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Jill Singer
Buffalo State University, singerjk@buffalostate.edu

Patrick McLaren
GeoSea Consulting

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Sediment Transport and Contaminant Behavior in the Buffalo River, New York: Implications for River Management

Patrick McLaren[†] **and Jill Singer**[‡]

[†]GeoSea Consulting
7236 Peden Lane
Brentwood Bay, BC V8M 1C5
Canada

[‡]Department of Earth Sciences and
Science Education
SUNY–Buffalo State College
1300 Elmwood Avenue
Buffalo, NY 14222, U.S.A.

ABSTRACT

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The lower 9 km of the Buffalo River that flows into the eastern end of Lake Erie has been designated by the International Joint Commission as a Great Lakes area of concern (AoC) because of poor water quality, degraded riparian and river habitat, and contaminated sediments—impairments related to a long history of contamination from the industrial legacy of the past century. As a designated AoC, attention is presently focused on sediment remediation, an endeavor requiring an assessment of the relationship between sediment transport processes and sediment contaminant concentrations. In 1990 a pilot sediment trend analysis (STA) revealed an upriver return of sediments from the mouth of the Buffalo River as far as 5 km inland. A complete STA conducted in 2004 confirmed the upriver transport regime. Examination of river discharge and Lake Erie water levels demonstrated that lake seiches occur at far greater frequencies than river discharges of a magnitude capable of transporting sediment. Thus the river is behaving in a similar manner to an estuary with seiche rather than tidal waves responsible for driving fine-grained sediments in an inland direction. The dynamic behavior of the sediments as determined by STA correlated well with the expected contaminant levels contained in the sediments of the main river channel. The findings are used to establish a conceptual understanding of the river that requires extreme river flows to transport sediments to its mouth, after which sediments recently deposited from plumes discharging into Lake Erie are re-entrained and transported upriver by seiche activity. Such an understanding is of considerable importance in sediment remediation as contaminants are also in a constant state of recycling both up and down the lower 5 km of the Buffalo River.

ADDITIONAL INDEX WORDS: *Sediment transport, contaminants, Buffalo River NY.*

INTRODUCTION

Within the Great Lakes basin, 43 areas of concern (AoCs) have been identified. In an effort to clean up the most polluted rivers and harbors, the United States and Canada, as part of the Great Lakes Water Quality Agreement, committed to the development and implementation of remedial action plans (RAPs) for all designated AoCs. The RAP process includes identification of impairments to any one of 14 beneficial uses (*e.g.,* restrictions on fish and wildlife consumption, restrictions on dredging activities, loss of fish and wildlife habitat) and consideration of remediation options and alternatives. The ultimate goal of the RAP process is the restoration of beneficial uses and delisting of the AoC.

The lower 9.2 km of the Buffalo River is classified as an AoC. The industrial legacy of the past century and current point and nonpoint pollution sources in the surrounding watershed contribute to the river's poor water quality, lost and degraded habitat, and contaminated sediments. Furthermore, much of the river is a federal navigation channel maintained through periodic dredging operations that have significantly affected the natural flow and sedimentation processes.

Of particular concern in remediation efforts for the river is how best to address the river bottom sediments that contain elevated levels of organic compounds and metals (AQUA TECH, 1989; IRVINE *et al.*, 2003; NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION, 1989; SAUER, 1979). Decision making for habitat restoration projects includes whether or not to leave sediments in place, or to remove selectively hot spots containing sediments with elevated levels of metals and organic compounds from the riverbed. Critical to such decisions is an assessment of the likelihood for recontamination after sediment removal, a requirement that demands (i) an understanding of the physical processes that are likely affecting sediment transport, (ii) how those processes relate to the actual patterns of net sediment transport, and (iii) an identification of existing sources of contaminated sediments and their probable transport behavior. The objective of this paper is to assess and discuss each of these criteria utilizing sediment trend analysis (STA), a method that determines sediment transport pathways and dynamic behavior on the basis of the relative changes of grain-size distributions taken from the river bottom (MCLAREN AND BEVERIDGE, 2006). The results presented are from two STA

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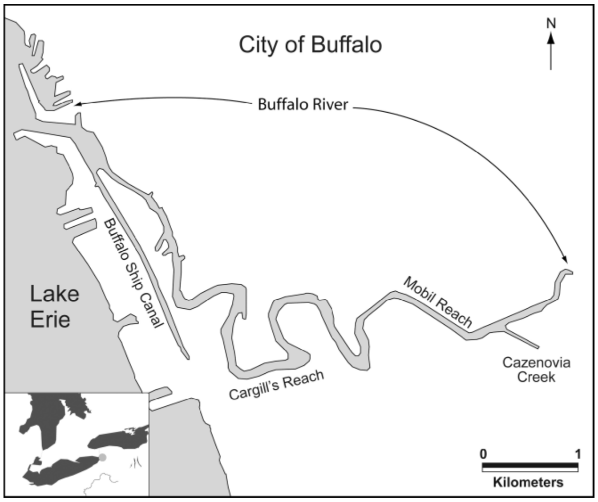

Figure 1. The Buffalo River area of concern (AoC). Names and locations referred to in paper.

investigations, a pilot STA based on a limited number of sediment samples collected in 1990 and a full-scale STA based on 495 samples collected in 2004.

STUDY AREA

Physiography and Hydrography

The Buffalo River flows from the east along the southern boundary of the city of Buffalo and discharges into the eastern end of Lake Erie near the head of the Niagara River (Figure 1). The drainage basin of the Buffalo River occupies two physiographic regions. The upper reaches of the various tributaries in the southern portion of the basin originate in the Allegheny Plateau. Progressing northwest, the greater part of the basin is contained in the Erie–Ontario province, a low-lying region composed principally of former glacial lakebed sediments. As a result, most of the watershed provides a fairly ubiquitous source of principally fine-grained (silt and clay) materials that are available for transport and eventual deposition in the Buffalo River. The gradient of the river is small, less than 17 cm/km (AVERETT *et al.,* 1996).

The three main tributaries contributing flow into the Buffalo River are the Cayuga (basin area 321 km^2), Buffalo (378 km^2), and Cazenovia (350 km^2) creeks, with a combined area of about 1049 km^2. Originating at the confluence of Buffalo and Cayuga creeks, the Buffalo River is about 100 m in width and 12.5 km long. From about the middle of Mobil Reach (Figure 1) the river is dredged for navigation to a depth of about 7.6 m. Nearly all sediment and modeling studies have relied on synthesizing average daily inflows from the combined flows of the three tributaries. Data are available since 1940 and are obtained from U.S. Geological Survey stream gauges located on Buffalo Creek at Gardenville, NY, Cayuga Creek at Lancaster, NY, and Cazenovia Creek at Ebenezer, NY. Summing the discharges out of each of the three tributaries results in a mean daily discharge of about 17 m^3/s (Table 1). Typically summer discharge is very small with velocities less than 0.02 m/s; fall and winter rainfall conditions result in highly variable mean daily discharges with sudden peaks that seldom extend more than a day or two (Figure 2). The average annual suspended sediment yield for the drainage basin is estimated at 95,600 metric tons (PASSINO-READER, HUDSON, and HICKEY, 1995). The substrate of the river itself is nearly everywhere composed of mud. Only in the region of Cazenovia Creek are sand and gravel-sized sediment present.

Table 1. *Summary of Buffalo River flow characteristics (cfs = cubic feet per second).*

Daily Average Streamflow (derived from USGS data 1995 to 2003)		
Average Daily Discharge	Maximum Discharge, January 8, 1998	Minimum Discharge, August 12, 2001
17 ± 32 m^3/s (603 ± 1122 cfs)	537 m^3/s (18,970 cfs)	0.33 m^3/s (11.55 cfs)

The day after completion of the sediment sampling for the full-scale STA the remnants of Hurricane Francis brought more than 100 mm of rain to the Buffalo region. Peak discharge attained 534 m^3/s, only slightly less than the maximum recorded flow measured in the previous nine-year period (537 m^3/s; Table 1). The event was sufficient to cause widespread urban and small-stream flooding. Observations made by the authors from various bridges during the period of high flow showed a Buffalo River significantly changed from the imperceptible flow experienced during the sampling program. The river had become heavily laden with sediment, together with large amounts of vegetation debris and garbage. The resulting plume was clearly visible entering Lake Erie. Significant slicks of gasoline and oil were also present. Flow velocity was estimated at 1.23 m/s and the river was characterized by extremely turbulent conditions including eddies and whirlpools. The event is clearly seen on the September hydrograph (Figure 3) and it is noteworthy that despite such a large event the river returned to "normal" discharge within a day or two. To assess the effects of this extreme

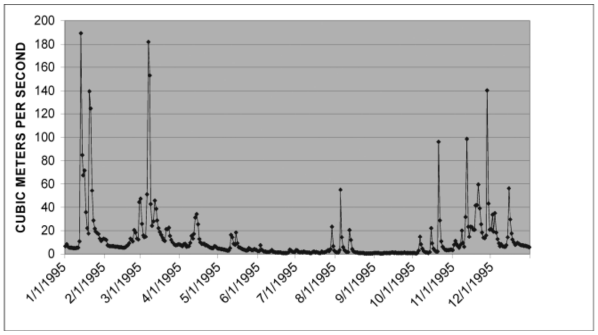

Figure 2. An example (for the year 1995) of the combined hydrograph of the three tributaries contributing to the Buffalo River.

