EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **37**, 957–970 (2012)
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Published online 13 March 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3215

Sediment mobility and bed armoring in the St Clair River: insights from hydrodynamic modeling

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Received 22 July 2009; Revised 28 November 2011; Accepted 30 November 2011

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: The lake levels in Lake Michigan-Huron have recently fallen to near historical lows, as has the elevation difference between Lake Michigan-Huron compared to Lake Erie. This decline in lake levels has the potential to cause detrimental impacts on the lake ecosystems, together with social and economic impacts on communities in the entire Great Lakes region. Results from past work suggest that morphological changes in the St Clair River, which is the only natural outlet for Lake Michigan-Huron, could be an appreciable factor in the recent trends of lake level decline. A key research question is whether bed erosion within the river has caused an increase in water conveyance, therefore, contributed to the falling lake level. In this paper, a numerical modeling approach with field data is used to investigate the possibility of sediment movement in the St Clair River and assess the likelihood of morphological change under the current flow regime. A two-dimensional numerical model was used to study flow structure, bed shear stress, and sediment mobility/armoring over a range of flow discharges. Boundary conditions for the numerical model were provided by detailed field measurements that included high-resolution bathymetry and three-dimensional flow velocities. The results indicate that, without considering other effects, under the current range of flow conditions, the shear stresses produced by the river flow are too low to transport most of the coarse bed sediment within the reach and are too low to cause substantial bed erosion or bed scour. However, the detailed maps of the bed show mobile bedforms in the upper St Clair River that are indicative of sediment transport. Relatively high shear stresses near a constriction at the upstream end of the river and at channel bends could cause local scour and deposition. Ship-induced propeller wake erosion also is a likely cause of sediment movement in the entire reach. Other factors that may promote sediment movement, such as ice cover and dredging in the lower river, require further investigation. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: St Clair River; numerical model; field measurement; gravel bed; sediment transport; armoring; till erosion; morphology; bathymetry

Introduction

The St Clair River is 64 km long and forms part of the international boundary between Canada and the United States (IUGLS, 2009). Although there is approximately 1·5 m of fall from Lake Huron to Lake St Clair, the longitudinal profile of the river bed suggests a negligible bed slope. Borehole records and seismic profiles show that the majority of the river bed comprises glacial sediments with shale bedrock beneath these deposits (Foster and Denny, 2009). Flow in the St Clair River is mainly driven by the head difference between the upstream (Lake Michigan-Huron) and downstream lakes (Lake St Clair-Lake Erie). From 1918 to 2008, the St Clair River has had a relatively stable monthly average discharge of 5150 m^3/s with a variation of 20 to 30% depending on lake levels.

The St Clair River is of strategic importance to the Upper Great Lakes region, as it is the only connecting channel between Lake Michigan-Huron and Lake St Clair-Lake Erie (Figure 1). The decrease in Lake Michigan and Lake Huron water levels and its concomitant long-term social and environmental effects has attracted much attention recently and has caused concern from a wide variety of stakeholders. Despite a small recovery in water level during 2009, the head difference between the Lake Michigan-Huron system and Lake Erie has

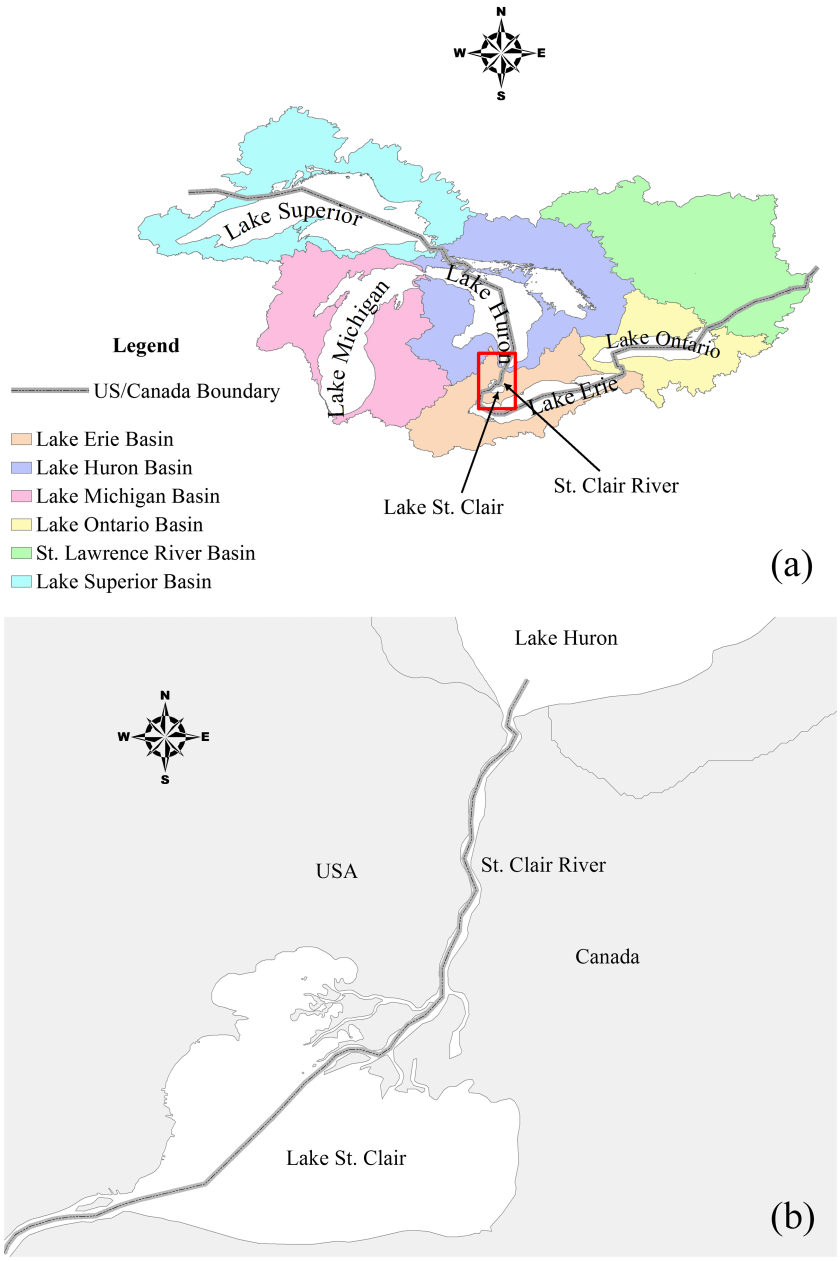

Figure 1. Study area: (a) Great Lakes area map; (b) location of the St Clair River. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

declined by about 0·6 m between 1860 and 2006, with 0·23 m of this change occurring between 1963 and 2006. For this same period (1860–2006), Lake Erie water levels have remained relatively constant. An investigation by Baird and Associates (2005) identified three likely causes for this decrease in Lake Michigan-Huron water levels: (i) a change in water conveyance of the St Clair River, (ii) a relative change in net basin water supply (NBS; i.e. the lake basin water balance), and (iii) differential glacial isostatic adjustment (GIA) in the Great Lakes basin. These three possible causes are still under investigation, primarily under the auspices of the International Upper Great Lakes Study of the International Joint Commission (IUGLS, 2009).

Baird and Associates (2005) speculated that man-made changes and bed erosion in the St Clair River could have increased the conveyance of water by the channel, thus, contributing to the decreases in Lake Michigan-Huron water levels. Man-made changes in the St Clair River have resulted mainly from dredging activities for commercial navigation, and mining of sand and gravel in the river bed dating back to the 1800 s. Three major dredging projects have been conducted in the St Clair River: (i) dredging of a 6·7 m minimum-depth navigation channel from 1910 to 1923; (ii) a 7·6 m minimum-depth navigation channel from 1933 to 1936, and (iii) an 8 m minimum-depth navigation channel from 1960 to 1962. Sand-and-gravel mining has also contributed to local changes in the river bathymetry (Quinn, 1985).

The supply of fine sediment into the St Clair River has also likely changed since the 1800 s. Shoreline protection (groins) and numerous harbor structures installed in Lake Huron, especially in the area near the outlet of Lake Huron and the upper St Clair River, may have reduced the sand sediment transport rates locally (Baird and Associates, 2005) and reduced sedimentation rates into the upper St Clair River. Such a reduction has been hypothesized (Baird and Associates, 2005) to have contributed to relative bed lowering within the channel and possibly changed the water conveyance. However, this hypothesis is based on the assumption that the bed material is predominantly sand, when in fact much of the bed is covered with coarse gravel or exposed till that is hard to erode and also less affected by sediment flux from the lake. Sands in the bed material tend to be confined to the channel margins or exist as thin layers on top of till (Czuba *et al.*, 2011: figure 9).

