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The shortcomings of "passive" urban river restoration after low-head dam removal, Ottawa River (northwestern Ohio, USA): What the sedimentary record can teach us

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ABSTRACT

The concept of "passive" river restoration after dam removal is to allow the river to restore itself, within constraints such as localized bank erosion defense where infrastructure or property boundaries are at risk. This restoration strategy encounters difficulties in an urban environment where virtually the entire stream corridor is spatially constrained, and stream-bank protection is widely required. This raises the question of the meaning of river restoration in urbanized settings. In such cases, the sedimentary record can document paleohydrologic or paleogeomorphic evolution of the river system to better understand long-term response to the removal of the dam. Secor Dam was a low-head weir on the Ottawa River flowing through the City of Toledo, Ohio, and its outlying suburbs. The dam was constructed in 1928 and removed in 2007 to enhance aquatic ecosystems, improve water quality, and avoid liability concerns. Predam removal feasibility studies predicted the hydrological and sedimentological responses for the dam removal and determined that reservoir sediments were not significantly contaminated. Postdam removal studies included trenching, sediment coring, geochronology, and surveying. The buried, pre-1928 channel was located and showed that watershed urbanization resulted in channel armoring. Incision in the former reservoir exhumed a woody peat layer that was subsequently shown to be a presettlement hydromorphic paleosol currently buried beneath 1.7 m of legacy sediments, mostly deposited since ca. 1959. Today, the river flows through an incised channel between fill terraces composed of legacy sediments. Additional coring and survey work documented that the channel lateral migration rates averaged 0.32 m/yr over the past ~80 yr, and that the meander wavelength is increasing in response to dam removal. Using sediment budget concepts, significant channel

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bank erosion and lateral channel migration should be expected until this river system reworks and removes accumulated legacy sediments currently in floodplain storage. In this dam removal project, "active" restoration practices, such as riparian wetland restoration, would have been more in accord with scientific understandings. That did not happen in this case because of disagreements among different constituencies and because of limitations of funding mechanisms.

INTRODUCTION

Dams have been removed, or proposed for removal, for a variety of reasons, including public safety, liability issues, ecosystem restoration, recreation enhancements, and aesthetics (Evans et al., 2000a; Bednarek, 2001; Heinz Center, 2002; Doyle et al., 2003). The recognition that dam removals are tools, among other tools, in the overall goal of river restoration has been slower to emerge, and it represents a focus of this paper. Important steps in this growing understanding have included distinguishing between short-term and long-term fluvial response to dam removal (Simons and Simons, 1991; Evans et al., 2000b; Pizzuto, 2002; Doyle et al., 2002, 2003; Evans, 2007) and distinguishing between passive and active management practices for reestablishment of equilibrium channel forms, called "late successional channels" by Selle et al. (2007). In the latter context, passive management practices are characterized by allowing the channel to evolve from early successional, headcut-driven form to an anticipated late successional form utilizing little, if any, intervention (Selle et al., 2007). Active management practices, in contrast, attempt to accelerate channel development and guide it toward an anticipated late successional channel form (Selle et al., 2007).

The concept of "river restoration" presupposes both that some criterion or set of criteria about the existing conditions in the river is unsuitable, and that some change or series of changes is feasible that can ameliorate those unsuitable criteria. There are many unspoken assumptions in this attempted definition; for example, feasible changes might be interpreted by some as economically and socially feasible (which might focus on short-term results), while others might interpret feasible to mean self-sustaining (with a long-term emphasis, and possibly with significantly greater economic cost). This is not merely an exercise in semantics because river restorations are societal decisions with trade-offs (Thornton, 2003) where public perception is an important component, most especially in the case of an urban river restoration and dam removal.

This paper is a description of how a passive urban river restoration project, centered around the removal of an obsolete low-head dam, led first to disagreements about restoration strategies, and then ultimately to additional research that documented the magnitude of recent historical change in this particular river. To summarize, this study reaffirms other recent findings that many rivers in the United States are undergoing long-term systemic changes due to human activity, resulting in channel instability (Wolman, 1967; Costa, 1975; Jacobson and Coleman, 1986; Evans et al., 2000c; Walter and Merritts, 2008; Bain et al., 2008; Wilcock, 2008; DeWet et al., 2011). Those involved in urban river restoration efforts need to be cognizant that short-term restoration strategies will have temporary and possibly mixed results, and that long-term strategies should be based on sediment budget concepts. In addition, this particular restoration project was complicated by the absence of a clearly articulated restoration plan at the onset, involvement of multiple agencies with different restoration goals, and an emphasis on short-term strategies driven by requirements of funding sources. None of these issues should detract from the fact that in this project the dam was successfully removed and ecosystem improvements have been observed.