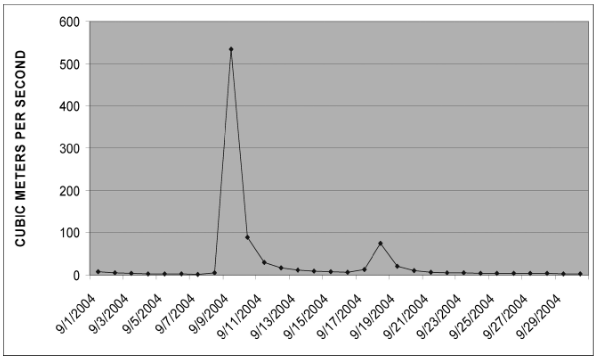

Figure 3. September 2004 hydrograph of the combined flow of the three tributaries feeding the Buffalo River. The rainfall associated with Hurricane Francis occurred on September 8 and 9.

event on sediment texture, a small number of sediment samples were collected in Cargill's and Mobil reaches (Figure 1) 4 days and 16 days after its date on September 9, 2004 (data sets 3 and 4, Table 2).

Seiches and Water Levels

Given that the Buffalo River flows into Lake Erie and is characterized by a low gradient and generally low flows, the flow dynamics in at least the lower portions of the river are likely affected by changes in lake levels. Water levels in the lake are subject to long-term changes as a result of prolonged and persistent deviation from average climatic conditions. Because of seasonal changes in the amount of water flowing into and out of Lake Erie, its level undergoes a natural cycle of changes throughout the year, being highest during the summer months and lowest during mid-winter. Typically, the level of Lake Erie fluctuates about 35 cm during a given year.

Superimposed on the long-term and yearly cycles are extremely common and rapid lake level changes. For example, a hydrograph of Lake Erie water levels at Buffalo shows a considerable drop in lake level occurring around October 5, 1995, followed by a rapid rise of about 1.7 m over about 9 hours or 19 cm/hour (Figure 4). Such abrupt fluctuations are the result of seiches that are common in Lake Erie because of its shallowness and its alignment along the axis of the prevailing southwesterly winds. Strong winds from the southwest cause water to pile up in Buffalo Harbor at the eastern end of the lake. As the wind subsides, the pile of water at the east end of the lake is released, causing it to "slosh" back and forth. The typical seiche period is about 14 hours for Lake Erie; this can be seen in Figure 4 where there are roughly 10 cycles in the 7 days following the October 5 seiche. Such events can be extraordinarily sudden. In 1844 a seiche was responsible for one of Buffalo's greatest disasters when a wall of water breached a 4.3-m seawall, drowning 78 people. During one storm in November 2003, the water level at Buffalo rose by 2.1 m, with waves of 3 to 4.5 m on top of that, for a cumulative rise of about 6.7 m. Although there is not a great deal of information on the dynamic effects of seiches on the outflowing Buffalo River, Passino-Reader, Hudson, and Hickey (1995) suggested that a rise in lake level of 1 m is sufficient to affect its whole 12.5-km length.

Table 2. *Data sources for grain size distributions used in this paper.*

Data Set	Date	Data
Data set 1	Summer 1990	145 samples with STA.
Data set 2	September 1–8, 2004	495 samples (Figure 5) with STA.
Data set 3	September 13, 2004	22 samples in Cargill's Reach and Mobil Reach immediately after a river flood event. Too few samples for STA.
Data set 4	September 25, 2004	9 samples in Mobil Reach. Too few samples for STA.

* Sample designs for data sets 1, 3, and 4 are not shown but may be seen in Singer *et al.* (2006).

METHODS

Sediment Trend Analysis

Unlike numerical modeling, STA is an empirical technique whereby the relative changes in grain-size distributions of bottom sediments are used to infer the directions of net sediment transport as well as the dynamic behavior of the substrate (*i.e.,* net erosion, net accretion, dynamic equilibrium, *etc.*). The theory was first published by McLaren and Bowles (1985) and many authors have since used the technique or endeavored to improve on it (*e.g.,* Chang, Scrimshaw, and Lester, 2001; Cheng, Gao, and Bokuniewicz, 2004; Gao, 1996; Gao and Collins, 1991, 1992; Lucio, DuPont, and Bodevan, 2004; Lucio *et al.,* 2006). Hughes (2005) provided an overview and critique of STA as applied to coastal management. The most recent discussion on STA is contained in an Appendix to a paper by McLaren and Beveridge (2006). The details to be found in this paper (which are not repeated here) are important to the understanding of results obtained using STA, the uncertainties associated with the technique, and the relationships between

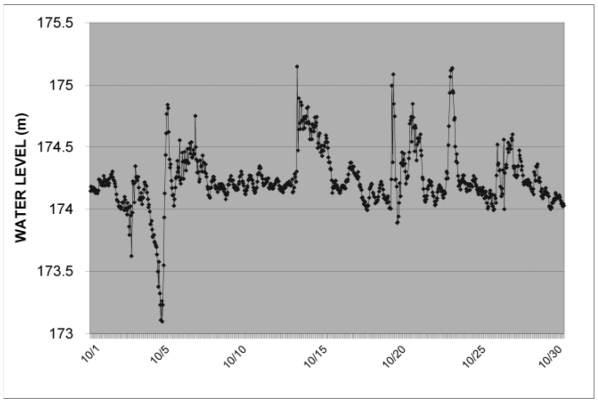

Figure 4. Hourly lake levels at Buffalo, October 1995.

Table 3. *Summary of sediment and contaminant dynamic behaviors on the basis of STA.*

Sediment Dynamic Behavior (Stability)	Shape of $X(s)$ Relative to $d_1(s)$ and $d_2(s)$ (See the Appendix in McLaren and Beveridge, 2006, for full explanation)	Contaminant Dynamic Behavior
Net erosion	The mode of $X(s)$ is coarser than the $d_1(s)$ and $d_2(s)$ modes. More grains are eroded than deposited and sediment coarsens along the transport path.	Contaminant levels decrease rapidly down the transport path and are dispersed to areas of deposition (not present in this study).
Net accretion	The mode of $X(s)$ is finer than the modes of $d_1(s)$ and $d_2(s)$. More grains are deposited than eroded and accretion occurs down the transport path.	Contaminant levels increase down the transport pathway.
Dynamic equilibrium	The modes of all three distributions are the same. The probability of finding a particular grain in the deposit is equal to the probability of its transport and redeposition (*i.e.,* there is a grain-by-grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.	Contaminated sediment will move down the transport pathway while remaining as a coherently defined hot spot.
Total deposition (type 1)	The $X(s)$ distribution increases monotonically over the complete $d_1(s)$ and $d_2(s)$ distributions. Sediment fines in the direction of transport; however, the bed is no longer mobile. Once deposited, there is no further transport.	Contaminated sediments form localized hot spots that undergo no further transport.
Total deposition (type 2)	$X(s)$ is horizontal. This type of X-distribution is found only in extremely fine sediments when the mean grain size is very fine silt or clay, Such sediments are usually found "far" from their source (compared with total deposition [type 1]) sediments. Deposition is no longer related strictly to size sorting. There is an equal probability of all sizes being deposited down the transport path.	Contaminated particles have an equal probability of being deposited anywhere in this type of environment. Hot spots do not form; rather there is a ubiquitous background level of contaminant concentrations (not present in this study.)

dynamic behavior and contaminant levels contained in the sediments.

