survey of the channel was conducted in the field to map all till patch exposures. This survey gave information about: how many patches exist, their size, their areal percentage of the total bed, spacing between them and relationship to other bedforms and large boulders. In addition, since till patches have varying degrees of exposures, they were visually classified to account for how much alluvium covers them (in percent). This classification helped in determining the annual erosion rates of till patches and their sampling strategy to represent the entire study site (see **h**). While **b** and **c** complement each other, the reason for separating them during the mapping phase is the bedforms and till patches do not always coincide (in terms of their borders and sizes). This allows better distinction and scale delineation of the till patches.

d. Morphologic analysis: Once the bed-feature map was created, it was analyzed in ArcGIS 10.1 (ESRI, 2012) and verified in the field to determine the spatial and morphologic characteristics (dimensions, spacing and distribution) of the dominant channel bedforms. A similar analysis of bedform morphology from a DEM (or long profile) was developed for step-pool channels by comparing it to visual measurements of the bedforms (Zimmermann et al., 2008). This determines the accuracy of the DEM.

e. Surface alluvium grain size distribution surveying: Each bedform (see **b**) underwent a grain size distribution (GSD) survey to characterize the alluvial cover. Each GSD survey of a bedform included at least three cross sections of Wolman (1954) pebble counts (upstream, center, and downstream) with at least 300 clast measurements of the b-axis per bedform as a minimum (Rice and Church, 1996). Because of the tendency to sample coarse material rather than finer sediment (Fripp and Diplas, 1993), and to avoid the misrepresentation of the fine tail, every time a clast smaller than 32 mm was encountered it was recorded as 'fines'. Once the GSD cross section was complete, 2-5 kg of fines (<32 mm) bulk sample from several locations in that bedform were bagged, taken to the lab, the silt-clay fractions were washed in a 63-μm sieve to avoid particle cohesion, air-dried, and subjected to sieve analysis. The Wolman pebble counts (grid by number) and the bulk sieve analysis (volume by weight) can be combined into a single GSD for each bedform, without requiring conversion (Kellerhals and Bray, 1971). Such hybrid procedure was utilized successfully by Rice and Haschenburger (2004), as the larger samples of <0.1% d_{max} criteria (Church et al., 1987) are impractical to sample because of their large size (~5 tons for a d_{max} > 128 mm; Haschenburger et al., 2007) and the disturbance such an invasive procedure would have on the bed structure. Relating the grain size distributions to the bedform map (see **b**) using statistical sedimentary attributes such as selected grain percentiles (d_5, d_{25}, d_{50}, d_{75}, d_{84}, d_{95}) and d_{max} also enabled detecting spatial trends, and deploying bed stability indices (Kaufmann et al., 2008; 2009; Kappesser, 2002; Lisle and Hilton, 1992; 1999).

It is noteworthy that both the fine and coarse tails of GSDs are prone to large errors associated with sampling procedures. Furthermore, the connection of the tails to the main curve using sometimes completely different sampling techniques (i.e., Wolman pebble count and sieving) is also problematic. To minimize the errors, all GSDs in this study were done by one individual and with identical sampling program for all bedforms.

f. Statistical grain size analysis: Statistical attributes (percentiles, sorting and types of distributions) were calculated for each bedform's GSD (see **e**). These statistics allowed comparison among similar bedforms and between different bedforms in the same channel.

g. Alluvial cover thickness and stratigraphy: In 26 random locations along the thalweg the alluvium (or its lack thereof) was characterized by measuring its depth to the boundary till by picking up clasts. In locations where alluvium was thick enough, pits were hand-dug. These pits revealed the vertical sedimentary structure of the alluvium (e.g., armor existence, framework, or censored gravel stratigraphy).