GEOLOGIC AND HYDROLOGIC BACKGROUND

The Ottawa River is located in northwestern Ohio and southeastern Michigan (Fig. 1). The low-gradient, 446 km^2 watershed flows into Maumee Bay at the western edge of Lake Erie (Roberts et al., 2007). The watershed is highly urbanized within its lower reaches up to river kilometer (RK) 18 within the City of Toledo, Ohio (2010 urban population of 287,208 people in an area of 218 km^2 or a population density of 1317 individuals/km^2). Further upstream (RK18 to RK40), the watershed is part of the outlying suburbs surrounding the City of Toledo (2010 greater metropolitan area population of 651,429 people in an area of 4193 km^2 or a population density of 155 individuals/km^2). Upstream of RK40, the watershed is predominantly used for agricultural use (corn and soybean row crops) or for mixed use (pasture, parkland, or sand and gravel quarries) (Gottgens et al., 2004; Roberts et al., 2007; Mannik-Smith Group, Inc., 2008; Gerwin, 2003). For the purpose of this paper, the watershed up to RK40 will be referred to as urban (making no distinction between urban and suburban).

The watershed geology consists of Devonian carbonate bedrock (Coogan, 1996) overlain by multiple late Cenozoic till sheets (Forsyth, 1973), ice-contact sand bodies such as glaciolacustrine deltas (Anderhalt et al., 1984), and lacustrine sediments representing multiple stages in the early history of Lake Erie (Forsyth, 1973; Larson and Schaetzl, 2001). Ottawa River sediments are primarily silt and clay, sourced from the fine-grained tills and glaciolacustrine sediments, but there is also a moderate supply of sand, sourced from glaciolacustrine deltas, postglacial beach ridges, and eolian dune fields.

Hydrologic data are available from U.S. Geological Survey (USGS) gauge station no. 04177000 located at RK17.3 at the University of Toledo campus. There are continuous stage-discharge records between 1945 and 1948 and from 1977

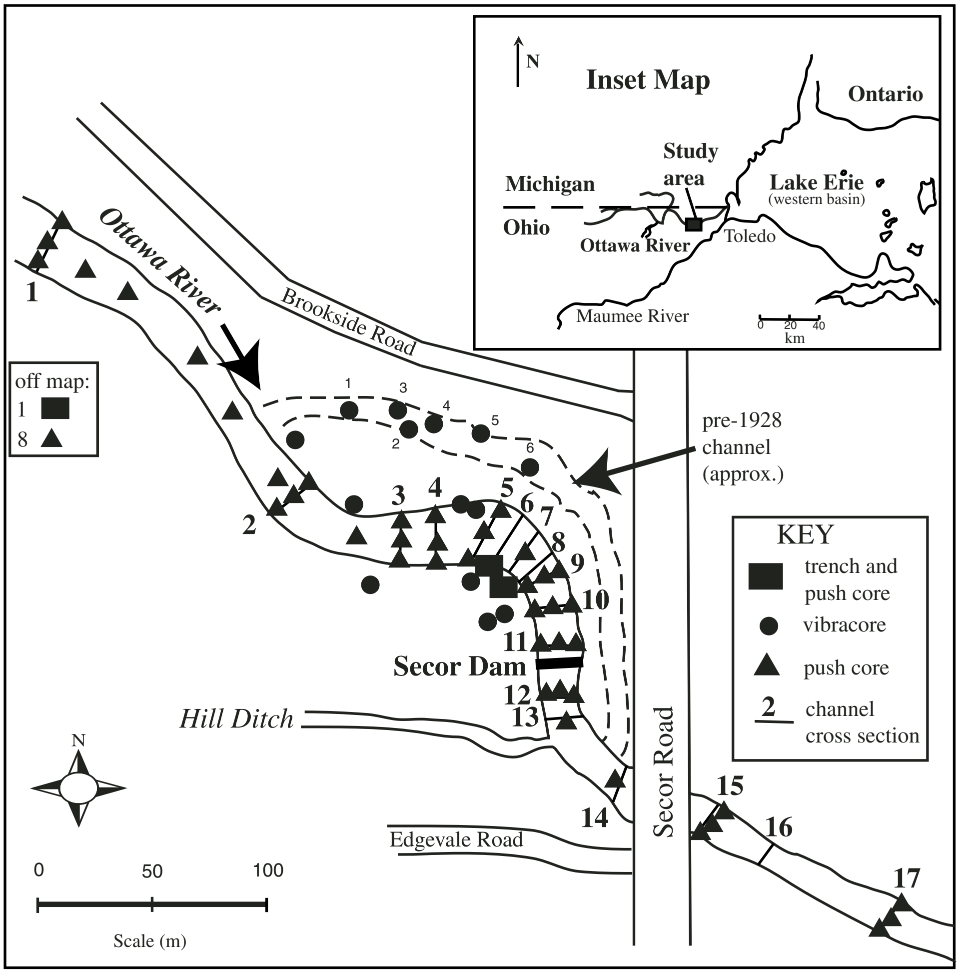

Figure 1. Location map of the study area in northwest Ohio (inset map) and locations of channel cross sections, vibracores, push cores, and trenches. Note the inferred position of the pre-1928 channel (the river was diverted when the Secor Dam was constructed). The trench and cores listed as "off map" are from 500 m upstream.