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In order to understand the mechanisms affecting the reduction in Lake Michigan-Huron water levels, a comprehensive interdisciplinary approach is required, combining the study of flow hydraulics, sediment transport, and hydro-climate. Many questions have been raised regarding the morphodynamics of the St Clair River, and this paper contributes to this debate by examining sediment mobility and bed armoring within the channel. Specifically, this paper describes numerical modeling of the spatial distribution of bed shear stresses within the channel and an analysis to determine whether these stresses are sufficient to erode the bed sediment and cause substantial conveyance change over realistic timeframes.

An open source numerical code, HydroSed2D, was applied to the entire St Clair River. (The open source numerical model HydroSed2D used in this paper can be found at http://sourceforge.net/projects/hydrosed2d.) HydroSed2D is a two-dimensional (2D) depth-averaged code that provides detailed hydrodynamic predictions (i.e. flow velocity and depth) within the channel (Liu and García, 2008). These predictions were then used to calculate sediment transport rates and analyze armoring effects using surface-based gravel bed transport equations based upon the Acronym routine (Parker, 1990a). The boundary conditions of the model were based upon detailed field measurements that were conducted on July 21–26, 2008. These measurements combined a multibeam echo sounder (MBES) bathymetric survey and an acoustic Doppler current profiler (ADCP) flow velocity surveys (see Czuba *et al.*, 2011). The numerical flow model was also calibrated and validated using these field measurements. The sediment characteristics within the reach (size and composition) were obtained through underwater video/image analysis (Krishnappan, 2009). Regions of exposed glacial till have been observed in the St Clair River (Foster and Denny, 2009; Czuba *et al.*, 2011). In the upper St Clair River where a 10 m thick or greater gravel layer is present, the till is rarely exposed (see Foster and Denny, 2009: figure 12). However, upstream of the Blackwater River, sand/gravel layers are thin and some till is exposed [see Czuba *et al.* (2011: figure 9) and elsewhere for more information]. Laboratory tests were conducted in a flume with laser Doppler velocimetry (LDV) to determine the critical shear stress required to erode these tills (Mier and García, 2011). The bed shear stresses predicted by HydroSed2D were used with these sediment size distributions as an input to Acronym.

This paper details this integrated modeling approach and presents the results of the analysis, including the distribution of bed shear stresses within the channel, and its implications for the ongoing debate on possible changes in water conveyance and Lake Michigan-Huron levels. These results are used to discuss the factors that could affect sediment erosion and transport within the channel, including ice cover/ice jams and entrainment from the movement of large ships that could generate heightened levels of bed shear stresses and, thus increased risk of bed sediment entrainment.

Numerical Models

A combined modeling approach is adopted here. HydroSed2D is used to obtain the distributions of bed shear stresses within the river over a range of 11 discharges spanning the flow-duration curve for the St Clair River. This flow model is then coupled to the Acronym code for sand-and-gravel transport to predict the movement of bed sediment. Information on these models and their implementation in this study is detailed later.

Hydrodynamic model

The 2D numerical model, HydroSed2D, solves the non-linear shallow water equations on an unstructured mesh, and is designed to solve both hydrodynamics and sediment transport. The shallow water equations have the form:

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}=0 \tag{1}$$

$$\frac{\partial(uh)}{\partial t}+\frac{\partial\left(u^2h+\frac{1}{2}gh^2\right)}{\partial x}+\frac{\partial(uvh)}{\partial y} = ghS_{ox}-ghS_{fx}+\frac{\tau_{wx}}{\rho}+hfu \tag{2}$$

$$\frac{\partial(vh)}{\partial t}+\frac{\partial(uvh)}{\partial x}+\frac{\partial\left(v^2h+\frac{1}{2}gh^2\right)}{\partial y} = ghS_{oy}-ghS_{fy}+\frac{\tau_{wy}}{\rho}-hfv, \tag{3}$$

where h is the water depth, u and v are the depth-averaged velocities in x and y directions, respectively, g is the gravity constant, ρ is the water density, τ_{wx} and τ_{wy} are surface wind shear stresses, f is the Coriolis parameter, and υ is the kinematic eddy viscosity. S_{ox} and S_{oy} are the bed slopes in the x and y directions, S_{fx} and S_{fy} are the friction slopes in the x and y directions, respectively, which can be estimated using Manning's equation (Yen, 1992).

The Godunov scheme is used to solve the governing equations, whereas Roe's approximation solver is implemented to solve the Riemann problem at the inter-cell boundaries (Toro, 1999). The interaction between the flow field and sediment transport can be modeled using either a quasi-steady or a coupled approach. In a quasi-steady approach, the flow field and sediment transport are solved in separate steps, whereas in a coupled approach, they are solved together in one step (see Liu and García, 2008, for full details). Although HydroSed2D is capable of solving hydrodynamics, sediment transport, and erosion/deposition of the river bed, only the hydrodynamic part of the code was activated in this study. This was done because the computational time for long-term morphodynamic prediction is not feasible for a channel with the dimensions as large as the St Clair River. Instead, after careful calibration, HydroSed2D generated a shear stress distribution along the river bed that was then used as input for an uncoupled sediment mobility analysis using Acronym.

Sediment transport model

For the portion of the St Clair River bed covered with sand and gravel, a surface-based bedload transport formula for sediment mixtures was used for the analysis (Parker, 1990a). The sediment characteristics (such as grain size distributions and composition) were obtained through extensive underwater video/image analysis conducted throughout the site (Krishnappan, 2009). The Parker (1990a) formula is used to calculate the transport rate based on the availability of each grain size group present in the surface layer. This surface-based bedload transport relation for gravel excludes sand because sand usually moves as suspended load when the flow can transport an appreciable amount of gravel. The basic assumption for the Parker (1990a) formula is a tendency toward equal mobility, which recognizes that a graded gravel-bed river must move the coarser half of its mean annual

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gravel load at the same rate as the finer half. Because coarser gravel particles are more difficult to move than finer gravel particles, the river will accomplish equal mobility by overexposing the coarser half of the gravel surface (Parker and Toro-Escobar, 2002).

The sediment transport model used here was implemented in a separate numerical code Acronym, which was originally reported in Parker (1990b) and used in Cui *et al.* (2003). Acronym computes the volumetric bedload transport rate per unit width, and the bedload grain size distribution from a specified surface grain size distribution (with the sand removed), a bed shear stress, and a specific gravity of the sediment. Given a flow-duration curve, the bedload transport rate and bedload grain size distribution are then computed for different flows on the curve, and averaged to yield both a mean bedload transport rate and mean bedload grain size distribution.

Bathymetric, Flow Surveys, and Flume Tests

A field survey of the outlet of Lake Huron and upper St Clair River was conducted from July 21–26, 2008 (see Czuba *et al.*, 2011). In this field survey, a RESON 7125 MBES system and a Teledyne RD Instruments ADCP were used on two survey boats to concurrently map the bed morphology and the three-dimensional (3D) flow velocity structure. The MBES and ADCP were temporally synchronized and spatially located using a Leica System 1230 real-time kinematic differential global positioning system (RTK-DGPS) that was accurate to ±0·02 m. The field survey covered an area that extended from 1·5 km into Lake Huron to ~2 km downstream of the Black River, covering approximately 8 km^2 (~7·5 river km; Figure 2). The survey of water velocities was within the domain of the bathymetric survey, and during the period of data collection, the average discharge in the St Clair River was approximately 5200 m^3/s or the mean annual flow. Laboratory flume tests were also later conducted on bed samples of the glacial till found in the river bed to determine the critical shear stress for this sediment.

Bathymetric survey and processing

The 400 kHz RESON 7125 MBES used to quantify the bathymetry projects a 128° fan of 256, 0·5° wide, acoustically-formed beams from a transmitter array, and measures the strength of the acoustic reflections as they pass through the water column and are reflected from the bed (see Parsons *et al.*, 2005; Czuba *et al.*, 2011, for further details). This return signal is then used to determine a range for each beam per sonar ping and, thus, when combined with the RTK-DGPS and an inertial motion senor, compute the bed elevation in a 3D reference for each individual point. The MBES data were processed using CARIS HIPS and ArcMap yielding a high-resolution digital elevation model (DEM) of the upper St Clair River with a 0·25 m horizontal resolution and 0·2 m vertical accuracy (Figure 2). The detailed mapping of the bed reveals a number of notable features, including bedforms, deeper areas of channels at the outside of the first bend downstream of the outlet from the lake, and a series of elongated