STA theory demonstrates that when two sediment samples (located at d_1 and d_2) are taken sequentially in a known transport direction (for example, from a riverbed where d_1 is the up-current sample and d_2 is the down-current sample), the sediment distribution of d_2 may become finer (case B) or coarser (case C) than d_1; if it becomes finer, the skewness of the distribution must become more negative. Conversely, if d_2 is coarser than d_1, the skewness must become more positive. The sorting will become better (*i.e.,* the value for variance will become less) for both cases B and C. If either of these two trends is observed, sediment transport from d_1 to d_2 can be inferred. If the trend is different from the two acceptable trends (*e.g.,* if d_2 is finer, better sorted, and more positively skewed than d_1), the trend is unacceptable and it cannot be supposed that transport between the two samples has taken place.

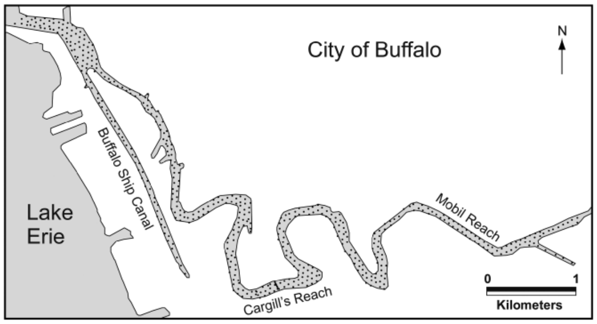

Figure 5. Locations of 495 samples collected in early September 2004.

In the above example, where the transport direction is unequivocally known, d_2(s) can be related to $d_1(s)$ by a function $X(s)$ where s is the grain size. The distribution of $X(s)$ may be determined by:

$$X(s) = d_2(s)/d_1(s)$$

$X(s)$ provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported, and deposited from d_1 to d_2. It is the shape of the $X(s)$ distribution relative to the shapes of the $d_1(s)$ and $d_2(s)$ distributions that determines the dynamic behavior (stability) of the sediments. There are five defined categories for dynamic behavior, each of which provides an assessment of how contaminants in the sediments are likely to behave (Table 3).

Field Methods

Sediment grab samples for data sets 1, 3, and 4 were collected using a ponar sampler and samples for data set 2 were collected using a small Van Veen grab sampler (Table 2). For all four data sets, samples were taken from the top 10 to 15 cm of sediment. The sample locations for data set 1 were determined by using U.S. Army Corps of Engineer's transect markers located along the riverbank; the position in the channel was recorded relative to the center of the channel and banks. The navigation to and positioning of sample locations for data sets 2, 3, and 4 were carried out using differential global positioning system instrumentation (Trimble DSM212L) to a nominal accuracy of 1.0 m. In most instances, samples were obtained at predetermined locations; however, where shoreline structures (*e.g.,* docks and marinas) and moored vessels interfered with navigation, samples were collected as close as practicable to the planned position.

The sampling plan for data set 2 (Figure 5) utilized an iso-

Table 4. *Comparison of sediment textural properties (phi units) among the four data sets (see Table 2). The asterisk for the mean grain size in Mobil Reach represents the only significant change from the previous data set at the 99% level. All other values show that no significant changes occurred from one sample date to the next.*

Location	Data Set (see Table 2)	Date	Mean	SD	Sorting	SD	Skewness	SD	No. of Samples
Buffalo River	Data set 1	Summer 1990	6.36	0.45	1.09	0.14	−0.04	0.12	131
Buffalo River	Data set 2	September 1–10, 2004	6.35	0.44	1.05	0.15	−0.03	0.09	332
Cargill's Reach only	Data set 1	Summer 1990	6.60	0.31	1.02	0.12	−0.05	0.09	17
Cargill's Reach only	Data set 2	September 1–10, 2004	6.35	0.48	1.09	0.27	−0.05	0.09	32
Cargill's Reach only	Data set 3	September 13, 2004	6.15	1.59	1.17	0.47	0.04	0.27	11
Mobil Reach only	Data set 1	Summer 1990	5.80	0.76	1.25	0.14	0.04	0.23	17
Mobil Reach only	Data set 2	September 1–10, 2004	5.94	0.21	1.08	0.11	−0.05	0.05	28
Mobil Reach only	Data set 3	September 13, 2004	**3.37***	1.99	1.07	0.55	−0.10	0.17	11
Mobil Reach only	Data set 4	September 25, 2004	4.69	1.68	1.01	0.30	−0.02	0.09	9

tropic regular triangular mesh generated by an in-house ArcView™ application that allowed for examining sample grids at various spacings. As described in the Appendix of McLaren and Beveridge (2006), the selection of the distance between samples is based on communications theory, which, when applied to STA, suggests that sample sites placed *x* km apart can only reliably detect transport directions occurring over a distance in the order of 2*x* km or more. Directions occurring over distances less than 2*x* km would appear as noise or could create spurious transport pathways through the process of aliasing. In practice, selection of a suitable sample spacing must take into account the number of sedimentological environments, the desired spatial scale of the sediment trends, and the geographic shape and extent of the study area. For this study, a 50-m spacing between samples provided an optimum number of samples to accommodate the achievement of valid trends in a river that is seldom more than 100 m wide. Because sample location generation is automatic, some areas, particularly in narrow channels, could result in an inadequate sample coverage, in which case extra samples were taken during the course of the field program.

Grain Size Analysis

Samples making up data set 1 (Table 2) were analyzed with a Malvern 2600L laser particle size analyzer. This instrument required lenses of different focal lengths to look at portions of the total range of grain sizes that may be present. The distributions, combined with sieve data for sizes >1500 μm, were then merged using an algorithm specifically designed for this purpose.

Grain size data sets 2, 3, and 4 (Table 2) were analyzed for their complete grain size distribution using a newer-model laser particle sizer (Malvern MasterSizer 2000). The laser-derived distributions were combined with sieve data for particles larger than 1500 μm in diameter. Given that the principle for the two types of instrument are the same, significant differences in the distributions due to instrumentation are not considered to be likely. The size distributions were entered into a computer equipped with appropriate software to establish sediment trends and transport functions.

RESULTS

Textural Changes

Within the area of the Buffalo River encompassed by data set 1, the textural properties for samples collected 14 years later (data set 2) and covering the same area remained essentially unchanged. As seen in Table 4, the average phi mean grain size, sorting (standard deviation, SD), and skewness for the two data sets are remarkably similar. Given the length of time between the two sampling programs, during which innumerable changes in river flow, large numbers of seiche events, and dredging activities have occurred, this finding suggests that the sediments and hydrodynamic conditions of the Buffalo River have remained extremely consistent over the years.

In the sediments associated with Cargill's Reach, there has been a slight progressively coarsening trend for the three data sets, although none is significant. Despite the September 9, 2004 extreme event, Cargill's Reach appears to be too far downriver to show a significant textural change. In Mobil Reach, which is much closer to the confluence of the Buffalo and Cazenovia creeks, the sediments remained unchanged over the 14 years separating the first and second sampling events; however, after the September 9 high flow event, the sediment changed significantly from coarse silt (5.94 Ø) to fine sand (3.37 Ø). The samples collected 16 days later on September 25 contained a noticeable stratigraphic succession of coarse sand overlain by mud. Unfortunately the two facies were not analyzed separately and were, instead, mixed into a single sample producing a mean grain size that is a composite of both sand and mud. The distribution of the mud only would likely be indistinguishable from the mud sediments collected before the high flow event, suggesting that the return to "normal" processes after extreme events is quite rapid.

Sediment Trend Analyses

The pilot STA (samples collected in 1990) carried out on 145 sediment samples was intended to establish the utility of this technique in developing a conceptual model of the dynamics of sediment transport, and in particular, the potential for resuspension of contaminated bottom sediments within

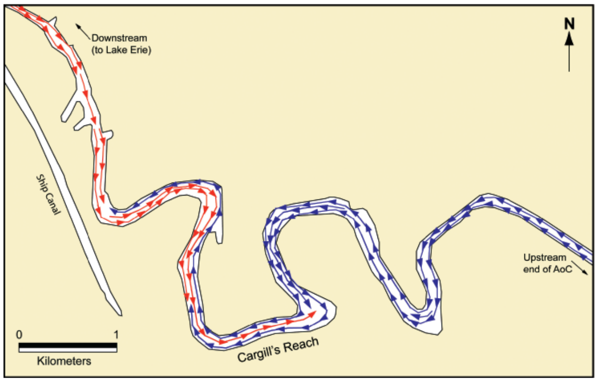

Figure 6. Sediment pathways as determined from a sediment trend analysis on the basis of 145 samples collected in 1990 (McLaren and Singer, 1995). Most of the trends that define the two opposing regimes meet in Cargill's Reach.

the Buffalo River AoC. Despite the relatively small number of samples collected for data set 1, good transport trends were, nevertheless, established using eight sample lines (Figure 6). A full account of the trend statistics for these lines is contained in Singer *et al.* (2006). As described in Singer *et al.* (1995), the sediment trends produced an unexpected result: the derived pathways identified two distinct transport regimes, one associated with the directional flow of the river, and a second apparently moving sediment upstream from Lake Erie as far as Cargill's Reach where both regimes meet. All trends produced *X*-distributions indicative of total deposition (type 1) behavior as defined and described in McLaren and Beveridge (2006).