to present (Fig. 2). The mean daily flow for this interval is 5.3 $m^3 s^{-1}$, and discharges for the 10, 25, 50, and 100 yr floods have been calculated as 91, 127, 170, and 219 $m^3 s^{-1}$, respectively (Harris, 2008). The Ottawa River is characterized by "flashy" discharges with relatively low base flows, high peak stormflows, and very short lags-to-peak (Harris, 2008). Similar behavior in other rivers in the region has been attributed to human activities such as draining wetlands, installing agricultural field tile drains, ditching, or channelizing tributaries (Baker et al., 2004). For the Ottawa River, flashy discharge responses to rainfall events are enhanced by the combination of agricultural impacts in the upper parts of the drainage basin and urbanization of the lower parts of the drainage basin (Webb, 2010).

Previous studies on the Ottawa River have shown a good correspondence between discharge and suspended load (r^2 = 0.87), and estimate that bed-load volumes are 10%–35% of suspended load volumes (Gallagher, 1978). Field bed-load measurements over short intervals of time using a variety of bed-load traps have documented highly variable bed-load transport, ranging from zero to 6.3 kg/h, with a maximum (Q_s) of 7×10^{-7} $m^3 s^{-1}$ (Harris, 2008). Between Lake Erie and approximately RK8, the Ottawa River is an extension of Lake Erie, with slopes approximately zero, and the channel substrate is dominantly silt and clay (Fig. 3). Between approximately RK8 and RK26, the gradient of the Ottawa River is ~0.7 m/km, and the channel substrate consists of moderately sorted, fine- to medium-grained sand that is armored with fine gravel (mostly bivalve shells and anthropogenic materials) and abundant particulate wood debris (Gottgens et al., 2004; Harris, 2008). In the headwaters above RK26, the gradient of the Ottawa River varies from 1 to 6 m/km, and the channel substrates are fine- to medium-grained sand with abundant particulate wood debris.

Within the urbanized portion of the drainage basin, the stream banks are engineered up to approximately RK14. Between approximately RK14 and RK34, the modern Ottawa River channel is incised ~2 m beneath its floodplain surface, creating the appearance of fill terraces (Fig. 4). Because these fill terraces are inundated at regular intervals, and because of other data about the sediment ages, presented in this paper and previously (Evans and Harris, 2008; Webb, 2010), the fill terraces are interpreted as anthropogenic in origin. Within this reach of the Ottawa River, evidence for active vertical and lateral bank erosion includes

