Understanding sediment dynamics using geological and engineering approaches: A case study of the Buffalo River area of concern, Buffalo, New York

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ABSTRACT
A combination of geological and engineering approaches was applied to better understand sediment movement along a contaminated river bed and provide support for remediation decision making. The geological approach, using sediment trend analysis (STA) and side-scan sonar mapping, helps interpret sedimentary processes acting over longer terms, while the engineering approach, based on a three-dimensional sediment transport model, illustrates sediment movement over shorter times, such as might be driven by storm events. The study site was the lower portions of the Buffalo River (Buffalo, NY), which is a tributary to Lake Erie and is an area of concern (AoC), as identified by the International Joint Commission due to beneficial use impairments primarily associated with contaminated sediment. Results from STA indicate two distinct flow regimes: a downstream regime dominated by fluvial processes and an upstream regime driven by changes in the level of Lake Erie. Where the two flow regimes intersect, sediment furrows are found. These features have been observed in this portion of the river over the past fifteen years and show characteristic ‘tuning forks’ opening in both upstream and downstream directions, indicating a bidirectional flow regime. Upstream movement of sediment also was found with the sediment transport model, which links hydrodynamic and particle tracking components to calculate transport pathways. Such movement is apparently generated by high amplitude seiches common to Lake Erie. Upstream sediment transport was not expected, but is consistent with the interpretation of results from each of the three different approaches. This combination of techniques has provided insights about short-term and longer-term sedimentation processes, which is helpful in choosing among management and remediation options for river restoration.

Keywords: Sediment transport; hydrodynamic modeling; transport pathways; river restoration; geophysical tools; lake seiche.

1 Introduction
The lower part of the Buffalo River has been designated by the International Joint Commission (IJC) as a Great Lakes basin Area of Concern (AoC) due to beneficial use impairments associated with poor water quality, degraded riparian and river habitat, and contaminated sediments. Much of the Buffalo River AoC is a federal navigation channel maintained through periodic dredging operations that have significantly affected the natural flow and sedimentation processes in the river. This urbanized ecosystem has experienced over a century of industrial and municipal impacts. While many former industries that lined the riverbanks are now abandoned, the legacy of past activities has left a record of contamination in the river sediments. Heavy metals and organic compounds contained within the sediments have been linked to a number of impairments including water quality degradation, low dissolved oxygen, loss of habitat, deformities in fish and other wildlife, and restrictions on fish consumption.

As mandated by the IJC Great Lakes Water Quality Board, a Remedial Action Plan (RAP) was developed for the Buffalo River. A Stage I RAP was completed in 1989 by the New York State Department of Environmental Conservation (NYSDEC). This document identified known and potential pollution sources and also evaluated beneficial use impairments (BUIs) – a change in the chemical, physical, or biological integrity of the Great Lakes system sufficient to cause any of 14 identified use impairments (e.g., restrictions on fish and wildlife consumption, degraded fish and wildlife populations, degradation of benthos, and loss of fish and wildlife habitat; IJC, 1991). The RAP also outlined the process by which progress towards delisting the river would be measured. The ultimate goal of the RAP process is the restoration of beneficial uses and delisting the AoC; to date, only two of 43 AoCs have been delisted, although substantial progress has been made in many other AoCs.

Of particular concern in restoring the Buffalo River is how best to address the river bottom sediments that contain elevated levels
of organic compounds and metals (Sauer, 1979; Aqua Tech, 1989; NYSDEC, 1989; Irvine et al., 2003). Decisions on river restoration include whether or not to leave the sediments in place, or to selectively remove contaminated sediments from specific portions of the river so that they are not periodically resuspended by navigational dredging, high flow events, and other processes, including human activities. These decisions are dependent upon the volume of sediment to be removed, the post-sediment removal monitoring plan, and the likelihood of recontamination in those areas where the removal of contaminated sediments took place. The present study aims to provide tools to better understand sediment dynamics in the river, in support of management decision making.