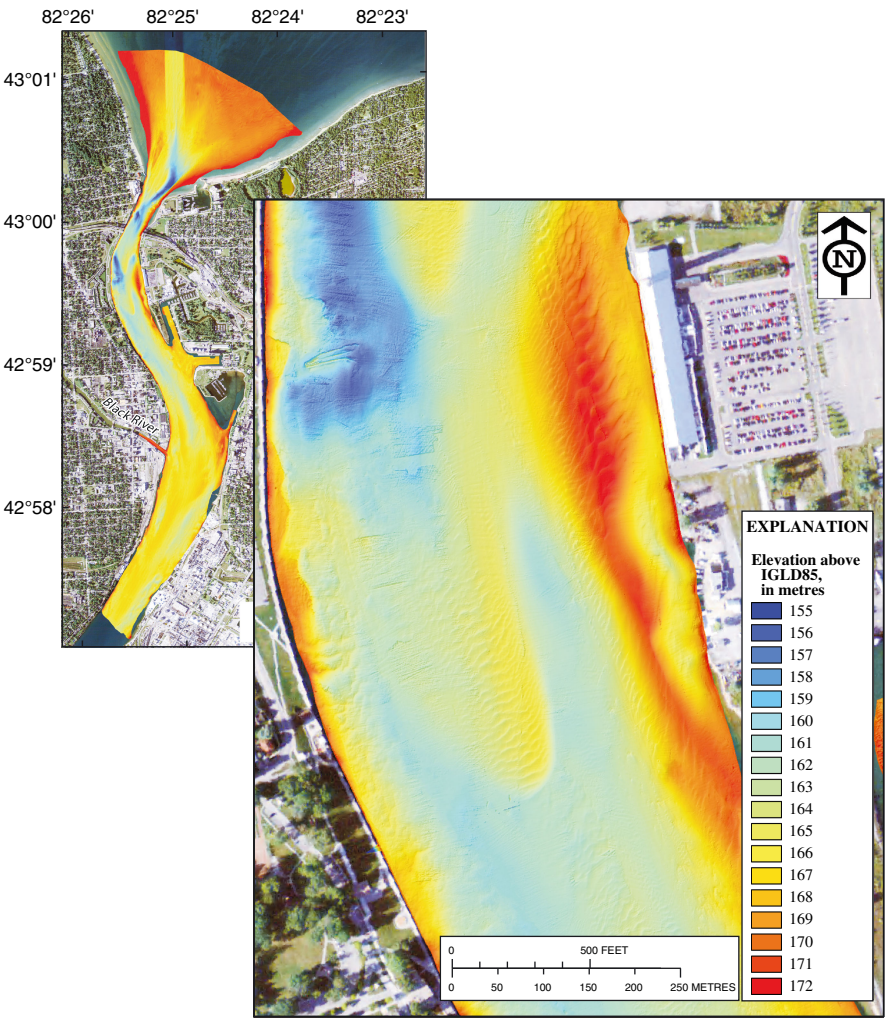

Figure 2. Bathymetry of the upper reach of the St Clair River (data from MBES survey). Various noticeable features include two elongated bars, deep scour holes up to 25 m, and superimposed bed forms. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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larger central bar features, within the first bend of the upper channel (see details in Czuba *et al.*, 2011). The bathymetry for the reach was combined with single beam echo sounder (SBES) measurements from the National Oceanic and Atmospheric Administration (NOAA) Geophysical Data Management System (GEODAS), in order to construct a DEM for the entire river channel to Lake St Clair, which is about 64 km downstream of the outlet from Lake Huron.

Flow velocity survey and data processing

ADCPs were used to measure the 3D water velocity within the channel at a total of 18 cross-sections in the lake near its outlet and in the upper channel (Figure 3a; see details in Czuba *et al.*, 2011). An ADCP emits high frequency pulses of acoustic energy through four beams oriented at a fixed angle (typically 20°) to the vertical. The acoustic pulse is returned to the ADCP transducers by reflecting off small particles within the water column. Assuming that these scatterers travel at the same speed as the water, the Doppler shift principle is then used to relate the change in frequency between the emitted and returned signal to determine the flow velocity towards or away from the source for each beam. These measurements for each beam can then be combined to compute velocity vectors in 3D for a series of depth cells, thereby producing vertical profiles, or ensembles, of 3D water velocity. Full details of ADCP operation are given in Mueller and Wagner (2009).

A 'transect' of 3D water velocities for an entire cross-section is measured when the ADCP traverses across the channel (Simpson, 2001), permitting quantification of flow discharge (Oberg *et al.*, 2005). Cross-sectional measurements can also be used to map the flow structure through the reach. Dinehart and Burau (2005) and Szupiany *et al.* (2007) identified an assemblage and grid-based average of five or six individual transects as the practical minimum to approximate time-averaged velocity fields through cross-sections. The flow measurements reported here, therefore, used an average of at least six transects for mapping the flow field in each cross-section at a particular time.

Image analysis for sediment size distributions

Extensive underwater videos and images of the bed were taken at cross-sections spaced 2 km apart from Sarnia Water Works to Port Lambton in 2007 and 2008 as well as miscellaneous point and longitudinal surveys in the upper St Clair River (see Krishnappan, 2009). This imagery was used to extract information on the bed grain size distributions and spatial patterns through the reach. Image analysis, in contrast to the labor-intensive sieve analysis, is a rapid method to provide input for the numerical model. There are various methods available for sediment size determination from imagery, including shape boundary delineation (Butler *et al.*, 2001) and autocorrelation (Rubin, 2004; Buscombe and Masselink, 2009). The shape boundary delineation method used here is based on the color information of the image to extract the boundary of each particle that can then be used to calculate the equivalent sizes of particles throughout the image. The grain size distributions, based on volume parameters (which is equivalent to sieve analysis), were generated according to the method in Ritter and Helley (1969). Krishnappan (2009) calibrated the results of the image analysis by sieve analysis of grab samples and concluded that the resulting grain-size distributions were reasonable. However, it is apparent that this technique makes use of 2D images to estimate a 3D property of the sediment. The accuracy of results depends on the resolution of the image and, especially, the light conditions, among other factors. When the sediment is a sand-and-gravel mixture, the sand patches might be recognized as a single clast (Butler *et al.*, 2001), which will bias the sediment size distribution towards the coarse end. Furthermore, there is a lower limit of the particle size (usually in the range of sand, silt, and clay) that can be represented by image pixels. This lower limit also will bias the sediment size distribution toward the coarse end. However, because sand was excluded from the modeling analysis, the bias due to the image pixel limitation is irrelevant and, thus, despite the tendency to bias grain size distributions to the coarse fraction, the effect is limited within the modeling results.

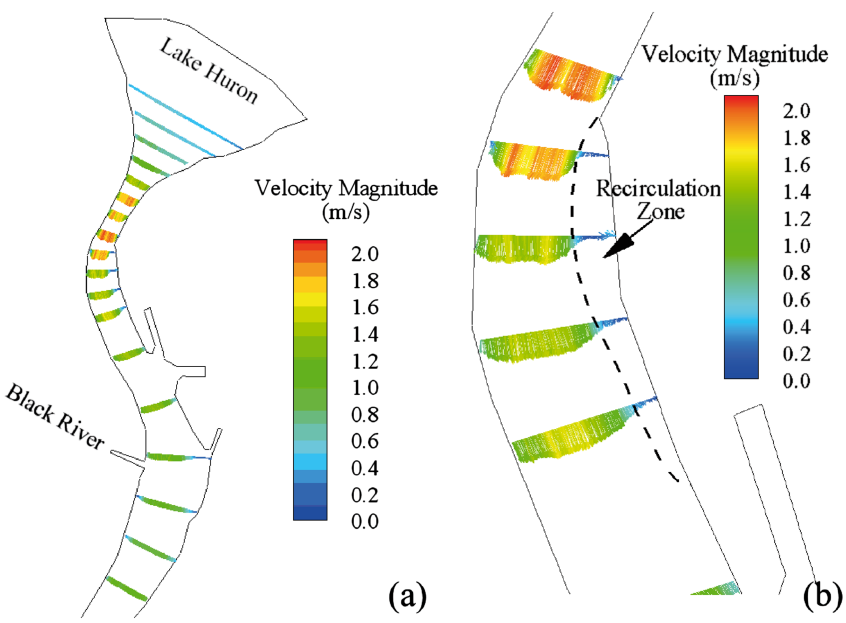

Figure 3. Depth-averaged flow velocity from ADCP measurements: (a) overall view of the flow velocities from the ADCP measurements; (b) the recirculation zone at the first bend. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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Till erodibility flume tests

Patches of exposed glacial tills have been observed in the St Clair River and the river as a whole is underlain by this till (Foster and Denny, 2009; Czuba *et al.*, 2011). A major unknown for these cohesive sediments is the critical shear stress for their erosion, and, thus, a series of laboratory experiments were conducted in a small unidirectional flume to quantify their erodibility (Figure 4). Till samples retrieved with a boat anchor from the St Clair River (Figure 4a) were placed in a sediment box on the bottom of the flume, and the discharge was increased gradually to the point when erosion was observed. A two-component TSI LDV was used to measure the velocity distribution above the till surface in the flume. LDV allows for non-intrusive, single-point velocity measurement by transmitting a monochromatic laser beam and recording reflections from seeded particles in the flow (Durst *et al.*, 1976; Drain, 1980). The measurement closest to the bottom wall was at 0·3 mm, which was essential to resolve the velocity distribution in the lowest part of the boundary layer. A logarithmic fit to the lower part of the velocity profiles was made (Figure 4c) to compute the shear velocity and, therefore, shear stress, using the law-of-the-wall for open channel flows:

$$\frac{u}{u*} = \frac{1}{\kappa} \ln\left(\frac{z - z_b}{k_s}\right) + B_s, \tag{4}$$

where u is the time-averaged flow velocity at a distance z above the bed, $u*$ is the shear velocity ($= \sqrt{\tau_b/\rho}$), κ is the von Kármán constant, which has a value of approximately 0·41, z_b is a fitting parameter to account for the true location of the $z = 0$ level (which is not accurately known a priori), k_s is the roughness height of the bed, and B_s is a function that takes into account whether the flow is hydraulically smooth, hydraulically rough, or in transition. Details of the laboratory tests can be found in Mier and García (2011).