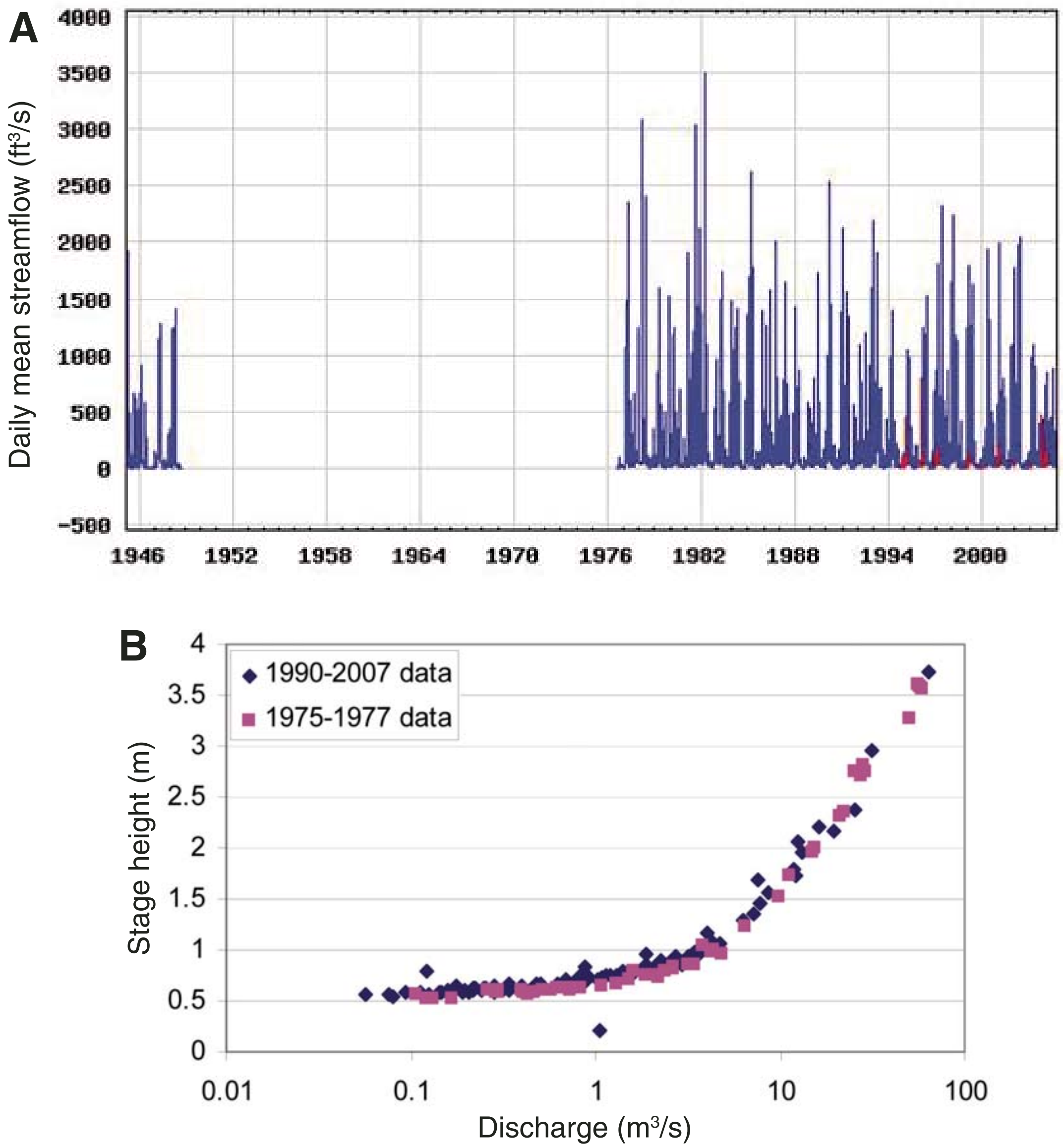

Figure 2. Hydrology data for the Ottawa River. (A) Daily mean streamflow from U.S. Geological Survey gauge station #04177000 between 1945 and 1948 and 1977 and 2006. (B) Rating curve for the gauge station.

undercut banks, rotational slumps, toe-of-slope deposits, small colluvial fans, small-scale soil avalanche or soil-fall deposits, and loss of riparian zone trees through undercutting, tree-lean, and tree-fall into the channel.

The recent land-use history can be summarized as follows. Prior to arrival of European settlers in the early 1700s, this part of northwestern Ohio was ~90% wetlands, wetland forest, and wet prairie known as the "Great Black Swamp." The technology to initiate large-scale drainage modifications did not exist until invention of steam-powered dredgers in the late 1800s (Wilhelm, 1984). By 1879, approximately half of the region had been deforested, and by 1900, almost all of the original forests were gone, thousands of kilometers of drainage ditches had been constructed, and networks of tile drains had been installed in farm fields (Black Swamp Conservancy, 2009). Today, the region retains only ~5% wetlands or wetland forests. The cleared and drained wetlands became highly productive agricultural land, and today the larger watersheds (Maumee River and Sandusky River) are ~85% agricultural land, primarily corn and soybean row crops. Soil erosion from farm fields is a major environmental problem in NW Ohio and adjacent areas; for example, the Maumee River watershed contributes ~1,000,000 m^3 of mostly fine-grained sediment to the City of Toledo harbor each year. Based on this evidence, it can be interpreted that the Ottawa River transitioned from a "blackwater" (organic-rich sediment) stream prior to European settlement to a