The Buffalo River AoC is confined to the lower 9.2 km of the Buffalo River, which flows through the southern part of Buffalo, New York, and discharges into Lake Erie near the head of the Niagara River (Figure 1). The Buffalo River watershed has an area of approximately 1,155 km² and is drained by three major tributaries. Land use in the upper portion of the watershed primarily comprises agricultural and rural communities. Closer to Buffalo, population density increases and active and abandoned industries line the banks of the river. Outflows from the Buffalo River are difficult to determine because estuarine-like conditions can occur during low flow periods when water levels at the eastern end of Lake Erie rise in response to set-up from strong southwesterly winds. Figure 2 details some of these short-term fluctuations for the month of October 1995. The significant drop in lake level that occurred around October 5, followed by a rapid rise of nearly 2 m is indicative of one of the large amplitude seiches within the lake. Seiches are common in Lake Erie due to its shallow water depth and alignment of its main longitudinal axis along the direction of the prevailing winds. As the wind subsides, the water that has piled up at the eastern end of the lake flows westward. The combination of dredging and very low hydraulic gradient, along with periodic forcing due to lake level fluctuations, leads to the river’s estuarine-like character. Thermal stratification arises as a result of the seasonal lag between river and lake temperatures, and this feature has associated impacts on mixing and transport characteristics (Kaur et al., 2007). Flow reversals and thermal stratification between lake and river waters have been observed for several kilometers upstream from the mouth during these times of wind set-up (Sargent, 1975, Irvine et al., 1993). (Note that we use the terms “upstream” and “downstream” to indicate normal river flow directions, that is towards the mouth and Lake Erie, even though water periodically moves in the upstream direction due to lake seiching.) While previous investigators noted the presence of Lake Erie seiches, and the Buffalo River Remedial Action Plan (NYSDEC, 1989) defined the upper end of the AoC as extending from the mouth of the Buffalo River to the farthest point upstream at which the backwater condition exists during Lake Erie’s highest monthly average lake level, the influence of the seiche on sediment dynamics within the AoC has been largely overlooked. Approaches developed in the present study show that these influences are not negligible and should be included when considering possible remediation actions.

2 Methods

The methodologies used in this study are side-scan sonar, sediment trend analysis (STA), and a particle tracking model (PTM) linked with a three-dimensional hydrodynamic model. All three methods provide information on sediment transport and the potential for recontamination, but use different approaches.
Understanding sediment dynamics using geological and engineering approaches

Because the three techniques are independent, STA and side-scan sonar can provide verification of predictions resulting from the PTM, and PTM results can confirm STA and side-scan sonar conclusions. Whereas STA results represent long-term sedimentation processes, the modeling reflects output for specified flow conditions acting over a limited period of time. Depending upon the interval between side-scan sonar surveys, information about short-term and longer-term sedimentation processes can be determined. Therefore, STA, side-scan sonar and PTM in combination can be used to provide an understanding of both short-term and long-term sedimentation processes operating in the river. This increases the level of confidence in each of the interpretations and provides the necessary framework for understanding sediment dynamics essential for making informed management decisions related to river restoration.

2.1 Side-scan sonar

A side-scan sonar unit transmits a fan-shaped sound beam to either side of the sonar “fish” instead of directing it downwards as in the case of conventional echo-sounders. Due to the high frequencies used (100–500 kHz) the sonar images only the surface of the river bottom and does not penetrate significantly into the sediment. This sideways oriented sound beam is narrow in the vertical direction and wide in the direction transverse to the “fish” track. The strength of the returned sound beam is affected by topography of the sediment surface as well as by differences in rock types and textures, and differences in bottom surface roughness.

Surveys of bottom morphology within the Buffalo River AoC were conducted annually from 1990 to 1996 using a side-scan sonar system (Singer and Manley, 1991; Manley et al., 1992; Manley and Singer, 1993; Singer et al., 1995). After a hiatus of eight years, the river was re-scanned in 2004 and 2005. Side-scan sonar surveys conducted prior to 2005 were done using a Klein dual frequency sonar system. In 2005, a digital sonar system was used. The use of digital side-scan eliminated the need for applying the GIS technique known as ‘rubber sheeting’ and data were mapped in the meandering channel in real time. This approach allowed us to place features in their actual position. The side-scan sonar surveys conducted in 2004 and 2005 were compared to side-scan records from the surveys conducted in the 1990s to document the presence and position of sedimentary bedforms, suggesting that the observed bedforms were a long-lasting feature of the river.

2.2 Sediment trend analysis

STA is a technique that enables patterns of net sediment transport to be determined by relative changes in grain-size distributions of naturally occurring sediments. STA can determine the dynamic behavior of bottom sediments with respect to erosion, accretion or dynamic equilibrium. Its underlying premise is that sedimentary deposits leave a signature in their grain-size distributions that is not random, and which can provide essential information for development of sediment management strategies. STA has been used in a variety of settings involving dredged material and contaminated sediment management (McLaren et al., 1993; Barrie and Currie, 2000). The theory to predict the relative changes that will occur in particle-size distributions of sediments through erosion, transport and deposition was first presented in McLaren and Bowles (1985). Based on the theory, several methods to carry out STA have been developed. The approach is one-dimensional, whereby the changes in grain-size distributions along individual sample sequences are tested for validity using the Z-score statistic to determine the preferred transport direction. A practical assessment of this approach is discussed in Hughes (2005).