Model Verification, Calibration, and Application

For a large, complex, lake-river system such as Lake Huron-St Clair River-Lake St Clair, a high quality numerical mesh is important for verification of the model and, thus, the creditability of the simulation results. For the present 2D model, the mesh was generated by the commercial gridding software Gambit (Fluent Inc., 2003). A mesh-independence study was performed using three meshes with different refinement (cf. Hardy *et al.*, 2003), with the final mesh used for all simulations presented here totaling 24 066 cells and being resolution-independent. Full details of the model setup and mesh-independence study can be found in Liu and Parker (2009).

Calibrations

The major parameter calibrated for the numerical model applied herein is the river bed roughness. The bed shear stress τ_b can be made dimensionless as

$$C_f = \frac{\tau_b}{\rho U^2}, \tag{5}$$

where C_f is the dimensionless bed resistance coefficient, ρ is the density of water, and U is flow velocity. Keulegan (1938) proposed a formulation for C_f as

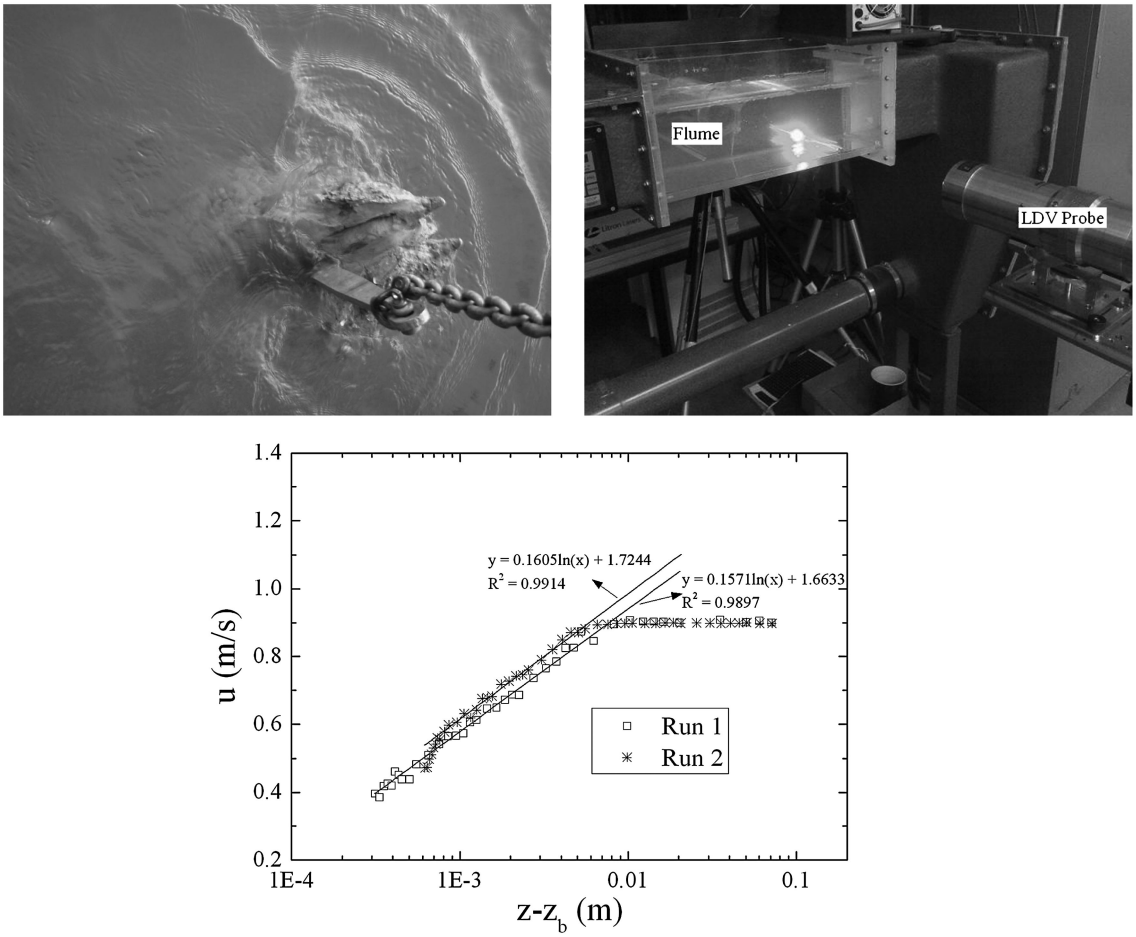

Figure 4. Till erosion experiment: (a) till sample retrieved from the St Clair River; (b) experimental flume and LDV system; (c) velocity profiles for the two runs when the beginning of erosion was observed.

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$$C_f^{-1/2} = \frac{1}{\kappa} \ln\left(11 \frac{H}{k_s}\right), \quad (6)$$

where k_s is bed roughness height, and H is the water depth. Manning's roughness coefficient n, which is used in the bed shear formulation of the numerical model, can be expressed as $n = H^{1/6} C_f^{1/2} / g^{1/2}$, where g is acceleration due to gravity (García, 2008).

For a river with a mixed bed material, such as the St Clair River, it is difficult to quantify the physical roughness height k_s. The most common practice is to relate k_s to the size of the sediment (García, 2008). For this paper, the roughness was determined from the sediment size distribution information and a calibration process. In the first step, the entire domain was divided into six roughness zones (Figure 5) according to the characteristics of the river bed (coarse sediment upstream and fine sediment downstream) derived from underwater videos and images. Statistics of the sediment size (such as mean diameter and standard deviation) for each of the identified roughness zones were obtained through image analysis. For a flat river bed, the roughness $k_s = n_k D_{s90}$, where D_{s90} denotes the surface sediment size such that 90% of the surface material is finer, and n_k is a dimensionless number between 1·5 and three (García, 2008). In this study, the value of n_k was fixed as two. The second step involved use of these roughness estimates as the starting point for calibration of the hydrodynamic model.

A sensitivity analysis of the roughness parameters in the hydrodynamic model was conducted, and three sets of roughness conditions in terms of Manning's n are listed in Table I. Meanwhile, three sets of hydraulic conditions, which represent the low, medium, and high flow conditions of the channel, were chosen as the simulation scenarios (see Table II). The discharges and stages for these scenarios were identified from gauges operated by the NOAA, the US Army Corps of Engineers, and the Canadian Hydrographic Service. Model calibration using water-surface elevation measurements indicated that Set 1 of the roughness conditions produced a relatively good match (Figure 6) and, was therefore used in this study.

Table I. Roughness calibration conditions

Zone number	Set 1	Set 2	Set 3
	Manning's n	Manning's n	Manning's n
1	0·017	0·020	0·016
2	0·028	0·028	0·028
3	0·025	0·033	0·017
4	0·023	0·029	0·015
5	0·020	0·023	0·016
6	0·021	0·028	0·019

Once the numerical model prediction of water-surface elevation was validated, the flow field generated by the numerical model was compared with the results from the ADCP field measurements. Because the model used in this study is a 2D model, the ADCP velocity profiles for each cross-section were depth-averaged. The ADCP flow velocity vectors were compared with the numerical results for 15 cross-sections (Figure 7), and that comparison indicates that the numerical model properly simulated most of the important flow features. These features include flow constriction and acceleration near the inlet from Lake Huron and the large recirculation/low velocity zone on the eastern bank, which extends across approximately one-third of the channel width, at the first bend downstream of the constriction. Any morphological change in the upper channel is probably most active within this region, particularly as the downstream flow velocity is accelerated to its maximum within the channel by the effect of both the width constriction and the recirculation zone (Czuba *et al.*, 2011). The simulated recirculation zone was not as well-defined as indicated by the ADCP measurements. The change in flow depth across the cross-section and the tendency for the