Because the pilot was based on relatively few samples and irregular sample spacing, the results could only be considered with a high degree of caution. They were reported to the U.S. Environmental Protection Agency (EPA) in Singer *et al.* (1995) with little explanation apart from suggesting that fluctuating water levels in Lake Erie might provide a mechanism to drive sediments in an upstream direction.

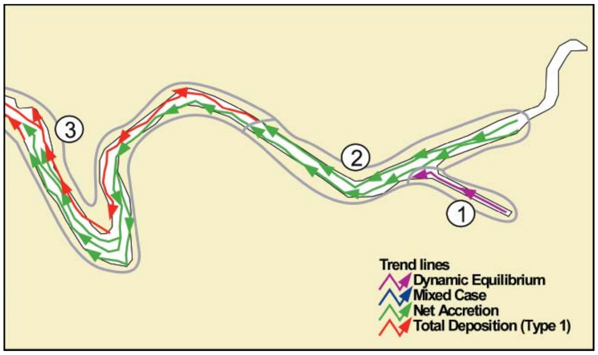

Figure 7. The transport pathways for upper river transport environments (TEs) 1, 2, and 3.

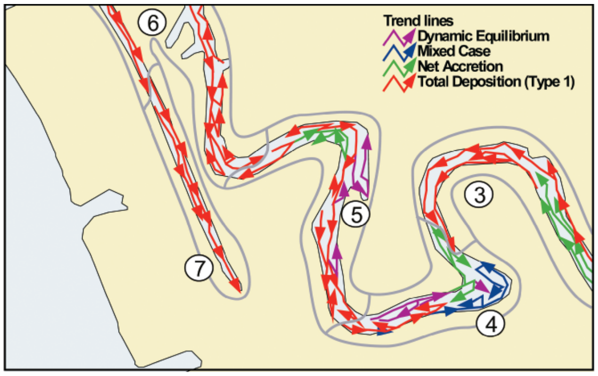

Figure 8. The transport pathways for middle river TEs 3, 4, 5, and 6.

The 495 samples that comprise data set 2 were collected specifically for STA and provide an interpretation in considerably more detail than could be obtained with data set 1. After the calculation of numerous sample sequences to determine significant trends, a total of 64 transport lines utilizing the grain size distributions at all the sample locations was used to identify the complete patterns of transport for the river. The full trend statistics for each of the lines are provided in Singer *et al.* (2006). For ease of discussion, the transport lines have been grouped into seven transport environments (TEs), starting from TE1 in the Cazenovia Creek tributary and progressing down the Buffalo River to Lake Erie. A TE is defined as an area within which transport lines are associated both geographically and "behaviorally". Generally, transport lines cannot be continued from one TE into another, and so a region in which transport lines naturally end (and begin) is a boundary between TEs.

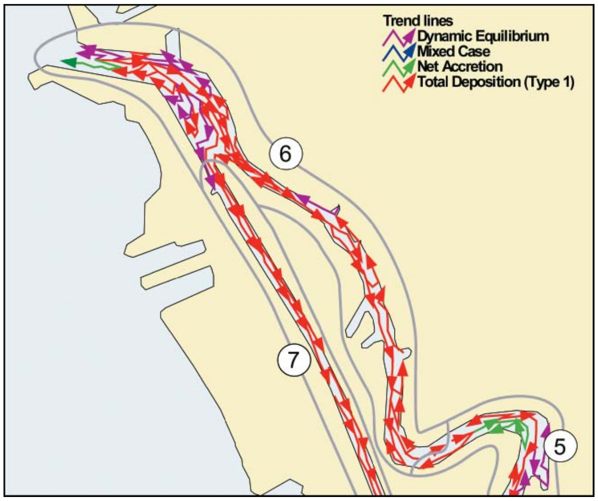

Figure 9. The transport pathways for lower river TEs 6 and 7.

TE1 (Figure 7)

Comprising a single line of samples taken in the Cazenovia Creek tributary, the sediments contain a wide variety of sediment types ranging from gravelly sand to mud. The trend extends in a downriver direction and joins the Buffalo River. However, the pathway could not be extended much beyond the junction of the two rivers, suggesting that the Cazenovia Creek input of sediment is small in comparison with the sediment supplied by the Buffalo River. The *X*-distribution for this line suggests total deposition (type 1) dynamic behavior.

TE2 (Figure 7)

Originating at the upstream end of the Buffalo River sampling area, these sample lines extend halfway down Mobil Reach. Above the confluence with Cazenovia Creek, sediments are quite coarse and varied but become quite muddy downstream. The trends terminate in the middle of Mobil Reach where several patches of sandy mud occur. Both trends indicate that net accretion is occurring down the transport path.

TE3 (Figures 7 and 8)

Commencing in the sandy mud sediments of Mobil Reach, this group of lines extends downriver to slightly upstream of Cargill's Reach. The sediments are almost all entirely mud. Four lines with *X*-distributions indicative of net accretion dominate the upper part of this environment. A further six lines dominate the lower half of the environment, suggesting that net accretion changes to total deposition (type 1). TE3 ends at Cargill's Reach (TE4), where the first determination of upstream transport is in evidence.

TE4 (Figure 8)

These lines originate on both banks of the downstream end of Cargill's Reach and suggest that upstream transport is occurring close to each of the shorelines. The lines on both sides, however, curve in gyres toward the center of the river where they reverse their trend to a downstream direction. Cargill's Reach is the first TE where an upriver transport regime encounters the more expected downstream transport. This TE displays a wide mix of dynamic behaviors; three lines show net accretion, two lines show total deposition (type 1), and five lines indicate dynamic equilibrium or mixed case.

TE5 (Figure 8)

This environment is composed almost entirely of mud sediments. The lines originate in the middle of the channel immediately upstream of TE6. Downriver transport is confined to the main channel but veers onto the channel sides as it approaches the opposing transport regime of TE4. Where upstream transport dominates the channel, there are gyres from the channel onto the sides where the trends reverse from an upstream to a downstream direction. Close to TE4, the situation is reversed, with upstream transport on the banks and associated gyres returning sediment to the channel where downstream transport can be observed. Similar to TE4, this environment also contains a mix of dynamic behaviors comprising two lines of net accretion, three lines in dynamic equilibrium, and six lines in total deposition (type 1).

TEs6 and 7 (Figure 9)

Originating in the mouth of the Buffalo River at Lake Erie, TE6 is similar to TE5 in which lake-dominated transport is contained in the main channel, whereas downriver transport is confined to the sides. The pathways for TE7 show transport down the length of the Buffalo Ship Canal, although the lines terminate and restart again about halfway down due to a significant source of sand that is stored on the west bank of the channel. Most of the pathways in TEs 6 and 7 show total deposition (type 1), with the exception of the river-dominated shoreline sediments that appear to be often in dynamic equilibrium.

INTERPRETATION AND DISCUSSION

Dynamic Behavior

In keeping with a perceived understanding that the Buffalo River is primarily a depositional sink that requires periodic dredging (Singer *et al.,* 1995), the dynamic behavior of the sediments as derived in both STAs is predominantly depositional. All the trends from data set 1 produced total deposition (type 1) dynamic behavior. In the more detailed analysis of data set 2, 55% of the lines were total deposition (type 1) and 18% were net accretion. The remaining lines (27%) were in dynamic equilibrium or mixed case. No erosional trends were observed. In general, the upper reaches (TEs 1 and 2) produced the most trends in net accretion (Figure 7). This is likely the result of two factors: first, sediment is coarsest in the upriver stretches and somewhat less cohesive than the sediments associated with the lower river where muddier sediment and total deposition (type 1) tend to prevail; and second, the dredged channel begins in the middle of Mobil Reach. At this location, the bottom of the river drops from a meter or two deep to nearly 8 m, resulting in a natural trap for rapid deposition.

Total deposition (type 1) dominates the rest of the river with the exception of the trends in Cargill's Reach, where there are a number of pathways in dynamic equilibrium and mixed case (TE4, Figure 8). Other sample lines showing dynamic equilibrium tend to be concentrated in the outflowing river regime along the banks of TEs 5 and 6 (Figures 8 and 9).

