The Effect of Channel Shape, Bed Morphology, and Shipwrecks on Flow Velocities in the Upper St. Clair River

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ABSTRACT

In the Great Lakes of North America, the St. Clair River is the major outlet of Lake Huron and conveys water to Lake St. Clair which then flows to Lake Erie. One major topic of interest is morphological change in the St. Clair River and its impact on water levels in the Upper Great Lakes and connecting channel flows. A combined multibeam echosounder (MBES) bathymetric survey and acoustic Doppler current profiler (ADCP) flow survey of the outlet of Lake Huron and the Upper St. Clair River was conducted July 21 – 25, 2008. This paper presents how channel morphology and shipwrecks affect the flow in the Upper St. Clair River. The river is most constricted at the Blue Water Bridge near Port Huron, Michigan, with water velocities over 2 ms^{-1} for a flow of 5,200 m^3s^{-1}. Downstream of this constriction, the river flows around a bend and expands creating a large recirculation zone along the left bank due to flow separation. This recirculation zone reduces the effective channel width, and thus increases flow velocities to over 2 ms^{-1} in this region. The surveys reveal several shipwrecks on the bed of the St. Clair River, which possess distinct wakes in their flow velocity downstream of the wrecks. The constriction and expansion of the channel, combined with forcing of the flow by bed topography, initiates channel-scale secondary flow, creating streamwise vortices that maintain coherence downstream over a distance of several channel widths.

INTRODUCTION

In the Great Lakes of North America, the St. Clair River is the major outlet of Lake Huron and is a connecting channel between Lake Huron and Lake Erie. Flow from Lake Huron converges into the St. Clair River and discharges into Lake St. Clair, from where the flow enters the Detroit River before reaching Lake Erie.

A recent study (Baird and Associates, 2005) has suggested that dredging and scour in the St. Clair River may have caused a change in conveyance that has led to a reduction in Lake Huron water levels. Baird and Associates (2005) highlights the section of the St. Clair River from Lake Huron to the Black River as a critical section of the river for flow and concludes that the there has been significant erosion of the riverbed in this section that may have caused significant changes to the flow in the St. Clair River.

In February 2007, the International Joint Commission appointed the International Upper Great Lakes Study (IUGLS) to investigate the factors affecting water levels and flows, develop and test potential new regulation plans, and assess the impacts of these potential plans on the ecosystem and human interests. The IUGLS study area includes the Great Lakes of North America upstream of Niagara Falls. A major topic of interest is morphological change in the St. Clair River and its impact on water levels in the Upper Great Lakes and Great Lakes Connecting Channel flows.

As part of several IUGLS-sponsored investigations of the St. Clair River, the authors conducted a field survey of the outlet of Lake Huron and the Upper St. Clair River to just below the Black River near Port Huron, Michigan from July 21 – 25, 2008. This field survey was conducted in order to develop a detailed bathymetric map of the bed of the river and the outlet of Lake Huron, evaluate any changes in channel bathymetry, investigate the nature of any sediment transport in the reach, and link the bathymetry to flow patterns measured in the upper section of the river.

The purpose of this paper is to summarize analyses of how channel morphology and shipwrecks affect the flow in the Upper St. Clair River. The paper summarizes methods used to collect and analyze the data followed by presentation of results for three selected cross sections.

METHODS

Two boats were used to map the bed and flow concurrently within the Upper St. Clair River. One boat was equipped with a multibeam echo sounder (MBES) for mapping the bathymetry and the other boat was equipped with an acoustic Doppler current profiler (ADCP) for measuring the flow structure in the river.

The RESON[1] SeaBat 7125 MBES operates at 200 kHz and projects a fan of 256 acoustic beams from a transmitter located just below the water surface. The MBES measures the strength of the acoustic reflections of each of the beams as they pass through the water column and bounce back off the bed. This return signal is then used to measure the depth of the water along the path of each beam, with the resulting data being used to construct a map of the height of the bed with great detail. A combined MAHRS gyro-motion sensor was used to monitor vessel orientation and three-axis movement (heading, roll, and pitch). This integrated MBES system thus remotely collects bed morphology at vertical accuracies of the order of ~0.5 cm (at millimetric resolutions) in a rapid and efficient manner, and can detect objects of only a few decimeters in size.