A pilot STA was completed using 149 bottom (surficial) sediment samples collected in 1990 and a full scale STA, based on nearly 500 samples, was undertaken in 2004. Complete grain-size distributions for these samples were determined using a Malvern MasterSizer laser diffractometer. Maps for these data sets were prepared and the sediment textural properties were compared. Using the techniques and theory of sediment trends, transport paths and stability of the bottom sediments were determined. A comparison was made with results from the 1992 pilot STA.
Sediment transport can be modeled using one-, two- or three-dimensional models. Two-dimensional (2D) models are either oriented in a vertical plane or are vertically averaged. In either case information on three-dimensional (3D) structure is lost, in the former case because lateral variations are neglected and in the latter case because there is no vertical resolution. In the Buffalo River both vertical and transverse variations are important. In particular, reverse flows are possible in the lower reaches of the river, where both downstream river flow and upstream flow driven by lake level rises may occur within the same section (Sargent, 1975; Irvine et al., 1993; Singer et al., 1995). Previous models applied to the Buffalo River have considered only one or two dimensions (Meredith and Rumer, 1987; Raggio and Jirka, 1988; Gailani et al., 1996). While 2D modeling is often adequate for riverine systems, only a 3D model can account for possible upstream sediment transport driven by lake seiches, as well as transverse variations due to lateral differences in bottom shears.

The sediment transport model in the present study is developed by linking a 3D PTM with a 3D hydrodynamic model. Traditional Eulerian (control volume) based models for sediment transport are available, but they are unable to provide answers to questions about specific sediment transport pathways, which is important, for example, when trying to determine the source location for material that may fill in dredged regions of the river. This is of particular concern when environmental dredging is being considered as a possible remedial option. The PTM is based on tracking large numbers of individual particles and uses the velocity and diffusivity fields produced by the hydrodynamic model, which in the present study is the ECOM (Estuarine and Coastal Ocean Model; Blumberg and Mellor, 1980; Hydroqual, 2002). Although there is a sediment transport extension for ECOM, called ECOMSED, the PTM was used instead because of its ability to illustrate transport pathways.

ECOM solves the governing hydrodynamic equations for continuity and momentum on a curvilinear orthogonal coordinate grid with a constant number of layers in the vertical direction (i.e., a “sigma” coordinate system, see Figure 3). Vertical mixing is calculated with a turbulence closure scheme (Mellor and Yamada, 1982) and horizontal diffusivities are calculated with the Smagorinsky model (Smagorinsky, 1963). The numerical domain for the ECOM model comprises 245 segments in the longitudinal direction, ranging in length from 23.4 to 107.7 m, and 8 segments in the lateral direction, ranging in width from 7.6 to 35.7 m. The depth was resolved in five layers of equal thickness, ranging from less than 1 m to about 1.5 m, depending on river depth. The grid resolution represents a balance between being able to resolve processes of interest, while keeping run times at a reasonable level. ECOM generates velocities and diffusivities resulting from different boundary conditions specified by upstream flow hydrographs and downstream lake levels, which in general are time-dependent. Application of ECOM to the Buffalo River, including comparisons with available data, is described by Williams (2004).

The PTM calculates particle movements according to

\[ x(t + \Delta t) = x(t) + \left( u + \frac{\partial A_H}{\partial x} \right) \Delta t + \left( \sqrt{2A_H \Delta t} \right) \xi_x \]  

\[ y(t + \Delta t) = y(t) + \left( v + \frac{\partial A_H}{\partial y} \right) \Delta t + \left( \sqrt{2A_H \Delta t} \right) \xi_y \]  

\[ z(t + \Delta t) = z(t) + \left( w - w_s + \frac{\partial A_H}{\partial z} \right) \Delta t + \left( \sqrt{2A_z \Delta t} \right) \xi_z \]  