Sediment Sources

The results of the two STAs (1990 and 2004) are remarkable both for their consistency and complexity. On initial consideration, the physical setting of a river flowing into an open lake might be expected to show a simple transport regime of downriver sediment movement, perhaps with several transport environments as a result of new sediment sources or local changes in the hydrodynamic flow conditions. Instead, both data sets clearly defined upriver sediment transport from Lake Erie to the vicinity of Cargill's Reach, a distance of about 5 km.

The initial source for sediments in the Buffalo River regime is clearly the incoming river itself at the upper end of the sampled area, with a relatively small contribution from Cazenovia Creek. There appears to be a new sediment source available to the river regime between TEs 2 and 3 (Figure 7) where the pathways end and begin again, forming the boundary between the two environments. Here there is evidence for a coarser source entering the river and, in the absence of a tributary, it may be related to dredging activities and sidewall slumping, which is in evidence from the side-scan sonar surveys described in SINGER *et al.* (1995). Apart from the upriver transport regime originating in Lake Erie, the river is apparently devoid of additional significant sources throughout the length of the sampled area. Despite the presence of 23 combined sewer outfalls (CSO), only one or two can be identified with small but separate sedimentological signatures.

At least one significant question that is not clearly resolved by the trends concerns the ultimate source of the sediment in the Lake Erie transport regime. Are the sediments derived from outside the Buffalo River altogether (*i.e.,* is the lake the sediment source?); or do Buffalo River sediments, in escaping to the lake, return to be transported back upriver? Had sampling been extended farther into the lake the answers to these questions might have been resolved. On the basis of the observations of the river behavior during the collection of data set 2 and during the extreme event of September 9, 2004 (Figure 3), it appears more likely that the sediments of both the upriver and downriver regimes have their ultimate source from the Buffalo River. There are, for example, no textural differences in the sediments between the two regimes; the mud distributions are more or less identical throughout the length of the river. It is reasonable to suppose that the textural properties of sediments unique to the lake would produce a more identifiable contrast with sediments associated with the river (*i.e.,* a totally different source). However, it seems likely that very little river-dominated sediment transport or significant deposition occurs during "ordinary" conditions. The mean daily discharge for the river is about 17 ± 32 m^3/s (Table 1). In a typical cross-section of river (90 m wide by 8 m deep), this amounts to a velocity of about 2.4 cm/s. At such flows current in the river is barely perceptible. On the other hand, as observations made on the September 9, 2004, extreme event (Figure 3) demonstrated, considerable amounts of sediment can be discharged into Lake Erie. Sediment plume studies reported (NAPIERALSKI, FRASER, and INAMDAR [2001]) indicate that levels of turbidity in the Buffalo River are relatively high during the beginning of storm events and gradually decrease as the storm dissipates, with much of the sediment settling outside the mouth of the river. It is this sediment that is occasionally carried to the river mouth by extreme events and that is then available for return transport back up the river to as far as Cargill's Reach.

Processes

It must be emphasized that in carrying out STA the actual processes responsible for the transport of particles along the derived pathways are unknown. They might in one environment be breaking waves in a littoral drift system; in another, the residual tidal currents; and in still another, the incorporated effects of bioturbation. Nevertheless, one of the great values in obtaining the transport patterns is to assess the probable processes that are likely taking place to achieve such patterns. Although it is beyond the scope of this analysis to determine the magnitude of river discharge necessary to constitute a significant sediment transport or depositional event, some idea was obtained from the flow statistics generated from nine years of records (1995 to 2003). These data (more fully shown and described in SINGER *et al.*, 2006) reveal that discharges greater than 1 SD above the mean of 17 m^3/s occur only 7% of the time. For 93% of the year it is unlikely that there is much river activity associated with significant sediment transport. Furthermore, it is quite possible that 1 SD or even 2 SD above mean flow would still not constitute a significant event. Discharges above 2 SD representing a current of about 12 cm/s occur on average for only about 4% of the year. In comparison, the September 9, 2004 extreme event achieved a discharge of 534 m^3/s (or 16 SD above the mean), but such events are evidently rare, with only one similar episode taking place in the nine years of studied hydrograph data.

From the above, it is evident that significant sediment transport and deposition caused by Buffalo River flow occur only rarely, but when they do, the river is then able to "load" sediment onto the bottom of Lake Erie in the vicinity of its mouth. The only possible or probable mechanism to reverse the transport of sediment from the mouth back up the river lies in the activity of seiches.

Utilizing hourly lake level data for the same nine years describing river discharge, a count was made of every apparent seiche event. The latter was defined when the lake level at Buffalo rose 0.6 m or more in the course of two to three hours. For example, Figure 4 shows about five such events for October 1995. Again, it is beyond the scope of this study to assess the water level change that must take place to resuspend and drive sediment upstream against the natural flow of the Buffalo River. However, a sudden rise of 0.6 m or more produces a dramatic and easily readable change in the hydrograph; given the small gradient of the lower reaches of the Buffalo River, it seems likely that a rapid rise of this magnitude, or more, would at least have some effect in moving water and sediment upriver.

Given that the lower river shows predominantly upstream transport in the main channel it would be reasonable to suggest that seiche events must occur with greater frequency than river events. In the nine-year period examined for river flow, there were a total of 236 seiches, which was almost equal to the number of daily discharge events greater than 1 SD above the mean. However, flow events greater than two SD above mean occur only half as many times as seiche events. It is likely that such discharges are still far from the flow required to result in significant sediment transport in the river. The comparison between river flow events and seiches very clearly demonstrates that only occasionally does the river achieve flows that are sufficient to transport sediment all the way to Lake Erie, but seiches, which are far more common, are almost continuously redistributing the sediment back up the river. In addition, the dredged channel would help to focus the incoming seiche in a manner not unlike a tidal wave entering an estuary, increasing in amplitude as the flow of large amounts of lake water is restricted by the channel sides. Downstream river flow is apparently pushed to the riverbanks as in TEs 4, 5, and 6 (Figures 8 and 9) and the incoming sediment within the main channel can get caught up in this reverse flow. As the seiche weakens in its upstream progression, the converse occurs, its flow becoming pushed to the sides until the river becomes dominant altogether (above TE4; Figure 8).

The analogy to estuaries may also be applicable to the mechanism by which mud is transported upriver. In estuaries, a division in transport direction between mud and sand deposits can occur where tidal currents are frequently characterized by a short-duration, fast-flowing flood, followed by a slower, longer-duration ebb. This asymmetry of the tidal currents provides the mechanism to transport mud upstream. Fine sediments are carried in suspension on the flood with deposition occurring at high water slack. Given the cohesive nature of mud, the ordinarily weaker ebb regime is unable to resuspend and return the sediments seaward as easily as the stronger flood currents. In this way there is a continual tidal pumping of mud in the landward direction (Postma, 1967).

Elements of this process could well be occurring in the Buffalo River with the seiche producing a short, sharp burst of upriver transport that, when it becomes balanced by the opposing river current, results in rapid sedimentation. In any one seiche event, the point at which slack water occurs is likely to be variable depending on the amplitude of the seiche and the synchronous level of river discharge. Once the seiche event is finished and the river returns to a more "normal" downriver flow rate, it is insufficient to resuspend the newly deposited mud.

Dredging Impacts

In the above discussion of the transport pathways and their dynamic behavior, it is important to recognize that the derived interpretations are very likely the result of the maintenance dredging to maintain a navigation depth of about 7.6 m. The present dredged channel runs as far as Mobil Reach, which, in this area, receives the greatest proportion of incoming sediment. Downstream of the mid-point of TE3 (Figure 8), deposition rates decrease rapidly (U.S. Army Corps of Engineers, Buffalo District, personal communication). The maintenance dredging, therefore, ensures the continuance of deposition, both by increasing the depth and lowering water velocities at the Mobil Reach end of the river, and by maintaining a preferred channel through which seiche-generated transport can propagate. Because of the influence of the seiche, sediment is in a constant state of recycling, downstream at times of extreme river events, followed by seiche-driven upriver transport and deposition. Undoubtedly, the recycling is not 100% and some sediment transported downstream by extreme river events is irretrievably lost to Lake Erie and the Niagara River; but deposition in the river dominates and eventually, should dredging cease, it would likely fill to some equilibrium depth, probably in the order of a meter or two. In the absence of a dredged channel the effects of seiche transport and deposition would likely be reduced and the dynamic behavior of the sediments possibly quite different.