An ADCP was used to measure the velocity of the flow within the river. An ADCP uses the principle of the Doppler shift to relate the change in frequency between the transmitted signal and the returned signal to determine the velocity of the water with respect to the instrument. The ADCP also tracks the bottom of the river to

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[1] Any use of trade, product, or firm names is for descriptive purposes only and does not constitute endorsement by the U.S. Government.

obtain the velocity of the bed with respect to the instrument and to locate the ADCP spatially in the absence of a Global Positioning System (GPS). The velocity of the water is obtained by relating the velocity of the water to the bed. An ADCP measures vertical profiles, or ensembles, of three-dimensional water velocity, from just below the water surface to just above the channel bed. Each ensemble contains a number of bins, or locations in the vertical where a three-dimensional water velocity is measured. When the ADCP moves transverse to the flow, a transect is obtained, resulting in three-dimensional water velocities for the entire cross-section (Simpson 2001). Velocity measurements were made using a Teledyne RD Instruments 1200 kHz Rio Grande ADCP with water mode 1 and 50 cm bins for the data analyzed in this paper.

The positions for the MBES and ADCP were obtained by means of a Leica System 1230 differential real-time kinematic global positioning system that was used to keep track of the boats' location with an accuracy of several centimeters. Eighteen cross-section measurements were made every 1 to 2 channel widths apart based on the narrowest channel width in the surveyed reach. For the purposes of this analysis, only a subset of the data, 3 of the 18 cross-sections which were collected on July 24, 2008, are presented herein. The discharge in the Upper St. Clair River was approximately 5,200 m^3s^{-1} during the field survey.

Standard procedures were followed for making a discharge measurement (Oberg et al. 2005). Dinehart and Burau (2005) found that six transects may be a practical minimum to approximate time-averaged velocity fields. Therefore, at least six transects were measured for a particular cross-section at a particular time.

The methods used for transforming a collection of transects into a transect-averaged cross-section were also similar to those employed by Dinehart and Burau (2005). The data were processed and reviewed using procedures outlined in Oberg et al. (2005). Differential Global Positioning System (dGPS) data was used to locate every ensemble in space. When invalid or erroneous GPS data were received, bottom track data was used to obtain an accurate position of an ensemble. Ensembles from individual transects were mapped to a mean cross-section line and then interpolated onto a uniform mean cross-section grid. The set of uniform mean cross-sections, one for each transect, were averaged together to produce a transect-averaged cross-section. Then the transect-averaged cross-section velocities were rotated to primary and secondary velocity components using the zero net cross-stream discharge definition (Lane et al. 2000). The primary velocity direction is orthogonal to the secondary velocity direction. The zero net cross-stream discharge definition defines the primary velocity such that there is zero discharge in the secondary direction for the entire cross-section. The transect-averaged cross-section velocities are not the mean velocities of the cross-section. Fluctuations still exist in the velocity data and in order to reduce the fluctuations, the vertical and secondary flow components were smoothed 3 bins and 21 ensembles, respectively.

RESULTS

The Upper St. Clair River MBES bathymetry, referenced to the International Great Lakes Datum of 1985 (IGLD85), is shown in Figure 1 with the locations of

ADCP cross-sections. The water surface elevation did not vary much during the field survey and was approximately 176 m (IGLD85). The thalweg of the lake outlet follows a north-south oriented ship channel and continues into a deep hole where the lake meets the river near the left bank (eastern shore). The thalweg then cuts across the river bed to the right bank just above the Blue Water Bridge (BWB). Further downstream, a large scour exists at the outside of a bend in the river, along the west bank, and a bar has formed on the inside of the bend, along the east bank.