where \( x, y, \) and \( z \) are the particle coordinate directions (\( z \) is vertical), \( u, v \) and \( w \) are the respective velocities, \( w_s \) is the particle settling velocity, \( t \) is time, \( \Delta t \) is the time step, \( A_H \) is the horizontal diffusivity, \( A_z \) is the vertical diffusivity, and \( \xi_x, \xi_y, \) and \( \xi_z \) are independent unit normal variate random numbers. The second terms on the right-hand-sides of Equations (1)–(3) represent a deterministic component of particle movement, driven primarily by the mean velocity field (including settling, in the case of vertical motion). The last terms on the right-hand-sides represent a random component that simulates stochastic motions due to turbulent diffusion. The hydrodynamic model provides values for \( u, v, w, A_H \) and \( A_z \), at locations determined by the grid used (Figure 3), and values for each particle position were interpolated from the grid values. Boundary conditions for the PTM incorporate deposition and resuspension, based on critical shear stress formulations similar to those in ECOMSED (also as used by Gailani et al., 1996). The PTM directly simulates the movement of individual particles, rather than treating a distribution of particles only by a mean concentration. This approach allows determination of the desired sediment transport pathways for a given set of flow conditions, for example, that may be driven by different combinations of relative strength of river flow compared with seiche-driven flow. A full description of the PTM and its application to the Buffalo River is given by Atkinson and Fraser (2006) and Nagaraja (2007).
The PTM was initially applied for a set of conditions similar to those used in the study by Gailani et al. (1996), and results were compared with their model which was vertically integrated, and with measurements of bed level changes over a six-month period in the Buffalo River (also reported by Gailani et al., 1996). Results indicated the PTM was capable of simulating the observed bed levels, even somewhat more accurately than the Gailani et al. model (Nagaraja, 2007). For the present study the model was used primarily to evaluate the relative impacts of flows produced by watershed drainage and flows generated by seiche motions. For this purpose three flow combinations were chosen: (1) high upstream (base) flow and no seiche; (2) high seiche-driven flow and low base flow; and (3) high seiche and high base flow. In each case the flows were chosen to be of sufficient magnitude to generate bottom shears exceeding the critical shear for erosion. Particles were initially “placed” on the bed in a relatively uniform fashion and their movements were plotted for each hour of a day to provide a picture of transport pathways under conditions when sediment was being resuspended. This procedure is reasonable for the modeling application since most of the time the river acts as a settling basin, and it is only during relatively infrequent short periods of time, on the order of a day, that significant sediment resuspension takes place (Gailani et al., 1996).

3 Results

3.1 Side-scan sonar

Several features were identified from side-scan sonar records collected over the past fifteen years, including sediment tailings, sand ribbons, sediment furrows, slope failures (most likely associated with over-steepening of banks from dredging activities), and assorted debris (natural and man-made). Based on sonar reflectivity, the bottom sediment is predominantly mud. This is confirmed by the size analyses performed to support the STA. A full description of sonar results can be found in Singer et al. (2006) and Manley and Singer (2007). Overall, the bottom morphology in the past fifteen years has remained constant allowing the river to be divided into four sections (Figure 4) based on bottom morphology and dominance of sediment deposition or erosion.

Section 1 extends from the uppermost end of the Buffalo River AoC to Cargill’s Reach (Figure 1 and Figure 4). Deposition and slope failures dominate in this section, and this portion of the river is dredged every few years. Scours produced by debris dragged along the bottom during high flow events and disturbance features created by the removal of sediment during maintenance dredging were clearly identified in sonar records, but a repeat survey showed them to be completely or largely removed three months later. The most noteworthy bottom features mapped in the side-scan sonar surveys conducted between 1990 and 1995 were sedimentary furrows found in Section 2 (Figures 4 and 5). Section 3 has current dynamics that create and destroy sedimentary bedforms. Dredge scours observed shortly after navigational dredging occurred were smoothed two months later and still evident one year later implying a lower sedimentation rate than observed in Section 1. The river bottom in Section 4 contains the fewest sedimentary bedforms and the greatest amount of debris. Much of the debris appears to originate from collapsing wood cribbing and pilings. Sand ribbons are transient features within this part of the river.

3.2 Sediment trend analysis

One of the most significant findings from the pilot STA was the identification of two distinct transport regimes: a downstream flow regime driven by the flow of the Buffalo River and an upstream flow regime driven by seiches, with the two flow regimes intersecting in the section of river known as Cargill’s Reach in Section 2 (Figure 6). The STA interpretation was consistent with the presence and persistence of sediment furrows. Although the pilot STA study provided an indication of two opposing transport regimes in the river and the importance of

![Figure 4](image-url) Results from the 2005 digital side-scan survey. Sections 1–4 are identified. Modified from Singer et al. (2006).
Figure 5 Sedimentary furrows from Cargill’s Reach (Section 2) mapped by side-scan sonar in 1990 (a), 1995 (b), and 2005 (c). The circled area shows where furrows branch in a characteristic ‘tuning fork’ pattern. (Figure modified from Singer et al., 2006.)