EVIDENCE FOR STA INTERPRETATION

Independent verification of our interpretation of sediment transport pathways and processes operating within the Buffalo River are provided by side-scan sonar surveys and from three-dimensional hydrodynamic modeling. Several side-scan sonar surveys of the river were conducted in the 1990s and again in 2004–05 and interpretations are provided in Singer *et al.* (1995, 2006). The sonar records revealed the presence of sedimentary furrows in Cargill's Reach, which were not only shown to be persistent through time, but their re-formation was rapid following their destruction by dredging activities (Monninger, 1998; Singer *et al.,* 1995).

The furrows ranged in depth from 1.5 to 2.25 m with a spacing of 4 to 5 m. These dimensions corresponded to type 1A furrows (Flood, 1983; Manley and Singer, 2007) that indicate erosion rates equal to or greater than depositional rates. The presence of this type of furrow suggested that this part of the river can be an area of active sediment erosion, and that furrow formation may result in the resuspension of sediment into the water column. Of particular interest with respect to the results of the two STAs was the observation that many of the furrows displayed joining patterns, creating the "tuning fork" morphology as described by Flood (1983) and Allen (1982). Similar to furrows observed for marine tidal environments, some of the furrow junctions opened in both the upriver and downriver directions, suggesting that a bidirectional water flow in Cargill's Reach can occur. As the STA results also showed, Cargill's Reach is the one stretch of river that would appear to be most susceptible to bidirectional flow given that it is the meeting area of upriver sediment transport trends from Lake Erie and the downriver sediment transport regime of the Buffalo River (Figures 6 and 8).

Over the past several decades, a variety of one- and two-dimensional numerical modeling studies focused on sediment and contaminant transport in the Buffalo River (*e.g.,* Atkinson *et al.,* 1994; DePinto *et al.,* 1995; Gailani *et al.,* 1994; Irvine, Pratt, and Marshall, 1993; Meredith and Rumer, 1987; Wen, Jirka, and Raggio, 1993). None of these models considered changes in the Lake Erie water levels as a possible driving mechanism for either sediment or contaminants in the river.

The first three-dimensional hydrodynamic model for the Buffalo River that demonstrated a significant degree of corroboration with the STA results was reported by Atkinson and Fraser in Singer *et al.* (2006). The Atkinson model was further developed so that model runs included the influence of lake seiches under low and high river flow conditions. For a low base flow of 2 cm/s combined with a seiche of 0.4 m amplitude and a period of 16 hours, a mix of both upstream and downstream transport was observed, with upstream transport in the central part of the channel and downstream movement closer to the shore. Furthermore, upstream movement could be discerned as far as Cargill's Reach.

The STA, side-scan sonar surveys, and hydrodynamic modeling were performed independently, with the ultimate goal of demonstrating the importance of combining geological and engineering approaches to achieve greater confidence in the interpretation of the individual results that were derived from each. The comparisons are more fully described in SINGER *et al.* (2007).

RELATIONSHIP BETWEEN STA AND CONTAMINANT LEVELS

With the confidence in our STA results provided by the mutually supporting evidence found in the side-scan sonar surveys and the application of hydrodynamic modeling, we now can consider the relationship between river dynamics and contaminant levels as well as implications for sediment remediation. The relationship between contaminant levels contained in sediments with the texture and stability of the sediments themselves is now known to be highly complex and is the subject of considerable research (*e.g.,* APITZ *et al.*, 2005). Site-specific conditions may result, for example, in a uniform distribution of contaminants throughout the particle size range of their associated sediments. In other instances, the distribution of contaminants may show bimodality with modes associated both with fine and coarse sediment fractions. It has, however, long been recognized that many contaminants tend to associate preferentially with the finer sediment fractions as opposed to the coarser sizes, and that pollutants tend to follow the same transport pathways of sedimentary material, tending to be transported to depositional sinks regardless of the exact source of the contamination (YOUNG *et al.,* 1985).

In the context of STA, and on the basis of the assumption that contaminants will preferentially follow net sediment transport pathways, MCLAREN and LITTLE (1987) predicted the accumulation and dispersal of hydrocarbons and heavy metals throughout a small estuary in southwest Wales. It was found that the relationship between the predicted concentrations in different portions of the estuary with actual measured concentrations produced a highly significant correlation (Spearman's rank correlation coefficient of 0.98 where 1.0 indicates complete agreement between the expected order of contaminant concentrations with the observed order of concentrations). Since this finding, the empirically derived relationships between contaminant levels contained in sediments and the results of STA have both improved and been supported in several studies (e.g., MCLAREN, CRETNEY, and POWYS, 1993; PASCOE, MCLAREN, and SOLDATE, 2002). These relationships, on the basis of all the assumptions made in carrying out STA, are summarized in Table 3.

Applying these relationships, it is instructive to consider the probable behavior of contaminated particles in the absence of all local contaminant sources. Assume there is a source of contaminated particles entering the Buffalo River at its upstream end. The first environment encountered is TE2 (Figure 7) where the trends indicate that net accretion is occurring. This dynamic behavior continues about halfway into TE3, with the result that contaminated particles should become increasingly concentrated in the downstream direction. The downriver half of TE3 is characterized by total deposition (type 1) behavior (Figure 8), with the result that contaminated particles can expect to be deposited as "hot spots", remaining in place unless disturbed by dredging, or an extreme river event mobilizes the sediment.

It is probable that many of the contaminated particles will become trapped in the total depositional area that characterizes the downriver half of TE3. Because of this, it could be expected that further contaminant levels found in the environments downriver of TE3 would become relatively depleted. The next environment (TE4; Figure 8) is at the meeting point of the downriver and upriver transport regimes. It contains a mix of dynamic behaviors and the presence of furrows indicates at least occasional erosive conditions. Contaminated particles deposited in such an environment are unlikely to remain long, and will eventually be moved farther downstream into TEs 5 and 6 (Figure 8). At this point the predicted behavior is unlikely to be quite as simple as that described in Table 3. On the basis of the above discussion of the processes that appear to be operating in the Buffalo River, any contaminated particles still available for deposition will be moved preferentially downriver along the banks, possibly all the way to the mouth, only to return back upriver, this time principally in the channel, as far as Cargill's Reach (TE4; Figure 8). Many of the trends along the banks are in dynamic equilibrium, so downriver movement of contaminated particles could be expected. However, the return transport is entirely in total deposition (type 1) dynamic behavior where the formation of hot spots will be favored (Table 3).

The difference in the Buffalo River when compared with most environments of total deposition (type 1) is that the sites of possible hot spots will not remain constant. On the basis of many STAs in harbors and estuaries, it has been found that the favored location for a hot spot to form is in an area of total deposition where two opposing transport regimes meet. Such a location is in Cargill's Reach, but despite the meeting point of two opposing regimes, the dynamic behavior in this region suggests that a hot spot could not remain stable for long. Downriver of Cargill's Reach, deposition of the potential hot spot will vary down the length of the river depending on the amplitude of the seiche event and the discharge of the river. In other words, depositional hot spot formation can occur randomly from the river mouth, all the way up channel to Cargill's Reach. Such a process will have the effect of "smearing" a hot spot throughout the length of the channel. It could, therefore, be expected that contaminant levels in the sediments associated with the upriver transport regime will show little variability throughout TEs 5 and 6 (Figure 9). The exception to this concept would be in the Buffalo Ship Canal where there is no opposing river regime, and incoming sediments are deposited and remain immobilized regardless of extreme events associated with the river.

Compared with the upriver contaminant levels that might be found in the lower half of TE3, the possible levels in TEs 4, 5, and 6 would likely be much reduced. Not only would TE3 likely have removed many of the contaminants, but the remaining particles still in the river have the potential of

Table 5. *Heavy metal data (parts per million [ppm]) from Engineering and Environment (1996). Sample locations shown on Figures 10, 12, and 14.*

Location	Sample	Arsenic	Chromium	Copper	Lead	Nickel
Figure 10	34	4.4	12	22	19	20
	48	6.3	19	30	27	30
	49	7.4	18	30	25	31
Figure 12	31	8.1	22	35	43	28
	51	6.2	17	34	38	27
Figures 12 and 14	50	7.4	19	33	28	32
	53	6.3	19	31	36	30
	52	7.7	22	38.5	39	34
	54	6.4	20	34	36	31
	29	8.3	24	41	35	39
	56	7.3	22	39	37	35
	27	6.4	21	36	37	31
Figure 14	55	8.1	34	55	54	42

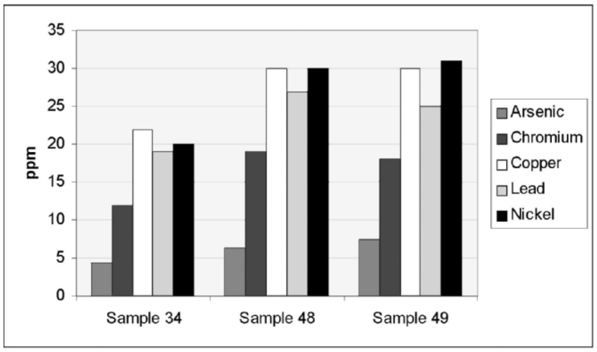

Figure 11. Heavy metal concentrations showing a general downriver increase in an environment of net accretion (see Figure 10).

being diluted because of the likelihood of at least some mixing with less contaminated lake sediments before being transported upriver again.