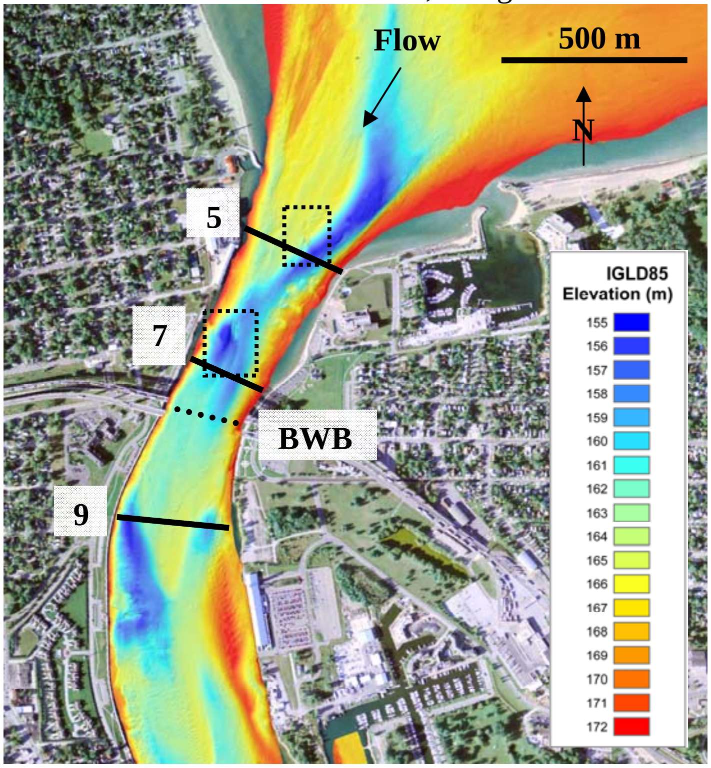

Figure 1. MBES bathymetry of the outlet of Lake Huron and Upper St. Clair River, July 2008. ADCP cross-sections are solid black lines, detailed bathymetry locations are dashed black boxes, and the Blue Water Bridge (BWB) is the dotted line.

The flow of water at the outlet of Lake Huron converges and accelerates into the St. Clair River as the banks constrict. At cross-section 5, the channel has constricted to a width of around 350 m with a downstream velocity of approximately 1.5 ms^{-1} (Figure 2). At a transverse distance of approximately 130 m from the east (left) bank there is a low velocity area.

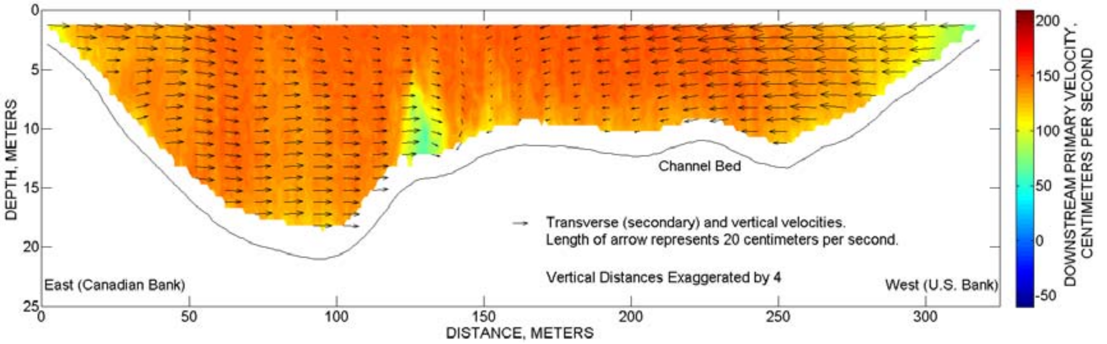

Figure 2. Flow through cross-section 5 as measured using an ADCP.

Examination of the bathymetry from the MBES survey upstream of this cross-section (Figure 3) and records of shipwrecks in the area, it appears that the low velocity area is just downstream of the wreckage of the *Fontana*. As the flow moves over and around the shipwreck, a low velocity area or velocity deficit is created just downstream. The detail of the bathymetric map also reveals bed forms that are oriented in the direction of the flow, downstream and toward the center of the channel.

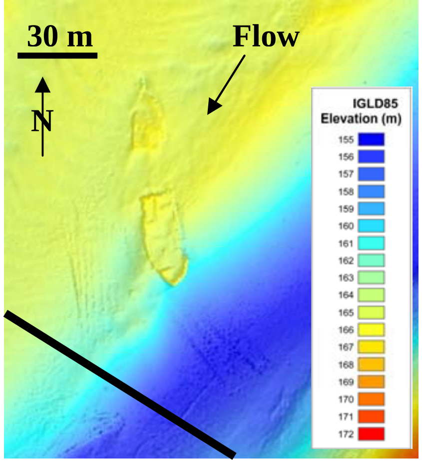

Figure 3. The *Fontana* wreckage revealed from the MBES survey with bed forms migrating around the shipwreck. Cross-section 5 is indicated by the solid black line.

The flow continues to converge and accelerate in the St. Clair River as the channel constricts further. At cross-section 7, the river has constricted to a width of around 270 m with a downstream velocity of approximately 2 ms^{-1} (Figure 4).