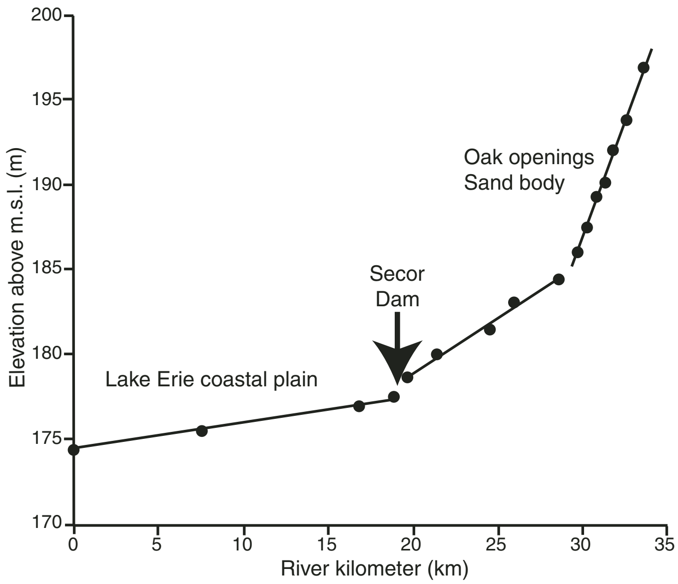

Figure 3. Longitudinal profile for the Ottawa River between Lake Erie (RK0) and the junction with Tenmile Creek and Schreiber Ditch at RK34.5. The Secor Dam was located at RK18.3. m.s.l.—mean sea level.

"brownwater" (mineral-rich sediment) stream as a consequence of land clearance activities.

The Ottawa River watershed differs somewhat from other regional watersheds because its lower portion (below RK40) has been affected by urbanization of the City of Toledo and surrounding suburbs. An analysis by Webb (2010) has shown that the population of outlying suburbs (Village of Ottawa Hills, City of Sylvania, Sylvania Township) increased dramatically in the suburbanization boom that occurred after the end of the Second World War. For example, between 1950 and 1970, the population of the Village of Ottawa Hills increased 86%, the population of the City of Sylvania increased 400%, and the population of Sylvania Township increased 136% (Webb, 2010). Between 1970 and 2000, subsequent population increases have been appreciably less (7%, 56%, and 55%, respectively). These suburban population increases were accompanied by plating and development of new subdivisions; for example, the total number of housing units in the City of Sylvania increased 369% between 1950 and 1970, compared to a subsequent (1970–2000) increase of ~113% (Webb, 2010).

METHODS

Fieldwork involved surveying, sediment coring using various techniques, trenching, bed-load and suspended load sediment sampling, global positioning system (GPS) tracking of bed forms, and specialized sampling for geochronology purposes. Surveying involved pre- and post-dam-removal channel cross sections at 17 locations (Fig. 1), using a Topcon GPT-3003W total station. Differential GPS was used to locate each cross-section pin location with a Trimble Pathfinder Pro® XRS base station unit. The location of each of the cross-section survey pins was established by repeated surveying over a 10 mo period with the Total Station and by direct measurement using differential GPS. The Total Station survey error was ±1 cm, both vertically and horizontally. From repeated measurements over 10 mo, the UTM position uncertainty of any point in a channel cross section was determined to be 0.44 ± 0.11 m (Harris, 2008). Each of the 17 channel cross sections was surveyed at least once prior to dam removal and then approximately monthly during the 6 mo following dam removal, after which time the survey pins had to be removed because of bank remediation efforts.

The types of sediment cores collected included 14 vibracores using a 7.5-cm-diameter aluminum core barrel, and 52 push cores using either 5.1 cm polyvinyl chloride (PVC) pipe or 7.5-cm-diameter aluminum pipe (Fig. 1). The maximum recovered sediment core length was 2.7 m. Trenching involved clearing slumped material from the channel bank at three locations (Fig. 1) and recording stratigraphic information and sampling layers in the field. The maximum trenched interval was 2.6 m depth. The base of each trench was extended downward by collecting an additional sediment core. Given stratigraphic overlap between trenches and cores, the composite stratigraphic interval examined in this study was ~4.5 m thick. Finally, samples were collected for ^{14}C and optically stimulated luminescence (OSL) dating, as described in the following.

In the laboratory, each of the 66 sediment cores was split lengthwise, and one half of the core was archived for future use. The working half was cleaned, photographed, described stratigraphically, and subsampled for grain-size analysis. Grain-size analysis involved removing particulate organic materials and shell debris, and then wet sieving to split sand and mud samples, if necessary. Sand samples were washed and dried, and then sieved through a nest of sieves using a sieve shaker apparatus. Mud samples were dispersed in 5% sodium hexametaphosphate solution, diluted to appropriate sediment concentrations, and then evaluated using a Spectrex PC-2300 laser particle-size analyzer. Grain-size statistics were calculated following the methodology of Folk and Ward (1957). Additional details are given elsewhere (Gottgens et al., 2004; Roberts et al., 2007; Harris, 2008; Webb, 2010).