In reality, more contaminant sources other than what may be entering the system at its upstream end must be considered. Not only is there a legacy of nearshore contaminant hot spots derived from past industrial activities such as Mobil Oil, PVS Chemicals, and Buffalo Color, but CSOs are present throughout the length of the study area, with a particularly high concentration along the lower stretches of the river (in TE6; Figure 9). In an attempt to illustrate contaminant behavior as described in the above conceptual model, a data set from ENGINEERING AND ENVIRONMENT (1996) has been selected (Table 5). These data, although few in number, are reasonably equally spaced and from the main channel. There are other reports that also contain contaminant data but nearly all are derived from surface samples or cores taken very close to the shoreline at sites associated with known contaminant sources. As a result, they are greatly influenced by large and variable local inputs. Their locations were also sporadic and no consistent correlations with STA could be established.

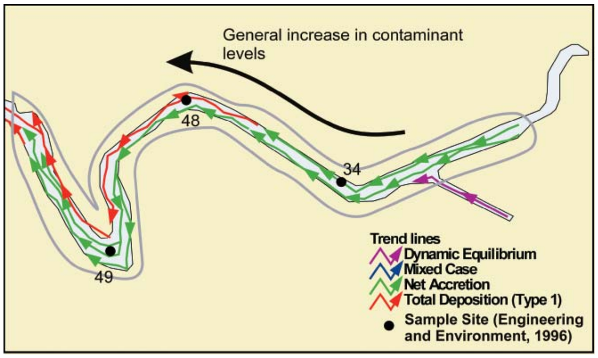

Figure 10. Probable behavior of contaminant levels in the upper river. Trends in this portion of the river are mainly in net accretion, resulting in increasing concentration in the downstream direction.

Again, progressing from the upriver end of the sampled area, the first environment encountered (TE2; Figure 7) is predominantly in net accretion, a dynamic behavior that continues halfway into TE3 (Figure 8). Given that this stretch of river is entirely river dominated and seiches have little or no influence this far upstream, an increase in contaminant levels would be expected. Although based on only three midchannel samples (Figure 10), the data do show this expected increase (Figure 11).

Only two samples are available in the lower half of TE3 where total deposition (type 1) is occurring (Figure 12). Contaminated particles that are transported into this area are likely to accumulate and higher levels than found in the proceeding environment of net accretion are both observed and expected (Figure 13).

The remaining TEs downriver from TE3 are all subject to the generation of a more or less continuous hot spot as a

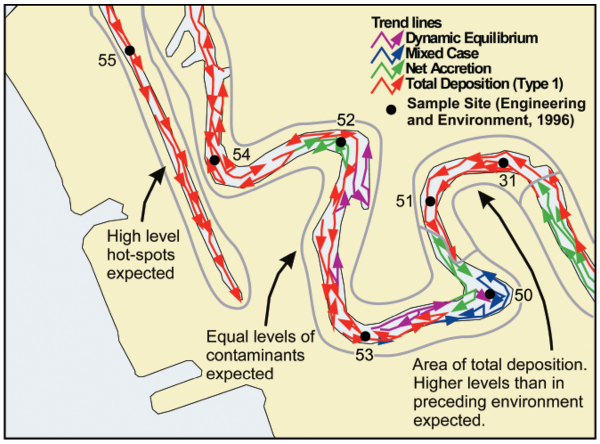

Figure 12. Probable behavior of contaminant levels in the middle river.

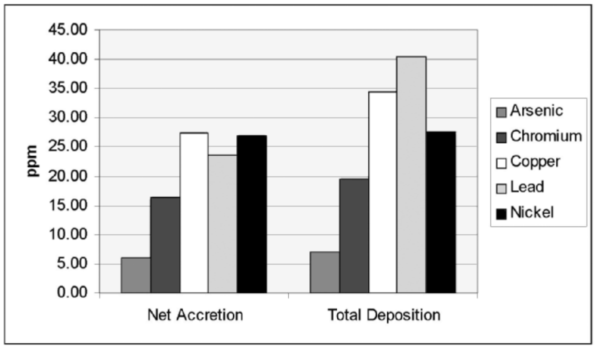

Figure 13. Mean contaminant levels in the zones of net accretion and total deposition of TEs 2 and 3. Note nearly all values are higher in the environment of total deposition (type 1).

result of the interaction between seiche and river processes as described above. Although local sources may generate high levels of contaminants, sediments within the channel should show little change in their levels regardless of their location. This appears to match closely the Engineering and Environment (1996) data set (Figures 14 and 15; Table 5), where it can be seen that samples along the length of the channel show very little variability in their concentration (Figure 15). Included is one sample (sample 55) from the Buffalo Ship Canal that, as expected, contains significantly higher levels than those found in the main river channel. As discussed above, the Buffalo Ship Canal is removed from the interaction of the seiche and river transport regimes, and long-term hot spots with high concentrations are able to develop.

IMPLICATIONS FOR ENVIRONMENTAL MONITORING, REMEDIAL OPTIONS, AND CONSEQUENCES

TEs 1, 2, and 3

An examination of the sediment transport pathways as derived from the STA (Figures 7–9) suggests that the river can be divided into three distinct sedimentological regimes. The first encompasses TEs 1, 2, and 3, all of which contain sediment derived principally from the inflowing Buffalo River and its tributaries. The direction of sediment transport is downstream and the dynamic behavior of the sediments tends to grade from net accretion in TE1 to total deposition (type 1) in the lower half of TE3. This portion of the river receives the highest rates of deposition as the inflowing river rapidly decreases its flow rate as it encounters the start of the deepened dredged navigational channel.

Contaminated particles entering the upstream end of the sampled area may adsorb onto the sediments and become increasingly concentrated in the downstream direction. Where total deposition (type 1) behavior dominates in the lower half of TE3, hot spots with relatively high contaminant concentrations can be expected. It is this region of the river that may well be a depositional sink for many of the contaminants associated with watershed and industrial activities that have taken place along the banks of TEs 1, 2, and 3. Only in extreme river flow events could sediment become resuspended and carried into the transport environments downstream of TE3.

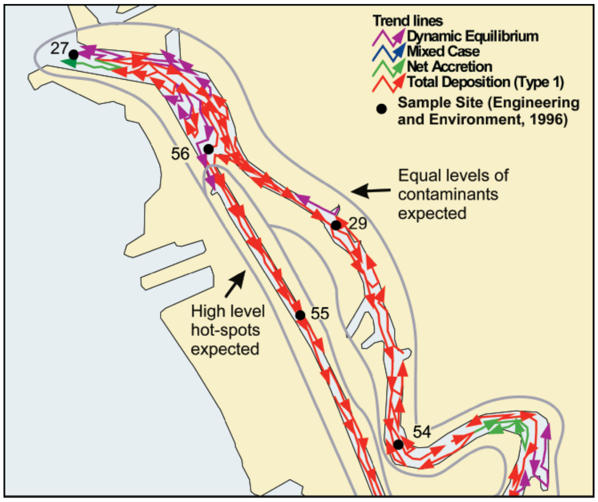

Figure 14. Probable behavior of contaminant levels in the Lower River.

The lower half of TE3 (Figure 8) is, therefore, an ideal place to remove contaminants from the river system, provided further input of contaminants from the hinterland and localized industrial sources have been adequately reduced or eliminated. Contaminated material can be safely dredged and normal sediment processes will ensure further deposition in the resulting voids without consequence to the present behavior of the river. Furthermore, the lower half of TE3 is also a logical location for contaminant monitoring. Repeat sampling to measure contaminant levels in this area would provide the best information on the efficacy of source control programs,

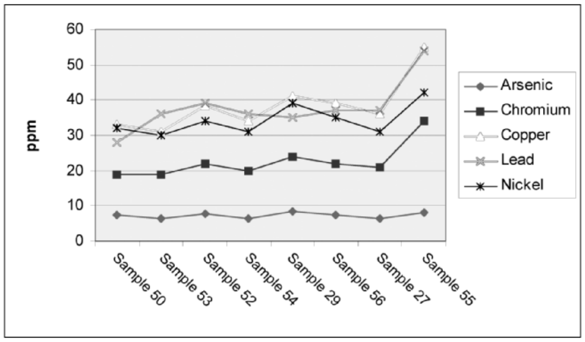

Figure 15. Contaminant levels down the main channel of the lower Buffalo River. Samples are ordered from upriver to downriver and are located in Figures 12–14. Sample 55 is in the Buffalo Ship Canal and shows, as expected, an increase in concentrations.

both from the watershed and from the local industrial sites and CSOs found on the banks of Mobil Reach.