h. Erosion measurement: To identify annual erosion rates of the till on a local scale, 94 erosion pins 25-30 cm long and 0.5 cm in diameter were inserted into three exposed till patches (between 25 and 35 pins per site): at the right bank of the channel (in 2010), at the center of the channel (in 2010), and in a riffle (in 2012). Using a 5 kg sledgehammer, erosion pins were carefully inserted, i.e., without visibly cracking the surface till (although subsurface cracks and micro-cracks may have developed due to the erosion pin's insertion), until flush with the bed. At the end of each hydrologic year, the exposure of each pin was precisely measured with a ruler, after which the pin was reinserted until it was again flush with the bed. Preliminary results indicated high erosion rates and substantial within-patch erosion variability. Consequently, the sampling strategy for the much larger scale of the entire study site was adapted. During hydrologic year 2013-2014, three additional sites were added on Medway Creek. The results were compared to longer term (geologic) incision rate from a topographic map (valley-scale) with the top of the valley serving as reference level divided by the time since the end of the last ice age. Results from the erosion analysis were compared to short-term channel incision rates for bedrock channels (Tinkler and Wohl, 1998a and references within; Stock et al., 2005). This comparison should account for the fact that Medway Creek is by not a natural river and accelerated incision is often associated with land clearance (Elliot, 1998), agriculture (Knox, 1989; Campo and Desloges, 1994; Woltenmade, 1994; Fitzpatrick et al., 1996) and particularly the construction of impervious surfaces in urban areas (Taylor, 1977; Taylor and Roth, 1979; Fitzpatrick et al., 1999; Annable et al., 2012).

i. Stability analysis: Hydrologic systems, including rivers, bedforms (Chin, 1998) and reaches (Kaufmann et al., 2009), are often investigated for their current stability or over a longer time scale if historic data is available. Such resilience can be hydrologic (Peterson et al., 2012) or geomorphic (Doyle et al., 2000), and can be defined as: (1) steady state (equilibrium), (2) quasi-equilibrium, or (3) instability due to some kind of internal or external perturbation (Schumm, 1973). Because natural river systems are non-linear (Phillips, 2003) and could exhibit self-organized criticality (Coulthard and Van De Wiel, 2007), it is possible for a system to have several steady and unsteady states that require crossing of thresholds to move from one state to the next (Church, 2002). In geomorphology, at least three distinct notions of stability are used. Most commonly stability/instability is used as general shorthand to distinguish landscapes and landforms that are static (exhumed and no longer going through erosion or deposition), slowly changing, or in steady state (quasi-equilibrium - changes are within natural variability), vs. those that are undergoing rapid change. A second notion is that of mechanical stability, which concerns the conditions under which change occurs. Finally, there is dynamic stability which determines resilience of geomorphic systems and whether they are sensitive to small perturbations or minor variations in initial conditions (Phillips, 2014). We relate to the first only, as our data set is too short to detect longer term changes.

On the reach scale, stability is generally defined as the ability of the stream to transport water and sediment of its watershed while maintaining its dimension, pattern and profile over time, i.e., without either aggrading or degrading (Pfankuch, 1975). Although stability changes in space and time (Myers and Swanson, 1996), the fact that each bedform repeats itself several times within the study reach allows stability determination at a specific point in time of that bedform, of all bedforms of that type and the generalization of the entire reach stability by combining all of them. Because different stability methods use different metrics, results might not be conclusive, and could even be contradictory to common assumptions (Doyle et al., 2000; Jordan et al., 2010; Annable et al., 2012).

There are two approaches to assess channel stability: qualitative and quantitative. A qualitative approach is based on professional judgment in the field of observed mass wasting of channel banks, riparian vegetation condition and bank profiles (Simon, 1994). The main advantage of this technique is its simplicity. Its major flaws are user bias and for our case also a lack of established protocol for a “healthy” stable reference reach to compare to, as these till channels have been disturbed for about two centuries (Campo and

Desloges, 1994). For example, the six-stage model of incised channel evolution by Schumm et al. (1984), based entirely on channel morphology, would classify our study reach as Stage I. This stage conforms to disequilibrium, sediment transport capacity exceeds sediment supply, bank height that is less than critical bank height, a U-shaped cross section and W/D ratios at bankfull that are highly variable (discussed in Bergman et al., 2021b). Phillips and Desloges (2014) described parts of southern Ontario large rivers as “glacially conditioned” but their work is hard to apply on a smaller, short reach-scale like our case study as they investigated entire watersheds long profiles and concurrent stream powers. Fitzpatrick et al. (1996) ranked twenty sites in agricultural areas of eastern Wisconsin as part of stream habitat characteristics to create benchmark streams. However, this complex classification (80 parameters) aimed at determining habitat quality according to the Michigan Department of Environmental Quality, Great Lakes Environmental Assessment Section (GLEAS) Procedure 51 (Michigan Department of Natural Resources, 1991), found no relation between GLEAS scores and relatively homogeneous units (RHU's) or the percentage of agricultural land in the drainage basins above the benchmark-stream sites. One of the RHU's they used included clayey surficial deposits like till on carbonate bedrock.