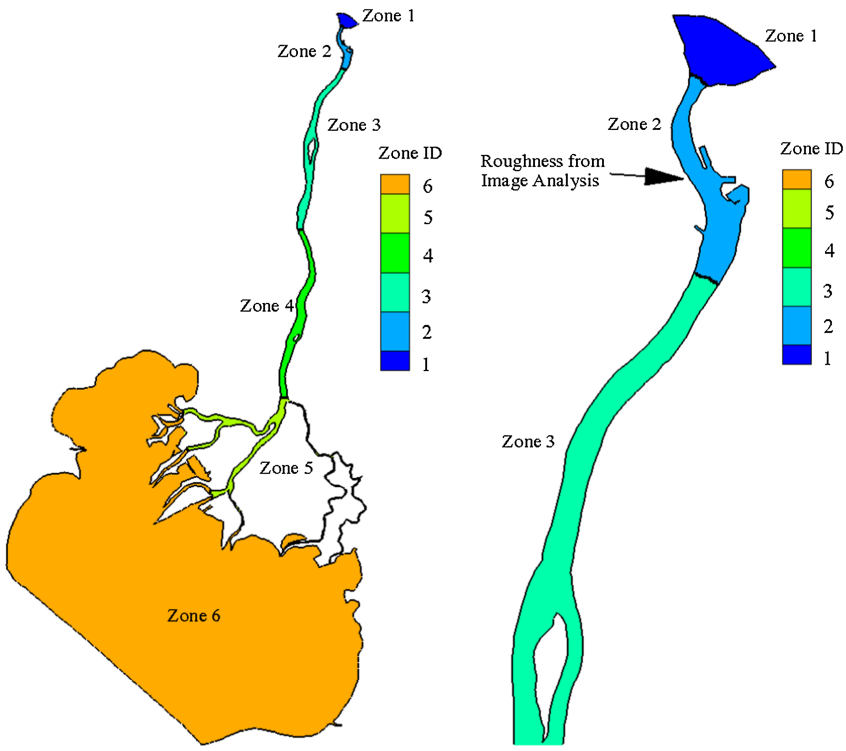

Figure 5. Roughness zones for the calibration of the hydrodynamic model (see Table I; roughness increases with number): (a) zones for the whole river reach and the St Clair Lake; (b) zones for the upper St Clair River (roughness for Zone 2, which contains the first two bends, comes from image analysis). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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Table II. Three typical flow and stage conditions for the calibration

Low flow scenario, Set 1		Medium flow scenario, Set 2		High flow scenario, Set 3	
Discharge (m^3/s)	Lake St Clair level (m)	Discharge (m^3/s)	Lake St Clair level (m)	Discharge (m^3/s)	Lake St Clair level (m)
4645	175·133	5282	174·937	6006	175·513
Date: April 27, 2005		Date: August 24, 2005		Date: August 1, 1998	

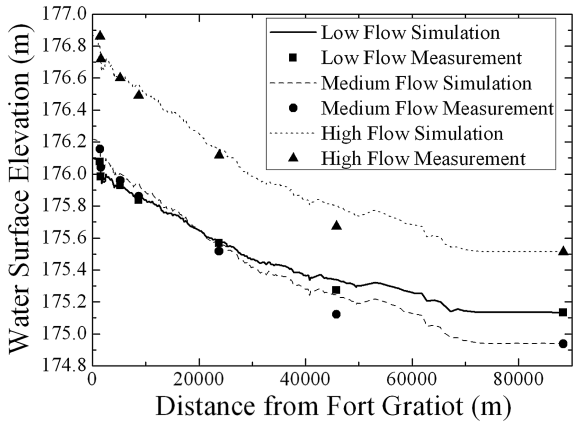

Figure 6. Calibration results for roughness Set 1 in Table I for the low, medium, and high flow scenarios listed in Table II.

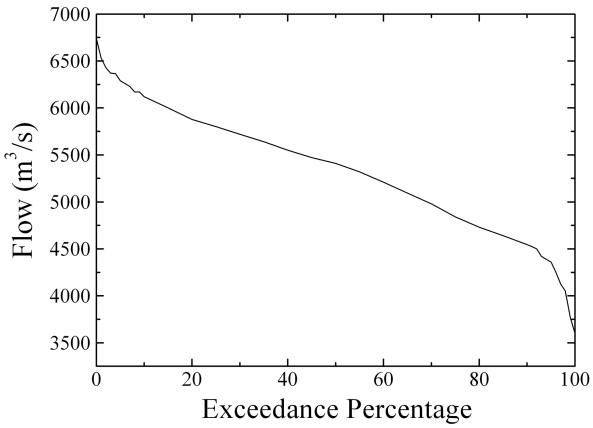

Figure 8. Flow-duration curve of the St Clair River based on the monthly average discharge from 1963 to 2006.

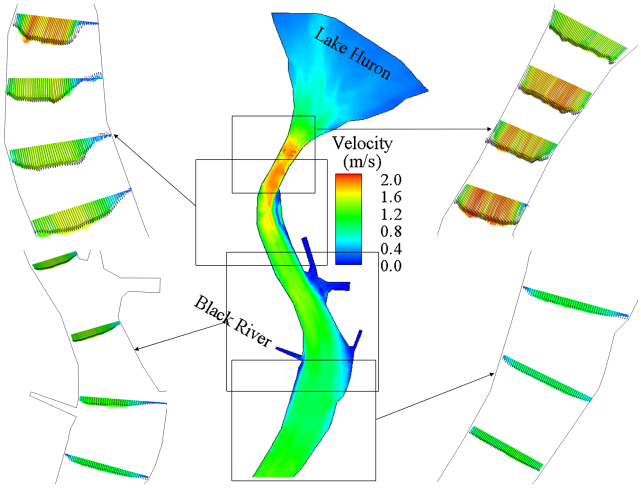

Figure 7. Comparison of depth-averaged velocity vectors between HydroSed2D numerical results and ADCP measurements. The velocity vectors in black are numerical results and those in color are from ADCP measurements. The color contour is the same as in Figure 3. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

primary downstream flow to be moving towards the right bank in this section of the channel make it difficult for a 2D model to simulate the complexity of the flow. In addition, the flow divergence seen in secondary currents in figure 5 of Czuba *et al.* (2011) cannot be readily captured in a 2D model, and the model mesh was scaled for simulation of flow and sediment transport from Lake Huron to Lake St Clair rather than to accurately represent all local features in the flow.

Model application

After calibration, HydroSed2D was run to generate the bed shear stress distributions under a range of different flow conditions that covered the entire flow-duration curve as shown in Figure 8 and

Table III. Discharge on the flow-duration curve for each simulation case

HydroSed2D case number	Q (m^3/s)	Percent time exceeded (%)
1	6740	0
2	6120	10
3	5878	20
4	5720	30
5	5550	40
6	5410	50
7	5210	60
8	4980	70
9	4730	80
10	4547	90
11	3600	100

Table III. The flow-duration curve was calculated based on the monthly-averaged flow data from 1963 to 2006. For each flow condition, the shear stresses on the bed at a total of 12 river cross-sections were extracted. These cross-sections (Figure 9) were chosen to be representative of the upper, middle, and lower reaches of the river. The bed material size distributions were input into the model, based on the analysis described earlier. The size distributions for 11 of the 12 river cross-sections (Figure 10b) show that the majority of the river bed is covered with gravels with a mean diameter of ~15 mm. With the predicted bed shear stresses from HydroSed2D and sediment size distributions as inputs, the Acronym code was then run for all the cross-sections to predict the sediment transport rate and analyze the evolution of armoring of the river bed. The general process for combining the results of the HydroSed2D model and the Acronym code is illustrated in Figure 11a, and the approach used to divide each transect into many small sections is shown in Figure 11b. For section *i*, the shear stress was given as the average value between the end points that defined the section. The transport rates were calculated at each of the sections and an average value was computed for the entire transect for further analysis.

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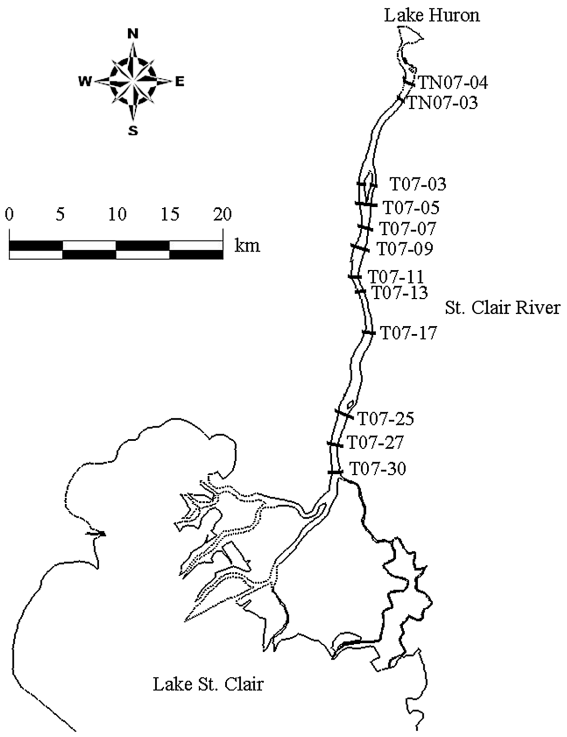

Figure 9. Locations of the transects analyzed.