TEs 4, 5, and 6

Downstream of TE3, the remaining TEs 4, 5, and 6 are comprised of sediment, ultimately derived from the inflowing Buffalo River, but which are now in a state of downstream and upstream recycling as a consequence of seiche activity. Extreme river events transport sediment downstream to Lake Erie, undoubtedly with some loss of sediments to the Niagara River, whereas seiches result in an upriver return of sediment as far as Cargill's Reach. Contaminants from the watershed or the Mobil Reach area that escape deposition in the lower half of TE3 are then available for deposition in the rest of the river, together with any new contaminants that may have entered the river through CSOs and from formerly active industries that line the banks of the lower reaches of the river.

As discussed above, this "recycling" of sediment between Lake Erie and Cargill's Reach has served to distribute particle-associated contaminants more or less equally throughout the whole stretch of the river. Although nearly all the trends indicated total deposition (type 1) where stable hot spots are to be expected (Table 3), the unique interplay between river and seiche processes throughout these lower reaches appears to have resulted in one long, more or less, continuous hot spot. Deposition rates in this part of the river are quite low, the result of much of the available sediment having already been deposited in TEs 1, 2, and 3. Thus dredging requirements are infrequent. Sediment removed by dredging will be replaced by sediment in the downriver–upriver recycling transport regime. It is probable that large amounts of contaminants emplaced into the river before source control measures are still in a state of recycling within the lower reaches of the river. With the combined efforts of source control programs, dredging, and the occasional losses of sediment to Lake Erie, it could be expected that contaminant levels in newly deposited sediments will inevitably slowly decrease. Increasing the rates of sediment removal by dredging would clearly have the effect of lowering contaminant levels at a faster rate as more and more of the sediment in the lower reaches is replaced or diluted by less contaminated particles.

It should be noted that not all contaminant levels in the sediments of the lower river are more or less equally distributed. Exceptions occur in samples taken both close to the riverbanks and close to industrial sources where contaminant data show widely variable levels due to large and localized inputs (see for example Atkinson *et al.,* 1994). Such hot spots can be viewed as probable long-term sources that have the potential to contribute further contaminants into the sediment-recycling regime. Their removal by dredging should be an effective way to decrease more rapidly the overall contaminant levels found in the lower river as a whole.

On the basis of the above concepts, future sediment/contaminant monitoring could be undertaken on a sequence of samples (perhaps 6 to 10 samples) taken equally spaced in the main river channel from Lake Erie to Cargill's Reach. In addition, monitoring could be undertaken at several of the known isolated hot spots found on the riverbanks at regular intervals after remedial dredging. In this way the progress of the combined effects of regular routine dredging, removal of hot spots, and the dilution of sediments with increasingly less-contaminated particles could be properly documented and charted.

TE7

The Buffalo Ship Canal appears to be a sediment and contaminant sink that does not share the benefit of the natural self-cleaning associated with the slow but continuous dilution and recycling of the sediments found in the main river. Like the lower half of TE3 as discussed above, the trends are all total deposition (type 1) and hot spots found in the canal are effectively removed from further transport and are unlikely to provide a further source for contamination elsewhere. Their removal is likely an effective option, provided that sediments from the outside that will inevitably replace the losses are sufficiently contaminant-free to ensure a worthwhile effort. A sequence of three or four samples down the length of the canal would likely be sufficient to establish a suitable monitoring program.

SUMMARY AND CONCLUSIONS

Two STAs were carried out on the Buffalo River AoC in 1990 and 2004 on 145 and 495 samples respectively. In addition, two further data sets (22 samples, September 13, 2004 from Cargill's Reach; and nine samples, September 25, 2004 from Mobil Reach) were collected after an extreme river flow event (caused by the remnants of Hurricane Francis) that occurred on September 9, 2004. About 90% of all the sediments collected consisted of unimodal mud. Coarser sediments containing sand and gravel were found principally in the upper reaches of the sampled region above the end of the dredged navigation channel. A comparison of the textural properties among the four sample data sets showed no significant change in the particle size distributions of the sediment during the 14-year period between 1990 and 2004. In the upper reaches of the sampled area, coarsening of the sediment occurred in Cargill's and Mobil reaches after the extreme flow event of September 9, 2004. The change, however, appeared to be very short-lived, with the September 25 samples showing a return to "normal" textures only 16 days after the event (Table 4). These data suggest that sediment sources and dynamic processes that are presently occurring in the Buffalo River are remarkably stable, showing only temporary disruptions caused by extreme events.

The two STAs produced remarkably similar results, and the findings provided the basis for dividing the river into seven transport environments (TEs 1 to 6 progressing from the upriver end of the AoC to the mouth at Lake Erie and TE7 including the Buffalo Ship Canal) defined by transport direction, sources, and dynamic behavior. Two distinct regimes were identified: downriver transport dominates the upper river in TEs 1, 2, and 3; and upriver transport occurs in the lower river (TEs 5, 6, and 7). The zone of mixing takes place primarily in Cargill's Reach (TE4), an area characterized by the presence of significant bedform features (furrows) exhibiting features indicative of bidirectional flow.

The upriver transport regime for the lower 5 km of river is explained by seiche activity with associated rapid rises in the Lake Erie water level. An examination of nine years of lake level and Buffalo River discharge data shows that rapid lake level rises of more than 0.6 m occur approximately at twice the frequency of river discharge events greater than 2 SD above mean daily river flow. It is suggested that a seiche-driven "wave" entering the mouth of the Buffalo River may be analogous to a tidal wave in an estuary. In such circumstances a short, sharp flood (or upriver) event is capable of suspending mud and carrying it upriver. At the point where opposing downriver and upriver currents balance each other (*i.e.,* where a null velocity is reached), deposition can be expected. Given the cohesive nature of mud, the generally slower river velocities are unable to return the sediment back toward the lake. Because the location where a null velocity might occur is dependent on both the size of the seiche event and simultaneous discharge of the river, there is no preferred area of deposition; rather, a depositional event may occur at more or less random locations from the mouth of the river to as far as Cargill's Reach.

For much of the time (at least 93%) Buffalo River discharge is likely to be too low to supply sediment input or initiate sediment transport in any significant amounts; however, with extreme rainfall events producing both high sediment yields and river discharge, downriver transport of sediment occurs throughout the length of the AoC and into Lake Erie. In such events, some sediment is likely removed from the river system altogether by the Niagara River; however, much of the sediment may be deposited in the immediate vicinity of the river mouth. It is this sediment that has been deposited from the Buffalo River discharge during extreme events that returns in the seiche-driven upriver transport.

Existing contaminant data from sediments taken down the central channel of the Buffalo River show levels that conform very well to their expected behavior on the basis of the transport dynamics of the sediments. Levels increase as expected down TEs 1 and 2; there are higher levels in the lower half of TE3, and levels are more or less everywhere the same in the portion of the river subject to seiche transport and deposition. The highest levels of all are found in the Buffalo Ship Canal (TE7).

On the basis of the conceptual model provided by STA, the lower half of TE3 would be an ideal place to remove contaminated sediments and to carry out future monitoring programs. The latter would determine the efficacy of hinterland contaminant source control programs. From Cargill's Reach to Lake Erie, the sediments are in a constant state of recycling through the combined action of extreme river discharge events and seiche activity. Contaminants enter this system from both upriver and shoreline sources. The latter have produced widely varying levels of contaminants and frequent hot spots close to shore. Such hot spots likely provide a long-term source for further redistribution and deposition of contaminants throughout TEs 5, 6, and 7. Their removal should have the effect of producing a long-term decline in contaminant levels throughout TEs 4, 5, 6, and 7. It is suggested that a monitoring program could consist of regularly spaced samples down the length of the river as well as on known hot spots associated with the shoreline. In the Buffalo Ship Canal contaminant hot spots can be effectively removed, and levels should decrease as remedial efforts in the rest of the river are successfully undertaken.

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