Figure 6 Pilot STA results showing two distinct flow regimes (blue and red arrowheads). The reverse flow is driven by Lake Erie seiche. (Figure from McLaren and Singer, J. Coastal Research, 2007.)

the seiche in carrying sediments in an upstream direction, the sample density and the irregularity of the sample spacing did not allow for more than a few transport lines to be tested. With such a paucity of data, the interpretation could only be considered with a high degree of caution.

Both the pilot (Figure 6) and full scale (Figure 7) STAs demonstrated the presence of a bidirectional flow regime, although the latter study provided considerably greater detail with respect to both the direction and location of the pathways within the channel. In particular, the upstream, seiche-driven transport regime evidently dominates the center of the channel from Lake Erie to as far as Cargill’s Reach (Figure 7). The river margins in this region however show downstream transport, suggesting the dominance of seiches compared to river flow. In Cargill’s Reach itself, the reverse occurs with the seiche-driven regime becoming confined to the banks whereas the river dominates the center channel. Upstream of Cargill’s Reach river transport dominates both channel and banks. In all, seven transport environments were identified, some examples of which are shown in Figure 7.

3.3 Particle tracking model

As previously noted, three test (flow) conditions were modeled to provide an indication of the relative importance of upstream (base) flow and flows generated by seiche motions. When both the seiche and the base flow are low there is no sediment movement, since the critical shear stress for erosion is not exceeded. When the upstream base flow is high, sediment movement is predominantly downstream, as would be expected. Even when large seiches are coupled with large upstream flows the net movement is...
downstream, since any tendency for upstream movement of sediment driven by lake level rise is counteracted by the downstream river flow. When the lake level drops there is an amplification effect on the flows moving downstream, and the potential for sediment movement is high.

Results are most interesting when a large seiche is coupled with relatively low base flows. For this simulation a seiche of amplitude 0.4 m and period 16 hours (these values are representative of conditions in Lake Erie) and a base flow of 2 m$^3$/s were chosen (this flow corresponds with typical summer low flow conditions). The simulation was started as the lake level started to rise from its mean position. The cumulative movements of sediment over a 24-hour period for this case are shown in Figure 8, with arrow length representing the distance particles traveled. Although not evident in this figure, during this simulation many particles moved several times, in some cases both upstream and downstream. In addition, some of the particles were redeposited and some were still in suspension – the plot does not distinguish between these two conditions. However, a more detailed examination showed that most of the particles had been redeposited. In the lower portion of the river the results indicate a mixture of transport directions, with some suggestion of mostly upstream transport in the center of the channel and downstream transport along the margins, especially the southern (lower) margin/bank of the river. In the middle reach of the river (Section 2, from Figure 4) again a mixture of transport directions is seen, and the particle movements are generally not as large as in the lower reach. This is the farthest location upstream where transport was observed in the upstream direction. These results are consistent with the sonar and STA findings and implications are discussed in the next section. Particle transports were in general minimal in Section 1 (upstream), and strongest in Section 3 (see Figure 4), probably due to the relative narrowness of the river in this section.

4 Discussion and application to river restoration

Neither the presence of sediment furrows within the Buffalo River AoC nor the upstream movement of sediment discovered in the pilot STA had been predicted. Furrows are longitudinal bedforms (grooves) that parallel the bank. Their formation has been
related to erosion of cohesive sediment (scouring of furrow) and re-deposition to form the inter-furrow ridges (Flood, 1983). Furrows have been identified in areas characterized by bidirectional flow regimes including large lakes, estuaries, tidal channels, continental shelves, and deep sea environments (Belderson et al., 1972; Flood and Hollister, 1980; Flood and Bokuniewicz, 1986; Viekman, 1994; and Manley et al., 1999). Furrows often bifurcate to form a “tuning-fork” junction that closes in the direction of flow. The furrows in the Buffalo River range in depth from 1.5 to 2.25 meters (Monninger, 1998) and their spacing is 4 to 5 meters. These dimensions correspond to Type 1C furrows (Flood, 1983) indicating erosion rates equal to, or greater than, depositional rates. The presence and persistence of this type of furrow in all side-scan sonar surveys conducted in the Buffalo River between 1990 and 2005 suggest that the Cargill’s Reach is an area of active sediment erosion and deposition, and that furrow formation may result in the resuspension of contaminated sediment into the water column.