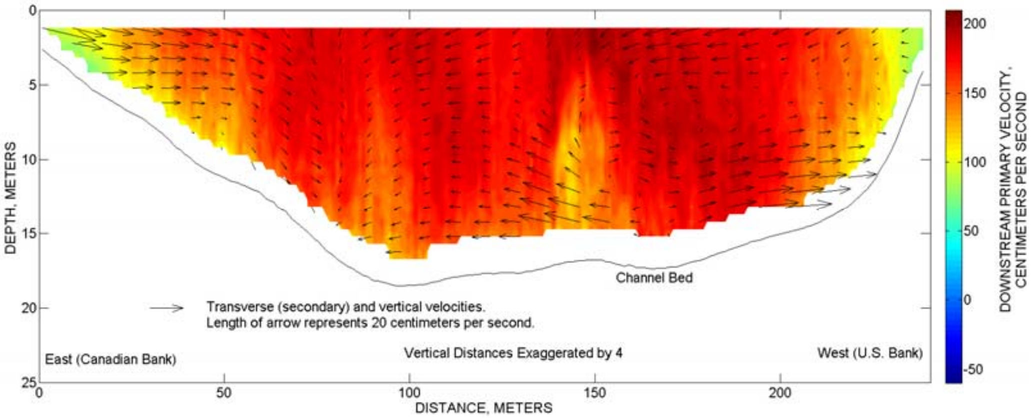

Figure 4. Flow through cross-section 7 as measured using an ADCP.

A counter-clockwise rotating secondary flow cell on the right (west) side of the cross-section is well developed. This counter-clockwise rotating secondary flow cell develops downstream of cross-section 5 in this position because flow in the thalweg moves toward the right bank along the bed of the river but at the surface the flow converges and flows toward the left bank. This causes the development of a counter-clockwise rotating secondary flow cell which then advects downstream. This secondary flow cell is well-developed in cross-section 7 and then diminishes downstream. The last remnants of this counter-clockwise secondary flow cell can be seen in cross-section 9, located at approximately 3 channel widths downstream of its initial development, or approximately 900 m, for the flow conditions analyzed.

Another low velocity area is observed at a transverse distance of approximately 150 m from the right (west) bank in Figure 4. Examination of the bathymetry upstream of this cross-section (Figure 5) and records of shipwrecks, reveals this low velocity area is just downstream of the wreckage of the *Martin*. As the flow moves over and around the shipwreck, a low velocity area or velocity deficit is created just downstream.

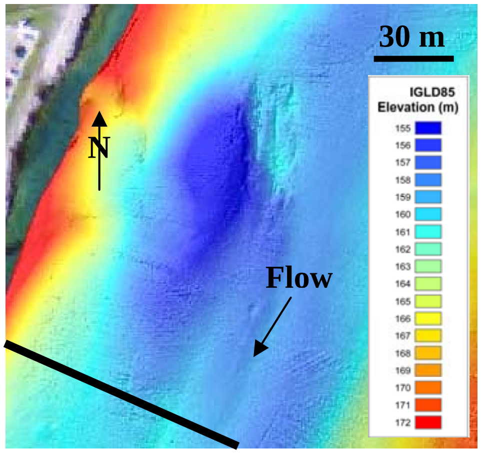

Figure 5. The *Martin* wreckage revealed from the MBES survey. Cross-section 7 is indicated by the solid black line.

The narrowest constriction in the Upper St. Clair River is at the Blue Water Bridge. After the flow passes under the Blue Water Bridge, the banks rapidly expand causing the flow to diverge toward the banks and forming a flow separation zone, with recirculating flow along the left bank. The length of the recirculation zone is approximately 5 channel widths downstream of the point of its initial development, or approximately 1500 m, for the flow conditions observed during the field survey.

At cross-section 9, the banks have expanded to a width of around 375 m with a downstream velocity of approximately 2 ms^{-1} (Figure 6). The recirculation zone at this cross-section extends from the left bank to approximately 90 m into the cross-section, and is defined by negative downstream velocities, indicating the flow along the left bank is moving upstream (Figure 6). The recirculation zone along the left (east) bank effectively narrows the cross-section available to the main downstream discharge, thus increasing the velocity of the flow in the center and near the right (west) bank of the river. Although the actual width of this cross-section is wider than cross-section 5, some areas have much higher velocities than cross-section 5 which is unexpected when passing the same discharge. This high velocity region created by flow acceleration due to the recirculation zone is one reason why navigation is so difficult in the Upper St. Clair River.