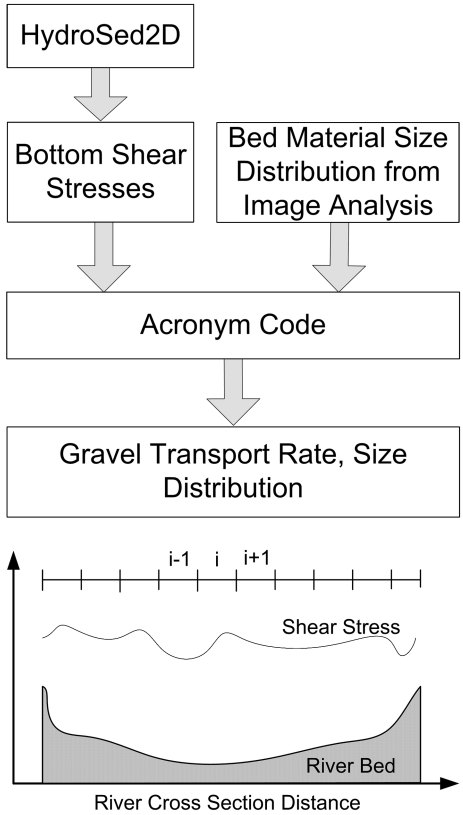

Figure 11. Scheme of the analysis: (a) flow chart for the analysis process; (b) division of the river cross-section.

Simulation results

Shear stress distributions

A typical flow condition, the case which corresponds to the 50% exceedance value, is shown in Figure 12. High shear stresses are only observed in the St Clair River channel, with the velocity and shear stresses declining as flow enters Lake St Clair. In the St Clair River, the highest shear stresses are located in the upper river channel close to the Lake Huron outlet, just downstream of the primary constriction of the channel at the Blue Water Bridge. In this area, the bed shear stresses are predicted to be approximately 8 to 10 N/m^2. Based upon Shields (1936), this value of shear stress is not capable of moving sediment coarser than 20 mm diameter. The bed

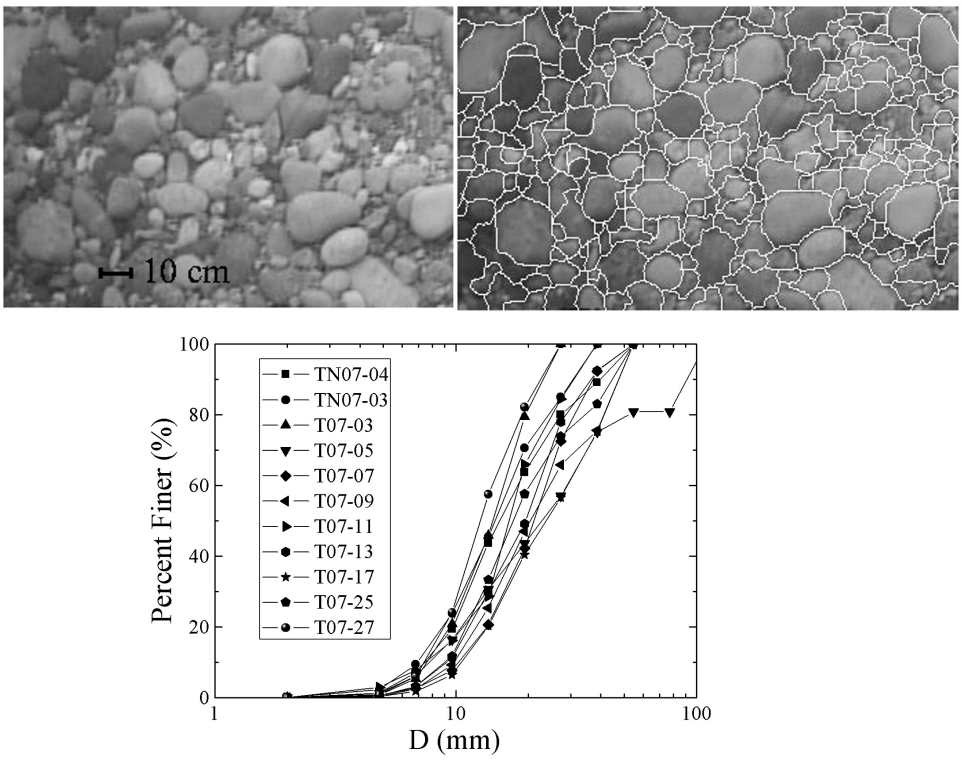

Figure 10. Sediment size distributions: (a) delineation of sediment particles with the image analysis; (b) surface sediment size distribution results for all the transects using the image analysis method.

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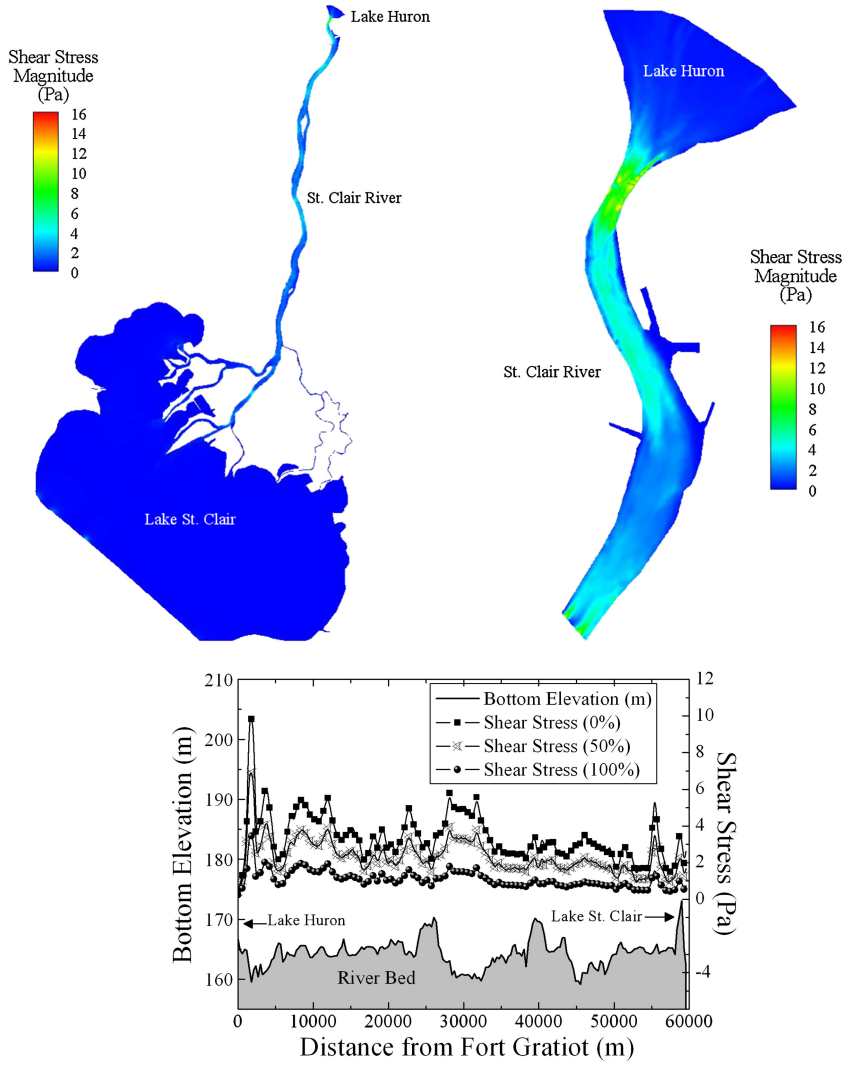

Figure 12. Shear stresses distribution: (a) shear stresses for the entire St Clair River (corresponding to 50% flow discharge on the duration curve); (b) shear stresses for the upper St Clair River (corresponding to 50% exceedance flow discharge on the duration curve); (c) shear stresses distributions along the center line of the river (corresponding to 0%, 50%, and 100% exceedance flow discharges on the duration curve). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

sediment in this region is 30 to 40 mm (Foster and Denny, 2009; Krishnappan, 2009; Czuba *et al.*, 2011), which is coarser than can be moved by the flow. However, the shear stresses are high enough to transport finer sediment, with likely deposition in the lee of the first bend of the upper channel, where there is a large outer bank scour and two large lobate gravel bars (Krishnappan, 2009; Czuba *et al.*, 2011) with shear stresses below ~5 N/m^2 through this zone. At this lower value of shear stress, the flow is only able to transport sediment finer than 10 mm. However, morphological tracking of these bars (Czuba *et al.*, 2011) shows that they have pro-graded slowly 20 m downstream between 2007 and 2008 (Bennion, 2009), suggesting that there are additional sources of shear stress that are capable of transporting gravels in this reach of the river (IUGLS, 2009).

The shear stress distributions corresponding to 0%, 50%, and 100% exceedance values along the center line of the river (Figure 12c) show that the bed shear stresses decrease downstream from peaks near the Lake Huron outlet, at the location of constriction. However, it is notable that, in general, the bed shear stresses along most of the length of the river are globally low, ranging in mean values from 1 to 3 N/m^2.