Geochronology methods included ^{14}C dating, OSL dating, and identifying the age of anthropogenic materials found in trenches. Four peat samples were collected by sampling stratigraphic horizons observed in trenching operations. These samples were sent to Geochron Laboratories for conventional ^{14}C dating, including $\delta^{13}C$ corrections. Details of the sample treatment are given in Webb (2010). The ages were converted to calendar yr before present (cal. yr B.P.) using radiocarbon calibration program Calib revision 5.0.2® (Stuiver and Reamer, 1993). This program produces a probability distribution, and from this, a mean and standard deviation (1σ) are herein reported. The OSL samples were collected in the field from quartz-rich sandy layers exposed in trenches. Six samples were collected by pounding metal pipes 20 cm in length and 2.5 cm in diameter into the stratigraphic layer

Figure 4. Field photographs from before the Secor Dam removal. (A) Secor Dam at high-flow stage, looking upstream. (B) Secor Dam reservoir looking upstream at high-flow stage. (C) Secor Dam at low-flow stage, looking upstream across the riffle-and-plunge pool. (D) Secor Dam reservoir at low-flow stage, looking upstream. (E) Trapped debris and algae growth upstream of the dam. Water-quality issues played a role in spurring efforts to remove the dam. (F) Fill terrace flanking the incised channel (AT—anthropogenic terrace), near cross section 5 (Fig. 1).

of interest. The pipes were then capped and excavated from the trench exposure. Sample preparation involved working removal of carbonates and organics, sieving the sediment, and several heavy liquid separations to obtain the quartz fraction, etching the surface of the grains, and then evaluating the luminescence using a Riso TL/OSL-DA-15A/B luminescence reader at the USGS facility in Denver, Colorado, using the methodology of Murray and Wintle (2000). The sample preparation protocol is described in detail in Webb (2010). Finally, the age of a glass bottle recovered from a stratigraphic horizon exposed in one of the trenches was obtained from its date stamp (Whitten, 2010), and several other anthropogenic materials could be generally matched to the interval of time they were commercially in use.

REMOVAL OF SECOR DAM

Background

The Secor Dam was constructed in 1928 by the Village of Ottawa Hills for recreational purposes. The Secor Dam was a run-of-river dam or weir, 2.5 m tall and 17 m wide, constructed of reinforced concrete (Fig. 4). An older structure of poorly known history was removed from the site, and the river channel was diverted at the time of construction of the Secor Dam. As part of this study, the location of the pre-1928 channel was located and cored to look at pre-urbanization channel substrates (see later section). This extended project spanned preremoval feasibility studies, an analysis of hydrological and sedimentological effects during and immediately after dam removal on 16 November 2007, and follow-up analysis that focused on historical changes in watershed hydrology. In addition, the process of obtaining approval for the removal of the dam necessitated public hearings and other public outreach and interaction. The removal was part of a larger watershed effort to improve water quality and ecosystem health, known as the Maumee River Remedial Action Plan (Maumee River RAP). The efforts involved interagency cooperation among stakeholders, including the owner of the dam (the Village of Ottawa Hills), the Toledo Metropolitan Area Council of Governments (TMACOG), the Ohio Environmental Protection Agency (OEPA), the Ohio Department of Natural Resources (ODNR), the Ohio Department of Transportation (ODOT), the U.S. Army Corps of Engineers (COE), the University of Toledo (UT), Bowling Green State University (BGSU), and a civic organization, Partners for Clean Streams (PCS).

Initial Impetus to Remove Secor Dam

The removal of Secor Dam was first suggested in 2001 by the U.S. Fish and Wildlife Service as a means of restoring natural flows, primarily for the purpose of removing a barrier to native fish migration (*Toledo Blade*, 18 July 2001). The proposal, with some public support, led the owner of the dam, the Village of Ottawa Hills, to hold several public meetings and solicit public comments. A number of other developments helped spur the possibility of the Secor Dam removal. The first was the fact that discussion began almost simultaneously about removing the only other low-head dam on the Ottawa River, which was privately owned and located further upstream (*Toledo Blade*, 6 December 2001). This second dam, the Camp Miakonda Dam, was actually breached, thus posing a clear safety hazard, and was subsequently removed in January 2003. Removing both dams raised the possibility of the Ottawa River becoming free-flowing along its entire length again. The second development was linking improvements in the water quality of the Ottawa River with the larger regional watershed improvements mandated by the Maumee River RAP (*Toledo Blade*, 30 April 2002). Both the Ottawa River and Maumee River flow through the City of Toledo and enter Lake Erie in close proximity. Improving the water quality of the Ottawa River by removing the dams would also be in accord with the ongoing remediation of contaminated sediments at a Superfund site (Hoffman Road Landfill) near the mouth of the Ottawa River. As of 2010, this remediation has grown to a $49 million effort involving dredging of ~200,000 m^3 of contaminated sediment (*Toledo Blade*, 6 May 2010). Finally, $2.5 million funding became available for river mouth dredging for recreational boaters, gaining another constituency for improving the overall health of the watershed.