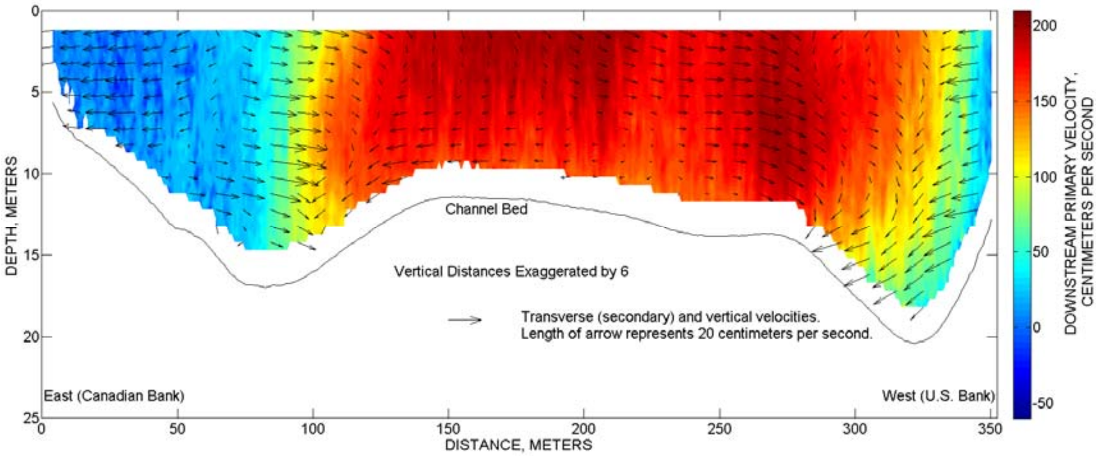

Figure 6. Flow through cross-section 9 as measured using an ADCP.

At cross-section 9 (approximately 400 m downstream of the BWB) the counter-clockwise rotating secondary flow cell seen in cross-section 7 has virtually disappeared and been replaced by a clockwise rotating secondary flow cell that has developed on the right (west) side of the cross-section. This clockwise rotating secondary flow cell appears to develop due to the flow diverging around a bar in the channel (see Figure 1) and being forced towards the right bank and into the hole. This diverging flow interacts with the counter-clockwise rotating secondary flow cell, directing the diverging flow downward and into the hole. This interaction lifts the counterclockwise rotating secondary flow cell away from the bed and is responsible for its lessening coherence. This clockwise rotating secondary flow cell extends approximately 3 channel widths downstream of its initial development, or approximately 900 m, for the flow conditions observed during the field survey.

SUMMARY

The St. Clair River is the major outlet of Lake Huron and connects Lake Huron and Lake Erie. A recent study (Baird and Associates, 2005) has suggested that dredging and scour in the St. Clair River may have caused a change in conveyance that has led to a reduction in lake levels. In 2007, the International Joint Commission appointed the International Upper Great Lakes Study (IUGLS) to investigate the factors affecting water levels and flows, develop and test potential new regulation plans, and assess the impacts of these potential plans on the ecosystem and human interests.

In July 2008, a field survey of the outlet of Lake Huron and the Upper St. Clair River was conducted using boats equipped with a MBES, an ADCP, and dGPS. A subset of the data collected was then analyzed in order to determine how channel shape, bed morphology, and shipwrecks affect the flow in the Upper St. Clair River.

The Upper St. Clair River is most constricted at the Blue Water Bridge near Port Huron, Michigan. Velocities measured at or near to the Blue Water Bridge can exceed 2 ms^{-1}. Downstream of this constriction, the river flows around a bend and expands creating a large flow separation zone with recirculating flow along the left (east) bank. The recirculation zone extends approximately 5 channel widths, or approximately 1500 m, based on the flow conditions observed during this 2008 field survey. This recirculation zone is found to reduce the effective cross-section width available for passage of the flow discharge, thus increasing the flow velocities in the center and right (west) bank of the river.

The MBES survey revealed several shipwrecks along the bed of the St. Clair River while the ADCP measurements indicated the effect of flow around these shipwrecks. As flow moves over and around the shipwreck, a low velocity area (evident in the ADCP data) is created in its wake.

The constriction and expansion of the channel, combined with forcing of the flow by bed topography, initiates secondary flow, creating streamwise vortices that maintain coherence downstream over a distance of several channel widths. The secondary flow cells are found to extend approximately 3 channel widths downstream of their initial development, or approximately 900 m, for the flow conditions observed during the field survey.

Ongoing analysis of the integrated bathymetric and flow dataset is examining the detailed morphology of the bed, the movement of sediment, and the role of the bed morphology in dictating the flow patterns within the river.

ACKNOWLEDGEMENTS

This work was funded by the International Upper Great Lakes Study (IUGLS), International Joint Commission (IJC) and the U.S. Geological Survey Office of Surface Water. The authors acknowledge the assistance provided by staff at the U.S. Coast Guard base at Fort Gratiot. We also acknowledge Don James of the U.S. Geological Survey, Michigan Water Science Center and Ryan Jackson of the U.S. Geological Survey, Illinois Water Science Center for their support and assistance in collecting the data for this study.

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