Sediment transport rate and armoring analysis

The sediment transport rates and size distributions for the bedload were calculated for the 11 cross-sections for all of the modeled flow conditions. An annual-averaged load and full sediment grain-size statistics were calculated based on the probability of the exceedance for each flow condition. The statistics for the annual-averaged sediment size in the bedload and the bed surface in Table IV show the geometric mean of the bed surface sediment is larger than that of the bedload sediment, and the ratio between these two ranges from 1·28 to 2·33. Thus, the coarser bed surface indicates that the bed is armored.

Table IV. Statistics of sediment size distribution for surface and bedload

Transects	TN07-04	TN07-03	T07-05	T07-07	T07-09	T07-11	T07-13	T07-17	T07-25	T07-27
Surface geometric mean (mm)	15·95	14·23	23·6	20·0	21·0	15·8	18·4	22·9	18·4	12·7
Bedload geometric mean (mm)	9·88	9·00	10·1	13·1	12·9	9·4	12·2	14·2	11·9	9·9
Ratio (surface/bedload)	1·62	1·58	2·33	1·54	1·63	1·68	1·50	1·61	1·55	1·28

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The sediment transport rates and annual sediment yields for all of the cross-sections in Table V show that although in the upstream reach the river seems to move more sediment than sections further downstream, the capacity of the river to transport gravel-sized material at all transects is limited. The mean annual bedload transport rate, globally through the domain, was for all practical purposes calculated as zero. The effective Shields number ranged from about 0·004 to 0·015, which is less than the lowest reasonable value for a critical Shields number for gravel (0·03).

The results for cross-section TN07-04 are typical for the study reach. The bed shear stress distribution across transect TN07-04 for a discharge of 5410 m^3/s, which corresponds to a 50% exceedance value, is shown in Figure 13a. The bed shear stresses range from 3 to 5 N/m^2, which are low, particularly as this transect is located towards the upper reach of the river. The size distributions of the sediment of the surface and the bedload fraction are shown in Figure 13b. The surface geometric mean of the sediment size is 16 mm and the bedload geometric mean is about 9·9 mm, and the ratio between the two means is ~1·62. This ratio confirms that the bed is coarse gravel (Table IV). Results from these calculations indicate a limited river capacity for transport of gravel-sized material and that, overall, the bed is stable. Local scour may be possible, associated with flow acceleration in the upper reach, bend flow, ship wrecks, ice jams, and ship wakes. The bed elevation change, determined by repeated MBES surveys from 2006 to 2007, is below the noise threshold of the DEM comparison and, thus, the river bed shows little evidence of change (Bennion, 2009). However, local coherent variations are observed over a period longer than two years. For instance, there is a deepening of the scour hole on the outer bank of the first bend (Figure 2) and detectable downstream migration of the two elongated lobate bars in the center of the channel. Bedforms have also been identified at numerous places in the upper St Clair River (Figure 14; Czuba *et al.*, 2011), which shows active bed sediment transport. The annual bedload transport rate per unit width for transect TN07-04 is about $1{\cdot}07 \times 10^{-11}$ m^2/s, which is negligible. This value also translates to a low annual sediment yield of about 0·54 tons (the river width at this transect is about 600 m).

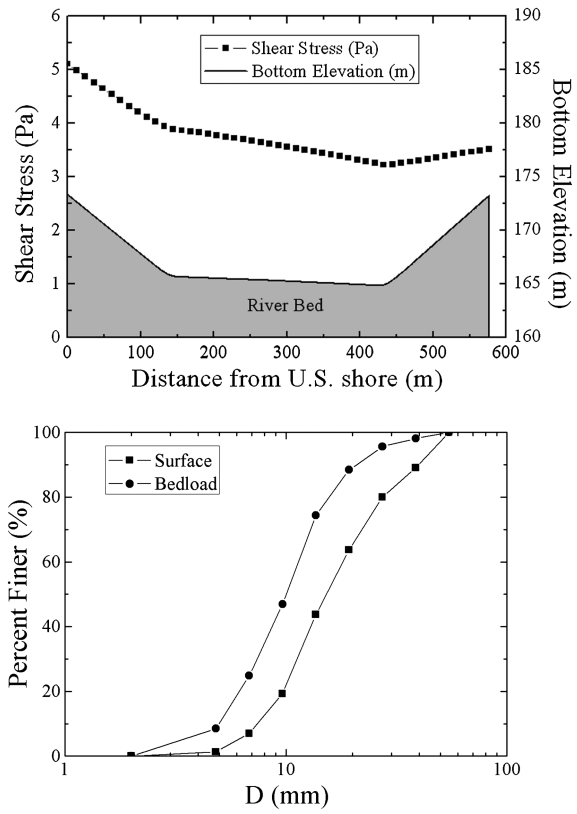

Figure 13. Sediment transport analysis results for transect TN07-04: (a) shear stresses distribution across the transect for discharge of 5410 m^3/s (corresponding to 50% exceedance on the flow-duration curve); (b) sediment size distribution for the surface and bedload.

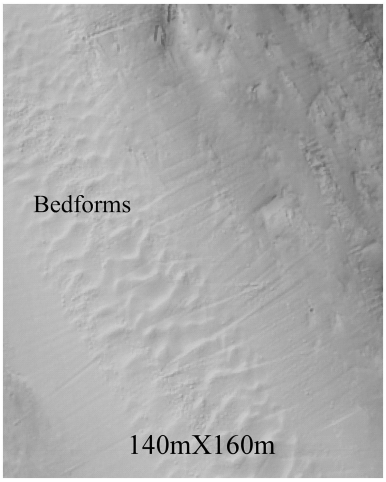

Figure 14. Bedforms observed in the upper St Clair River.

Model sensitivity analysis

Shear stress as simulated by HydroSed2D is the most important variable in the analysis; thus its sensitivity to the model parameters, notably roughness, requires investigation. For the range of sediment sizes found in the St Clair River, and therefore, the roughness, the dimensionless shear coefficient C_f shows a limited variation because of the logarithmic nature

Table V. Sediment transport calculation results for each transect

Transects	TN07-04	TN07-03	T07-05	T07-07	T07-09	T07-11	T07-13	T07-17	T07-25	T07-27
Mean annual Shields number based on surface geometric mean size	0·015	0·014	0·005	0·009	0·005	0·010	0·011	0·006	0·004	0·008
Mean annual shear velocity (m/s)	0·062	0·057	0·044	0·053	0·041	0·050	0·056	0·045	0·036	0·041
Mean annual volume bedload transport rate per unit width (m^2/s)	1·072E-11	8·273E-13	1·065E-18	1·083E-15	7·970E-19	9·106E-15	5·075E-14	2·591E-17	8·714E-19	1·410E-15
River width (m)	600	514	1080	600	990	625	525	700	900	640
Annual sediment yield (ton)	5·38E-01	3·56E-02	9·62E-08	5·44E-05	6·60E-08	4·76E-04	2·23E-03	1·52E-06	6·56E-08	7·55E-05

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of Equation 4 (e.g. Yen, 1992). A series of model runs were performed where C_f was systematically varied and the results analyzed for the difference in head. On average, the water depth, H, was found to only change ~0·3–0·4 m when using different roughness combinations (see Liu and Parker, 2009), which is 3–4% of the total water depth (~10 m). Therefore, for a given a channel width, B, and relatively constant flow discharge, Q, the mean velocity U [= $Q/(B \times H)$] should only alter 3–4%. Thus, according to Equation 5, the sensitivity of shear stress should also be limited.

Exposure and erosion of till

The erodibility of the glacial till is important to consider because scattered areas of till have been observed within the channel (Foster and Denny, 2009; Czuba *et al.*, 2011). The average value of the bed shear stresses that generates sediment erosion in the till sample is about 4·23 N/m^2; greater than the predicted bed shear stresses for most of the flow conditions in the entire St Clair River except at some local regions near the most upstream bend (near the Blue Water Bridge). These regions of high shear stresses also are generally coincident with the regions of thick glacial gravels (Foster and Denny, 2009). Therefore, the areas of exposed glacial till within the channel are generally stable and not subject to large-scale hydraulic erosion by the river. Since it appears that the gravels found in the upper St Clair River are fluvial-glacial in origin, predating the formation of the river, it follows that the river flows over these gravels, but did not deposit them. Lastly, there is no supply of gravels from Lake Huron to the St Clair River.

Discussion

The model-predicted shear stresses and those obtained from the velocity surveys at one flow condition (Czuba *et al.*, 2011) are low and therefore the river is generally not capable of transporting gravel, although it could transport fine sand. However, the presence of gravel bedforms in some river reaches is indicative of sediment transport. This apparent contradiction might be explained by a range of additional factors that could contribute to episodic bedload movement in the St Clair River that are beyond the range of the shear stress conditions simulated with the model. These factors include: (i) ice cover/ice jams that could increase the shear stress imparted on the bed, and (ii) ship-induced sediment transport (García *et al.*, 1999). These possible causal factors of entrainment are discussed later.