The Village of Ottawa Hills was also actively interested in the removal of Secor Dam from an environmental stewardship perspective. They wanted to restore the river to unregulated flow and remove the liability aspects of retaining the dam. The Village of Ottawa Hills encouraged, but could not fund, the necessary feasibility studies for the dam removal project. Specific concerns were the extent of sediment contamination, and the hydrological and sedimentological impacts of removing the dam. A group of scientists from two state universities in the region (UT and BGSU) completed these studies (Gottgens et al., 2004; Roberts et al., 2007) supported by a grant from the ODNR Coastal Management Program.

Feasibility Studies

Pre-dam-removal feasibility studies were conducted in 2002–2003. One part of the study was a sediment-routing model based on hydrologic analysis of seven channel cross sections between RK17 and RK27 (including bankfull stage height and bankfull width, and channel slope) and based on evaluation of the channel substrate determined by grain-size analyses of surficial samples and short cores (Gottgens et al., 2004; Roberts et al., 2007). After calculating boundary shear stress and entrainment critical shear stress using the methods described elsewhere (Evans et al., 2002), the sediment-routing model determined transport modes for different grain-size class populations. The results predicted that Secor Dam had trapped between 4500 and 9000 m^3 of mostly sandy sediment in the reach up to 1 km upstream of the dam, and that the anticipated effects of the dam removal would be deposition of most of these sands in a series of pools immediately downstream (<1 km) of the dam.

Another part of the feasibility study used the U.S. Army Corps of Engineers Hydrologic Engineering Centers–River Analysis System (HEC-RAS) to model flood-stage height and lateral flood extent both prior to and subsequent to dam removal for the 10, 25, 50, and 100 yr floods. Topography adjacent to the channel was generated from light detection and ranging (LiDAR) data with 0.3 m vertical resolution. The locations of features were input from digital orthophotography with 0.6 m pixel dimensions into ArcGIS. Following this, 400 valley cross sections oriented perpendicular to the channel were generated at 100 m spacing. The Ottawa River drainage basin was subdivided into 102 subbasins for the purpose of generating runoff curves for specific flood events denoted previously. The results show relatively minor impacts for removal of the dam (Gottgens et al., 2004; Roberts et al., 2007). This is probably because certain bridges located downstream of Secor Dam appear to have a greater impact on constricting flow and creating backwaters than the role played by the dam itself, a weir that had no flood-storage capacity.

Finally, geochemical analyses of Al, As, Cd, Cu, Fe, Ni, Pb, Zn, PCBs (polychlorinated biphenyls), PAHs (polyaromatic hydrocarbons), and petroleum hydrocarbons (C_{11} to C_{31}) were conducted using standard techniques (Gottgens et al., 2004; Roberts et al., 2007). The results showed a moderate level of metals contamination, where As and Cd commonly exceeded threshold effects levels (TEL), Ni and Pb occasionally exceeded TEL, and As and Cd rarely exceeded probable effect levels (PEL). Sediment PCB contamination was low (with rare samples that exceeded TEL values). In contrast, PAH contamination commonly exceeded PEL values, and the river sediments were considered moderately contaminated by petroleum hydrocarbons (Gottgens et al., 2004; Roberts et al., 2007). The observed higher levels of PAHs and petroleum hydrocarbons in Ottawa River sediments were attributed to gasoline, oil, and tar runoff from urban streets and parking lots.

Decision to Remove Secor Dam

The feasibility studies found no significant sediment contamination issues or potential harm from removing the dam. After receipt of these feasibility studies in December 2004, the Village of Ottawa Hills approved a village council resolution to remove the dam.

Public hearings in March 2005 attracted a diverse range of concerns and interests. Articulated concerns included worries that removing the dam would make flooding worse, change water levels, impact mosquito control efforts, or remobilize contaminants (*Toledo Blade*, 31 March 2005). Most of these concerns could be satisfactorily addressed based on the results of the feasibility study. An unexpected line of questioning was whether or not the existing low-head cement dam replicated the ecosystem impact of porous wood debris dams constructed by beavers (*Castor canadensis*), which used to be native to the area. Finally, some opposed the removal project due to possible effects on property values, taxes, or simply because they viewed it as an overstep by a governmental authority. Follow-up to these meetings included exchanges of letters-to-the-editor of local newspapers and news reports in the media for a period of 2 yr, until the dam was actually removed in November 2007. Nevertheless, following these hearings, in April 2005 the Village of Ottawa Hills decided to solicit bids to remove the dam (*Toledo Blade*, 5 April 2005).