The position of the furrow field is stable and furrows have been observed only in this one stretch of river. They appear to be dynamic with yearly increases and decreases in their numbers. Minimal lateral movement was noted, but in some years, the furrows showed greater downstream extension. The furrows exhibit the ‘tuning fork’ pattern, with the forks showing upstream and downstream bifurcation. This suggests that the flow regime in this stretch of the river is influenced both by the out flowing Buffalo River and an upstream flow regime likely related to seiches that drive Lake Erie waters up into the river.

The agreement between the pilot and full scale STA, along with virtually no change in sediment texture in the 14 years between sediment sampling (reported in Singer et al., 2006) suggests that despite all of the ongoing natural and anthropogenic processes (e.g., river floods, seiches, navigational dredging, and shipping activities) the dominant sedimentation processes in the river overprint any short-duration events. The existence and influence on sedimentation of a seiche-driven flow regime have important implications in management decisions applicable to river restoration. In particular, consideration must be made of the recontamination potential of Buffalo River sediments that may be returned to the river following their transport to Lake Erie. Napieralski et al. (2001) observed that during high flow events, sediment discharged from the Buffalo River enters the harbor as visible plumes. Identification of the source(s) of sediment deposited around the mouth of the Buffalo River (e.g., Lake Erie derived sediment, recently deposited Buffalo River sediment, or a combination of sources) and the potential for re-entrainment and transport upstream by seiches are not firmly established at this time, but can be evaluated by extending a STA as well as the PTM beyond the mouth of the river into Buffalo Harbor.

While the PTM results focused only on short-term events, the results are consistent with both the side-scan sonar and STA findings, and all three methods independently confirm the significant role played by high amplitude seiche conditions in Lake Erie. All three approaches point to the existence of two distinct flow regimes operating in the river, with the upstream and downstream regimes likely intersecting about 5 km from the mouth in the stretch known as Cargill’s Reach. The rapid changes in lake level are well known and have previously been documented, but prior to this study, the influence of seiches on river sedimentation was largely overlooked. Although findings from the pilot STA and side-scan sonar surveys conducted in the early 1990s identified the bidirectional flow regime, those findings were not supported by the modeling efforts that considered only downstream flow. This study demonstrates the value of combining geological (STA and side-scan sonar) and engineering (modeling) methodologies to understand sedimentation in a system with complex hydrology. While there exists some degree of uncertainty in the results obtained from each approach, it is the agreement among all three that builds a compelling case making it difficult to dismiss the role of the lake seiche in transporting sediments upstream.

The PTM also demonstrates why two-dimensional models are insufficient in systems such as the Buffalo River where reverse flow influences circulation and transport. Clearly, upstream sedimentation caused by a seiche-driven flow regime has important implications in management decisions related to river restoration. Future efforts are being directed to determine the source of sediment being transported by seiches. Possible sources include re-entrained Buffalo River sediments deposited in the area around its mouth following extreme river flows, sediments transported as part of the Lake Erie longshore system, or a combination of both. Further model development and refinement are also being pursued, including calibration of the model under different flow conditions generated by combinations of Lake Erie seiches and upstream flow.

5 Conclusions

The combination of geological (STA and side-scan sonar mapping of river bottom features) and engineering (3D modeling) approaches provides a framework for understanding sediment transport pathways and flow conditions in the Buffalo River AoC. These approaches, while proving to be complementary, were performed independently of each other. STA results provided information about long-term sedimentation processes and the modeling results reflected output for specified flow conditions acting over a limited period of time. The time interval between sonar surveys (from several months to years) revealed information about both short-term and longer-term sedimentation processes. The agreement in results among the three methods increases the level of confidence in each of the interpretations and provides the necessary framework for understanding sediment dynamics essential for making informed management decisions related to river restoration. All three approaches suggest the significant role played by rapid elevation changes due to Lake Erie seiches in transporting sediment upstream, a result not necessarily anticipated. Sediment from around the mouth and lower portion of the Buffalo River can be entrained and carried back upstream, potentially recontaminating remediated upriver sites. Not only does this finding have implications for planning remediation projects within the Buffalo River AoC, but it also suggests that in any river system where reverse flows occur, detailed
sedimentological, geophysical and 3D hydrodynamic models should be considered so that the source and pathways of sediment particles can be more completely understood.

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