Ice cover/ice jams

The St Clair River is prone to large-scale ice cover and ice jams that tend to increase and redistribute the resistance of the river channel, and thus reduce the sediment transport rate (Derecki and Quinn, 1986). However, on a local scale, ice cover can redistribute the flow laterally, which may cause both sediment scour and deposition (Ettema and Daly, 2004; Hains and Zabilansky, 2004; García, 2008). Notably, during the surge of water and ice following the breakup of an ice jam, the water discharge and flow velocities may increase, which may result in increased sediment transport rates. As such, it has been speculated that some of the past major ice jam events may have caused bed scour and changed the hydraulic regime of the river. For instance, in April 1984, the record 24-day ice jam in the St Clair River caused the level of Lake St Clair to drop by ~0·6 m and, at the peak of the ice jam, the flow in the St Clair River was reduced by about 65% (Derecki and Quinn, 1986). After the breakup of the ice jam, a surge of flow through the channel was observed due to the sudden release of water. A current-meter measurement just downstream of the first bend showed a surge in mean flow velocity from about 0·4 m/s to 1·2 m/s, with velocities greater than 1·2 m/s likely within portions of the cross-section not sampled during these measurements (Derecki and Quinn, 1986). Predictions from HydroSed2D and more recent ADCP measurements (Czuba *et al.*, 2011) indicate that velocities under normal flow conditions at the measurement location do not exceed 0·8 m/s. If it is assumed that the sediment transport rate $q_s \sim \tau_b^{3/2} \sim u^3$, where τ_b is the bed shear stress, and u is the velocity magnitude, then this surge in velocity because of ice cover release would cause sediment up to 10 mm diameter to be entrained and the sediment transport rate to increase by ~237% (assuming a river depth of 10 m). As a result of this increase in flow velocity and bed shear stress, coarser bed materials, which could not be entrained under normal flow conditions, would begin movement and cause substantial change in the river bathymetry. According to Derecki and Quinn (1986), following the breakup of the ice jam in 1984, the water level recovered to about 75% of normal in Lake St Clair (downstream). Their calculation indicated that it took up to three years for the entire river system to return to pre-ice jam conditions, and therefore substantial increases in sediment transport were possible during this period. Even though ice cover/ice jams provide a mechanism for transporting coarse sediment, the ~20 m downstream migration of the mid-channel bars observed by Czuba *et al.* (2011) between 2007 and 2008 was not due to this mechanism because no major ice jams formed during the winter of 2007 to 2008.

Navigation

Bed sediment transport could also be induced by propeller wash from large ships. Wuebben *et al.* (1984) investigated the effects of ship propeller wash, ship waves, and ship drawdown/surges, for the connecting channels of the Great Lakes. Wuebben *et al.* (1984) concluded that such propeller wash can cause scour for most parts of the river, although ship induced waves were shown to only cause minor erosion. The drawdown/surges by a downbound (i.e. moving downstream) ship were also shown not to cause erosion, but those produced by an upbound ship (i.e. moving against the current) could cause erosion. Similar to the analysis of Wuebben *et al.* (1984), as a rough estimation, jet theory was used herein to calculate the shear stress induced by propeller wash. For a 5·34 m diameter propeller typical of such large ships on the St Clair River that rotates at 90 rpm and drafts 7–8 m, the maximum flow velocity because of the propeller was estimated to be ~5·5 m/s with a corresponding bed shear stress of ~20 N/m^2. The river was assumed to have a depth of 10 m; therefore, the propeller was ~2 m above the bed. Such shear stresses are capable of transporting sediment of 64 mm, which is the upper limit of the D_{50} of gravels found in the river.

The transport and suspension of the bed material in the manner described earlier will result in downstream-biased sediment transport due to ship propellers (Figure 15). This downstream-biased effect is produced by two interrelated factors: (1) when a ship is traveling upstream, the thrust needed is greater than that when traveling downstream, and as a result higher, bed shear stresses will be produced, which have the potential to move the sediment downstream, and (2) on average, when sediment is entrained and re-suspended by the propeller, the river will transport this sediment downstream for a certain distance before this sediment is detrained. Although this effect may not be appreciable for the passage of a single ship, in the long term (years), the cumulative effect of navigation could

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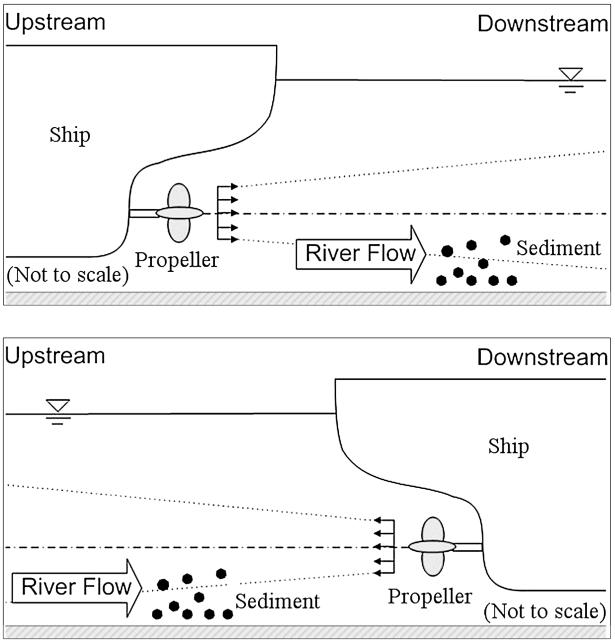

Figure 15. Downstream-biased sediment transport due to ship propeller wash in a river: (a) ship moving upstream, propeller wash in the same direction as river flow; (b) ship moving downstream, propeller wash in the opposite direction as river flow.

contribute to more appreciable volumes of sediment transport (García *et al.*, 1999). Czuba *et al.* (2011) also noted that the region of the river in which the mid-channel bars are formed from gravels and where detectable downstream migration of the bars had been observed (~20 m), are primarily within the principal shipping lane.

Factors other than those described earlier and relating to navigation include the maneuvering of ships and dredging. At the upstream bends, where sediments already have a larger transport potential because of the contraction of flow, ships need to maneuver by increasing thrust and rudder angles, which have been reported to appreciably increase the bed shear stress (Hamill, 1988; Hamill and McGarvey, 1997). In order to maintain safe navigation under these conditions, regular dredging is needed. The three major dredging projects mentioned in the introduction have been identified as having a major effect on the river cross-section and conveyance. In addition, the sand-and-gravel mining activities in the river also affect safe navigation. Further investigations, based on available historical data, are necessary in order to evaluate the effect that these factors (safe navigation and possible dredging) have on sediment transport in the St Clair River.

Conclusion

Using field-based measurements, the HydroSed2D model was calibrated, validated, and applied for the entire St Clair River. A shear stress analysis was performed to examine the amounts of bed sediment transport in the St Clair River. The average shear stress in the St Clair River was predicted to be 3–4 N/m^2, indicating that the St Clair River is incapable of transporting the mean size of bed sediment. A maximum shear stress (~10 N/m^2), located at the main constriction of the river channel just downstream of the Lake Huron outlet, is capable of entraining and transporting coarse bed sediment materials ($D_{50} < 20$ mm), but the bed contains coarser sediment in this region than cannot be transported by the flow alone.

High resolution maps of the streambed indicate sediment transport does occur. Analysis by Czuba *et al.* (2011) indicated that two mid-channel bars migrated about 20 m between 2007 and 2008. This apparent inconsistency between the measured and modeled shear stresses and evidence of sediment transport, may be a result of episodic events such as ship passages. Another mechanism capable of transporting coarse sediment is an ice jam locally increasing shear stresses. However, no major ice jams formed during the winter of 2007 to 2008 that could explain the ~20 m migration observed by Czuba *et al.* (2011). Till erosion experiments were conducted and the critical shear stress was found to be ~4·23 N/m^2, which indicates that the St Clair River has little capacity to erode any of the glacial till exposed to the flow.

Ice jams and ship propellers are likely to produce some increase in sediment transport in the river. The record ice jam of 1984 on the St Clair River is thought to have caused some local scour and deposition around and downstream of the jam in the upstream section of the river. During the ice jam breakup, the sudden release of water caused a surge of flow and increased the potential for sediment motion. Moreover, propeller-wash-induced maximum shear stresses are predicted to be capable of transporting sediment with a size of ~64 mm. This size corresponds to the upper limit of D_{50} of the gravels found on the river bed, and downstream sediment transport because of navigation is hypothesized to be a result of sediment entrainment by propeller wash. The cumulative effect of this downstream-biased sediment movement over a long time period may be appreciable in changing the bed morphology and affecting conveyance of this important channel. More studies are needed to investigate in detail the likely effects of these factors on sediment transport and channel change.

Disclaimer

Use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the US Government.

Acknowledgments—The authors are thankful for the financial support provided by the International Upper Great Lakes Study (IUGLS) and the International Joint Commission (IJC). This paper also benefited from the startup fund to Xiaofeng Liu from the University of Texas at San Antonio. D. Parsons thanks the UK NERC for his Fellowship funding and also acknowledges the World Universities Network (wun.ac.uk) for a Research Mobility Program award which facilitated his participation in this project.

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