This decision to remove the dam initiated two simultaneous and linked discussions, the river restoration plan and the source of funding. After a number of false starts, the funding issue was resolved in the following way: The removal of the dam would be accomplished by an independent contractor hired, supervised, and paid for by the ODOT as part of a wetlands mitigation project in exchange for wetland loss related to widening U.S. Highway 24 adjacent to the Maumee River, in the same watershed. The habitat restoration itself would be funded through an OEPA Section 319 Non-Point Source Program grant, as administered by TMACOG in conjunction with their efforts to improve water quality in Maumee River RAP. TMACOG then consulted COE for advice regarding stream-bank erosion mitigation.

Hydrologic Response to Dam Removal

The dam was breached on 19 November 2007 (Fig. 5A). The sedimentological response to the dam removal included erosion of the sandy bed-load deposits from the former reservoir up to ~150 m upstream of the former dam, translation of sandy bed-load downstream through the site of the former dam, and deposition of most of the material in pools within ~100 m downstream of the former dam, as predicted (Evans and Harris, 2008). In comparison to other dam removals, this response was more localized because the reservoir sediments were primarily sands with fluvial pavements (see later section).

Initially, a knick zone (diffuse knickpoint) formed near the downstream end of the reservoir and migrated upstream (Fig. 5B). The knick zone had an erosional relief of ~10 cm, and it migrated upstream ~83 m within the first few hours before it stalled upon a resistant layer, becoming a broad riffle. The resistant layer was subsequently determined to be an exhumed peat layer (Fig. 5C) representing the presettlement paleosol (see later section). Upstream migration of the knick zone exposed underlying sandy sediments in the former reservoir, and resulted in the formation of several bed forms (Fig. 5D) that migrated down channel and could be tracked using GPS at rates of ≤0.5 m/h (Harris, 2008). An analysis of cross-section data allowed creation of digital elevation models (DEMs) of the channel bed surface topography prior to dam removal, 3 mo after dam removal, and 6 mo after dam removal. The difference indicates that a volume of ~500 m^3 of mostly sand was eroded from the former reservoir within about 3 mo of the dam removal (Harris, 2008), and a volume of ~800 m^3 of mostly sand was eroded within the first 6 mo.

Within the first 6 mo, sequential changes to channel cross sections upstream of the former dam were consistent with predictions from channel evolution models: (1) incision of former reservoir sediments, (2) channel widening facilitated by bank

Figure 5. Field photographs of the Secor Dam removal and impacts. (A) Dam removal on 19 November 2007. (B) Upstream channel incision and reservoir dewatering near cross section 6 (Fig. 1), showing exhumation of the peat layer (shown in C) and downstream bed-form migration (shown in D). (C) Exhumed peat layer discovered to have wide lateral extent, near cross section 6 (Fig. 1). (D) Tracking bed-form migration within the first days after the dam removal, near cross section 8 (Fig. 1). (E) Point bar at the downstream end of the inner bank immediately upstream of the dam prior to dam removal near cross section 9 (Fig. 1). (F) Point bar incision at the same location, 41 d after the dam removal.

failures during continued incision, (3) channel aggradation and incipient floodplain formation, and (4) quasi-equilibrium due to bank consolidation and revegetation (Doyle et al., 2003; Evans, 2007). The Secor Dam removal differed in some details from these models because the reservoir sediments were primarily sands and because there was a preexisting low-stage channel through most of the reservoir sediments (Harris, 2008). For example, in this case, incision began immediately throughout the former reservoir, even though the dam was removed under low-stage conditions, resulting in mobilization of sand as a series of downstream-propagating bed forms, as described earlier, and causing the channel to rapidly narrow. The initial phase of channel incision, reaching a maximum depth of ≥1.3 m, was essentially completed within approximately the first week, and channel widening began within the first several weeks (Fig. 6A).

Within ~100 m downstream of the former dam, two pools acted as sediment traps: the former foot-of-dam plunge pool and a confluence bar pool at the junction of the Ottawa River and Hill Ditch, a small tributary (Fig. 1). Both pools were significantly infilled by the sandy sediment released from the former reservoir; in addition, a gravel riffle between the two pools was significantly modified by sand infilling the gravel matrix (Fig. 6B). Further downstream, there were minimal changes between pre- and post-dam-removal channel cross sections, indicating that very little of the reservoir sand reached as far downstream as cross sections 15–17 (Fig. 1). These survey results were verified by bed-load and suspended load field measurements (Harris, 2008). In summary, the data suggest that most of the ~500 m^3 volume of sand mobilized from the former reservoir in the first 3 mo was either trapped in former pools immediately below the dam or transported completely through the study area during high-stage flows when channel surveys or field measurements were not possible (Harris, 2008).

There is evidence of improvements in aquatic ecosystems due to removal of the dam that was a barrier to fish migration. Preliminary results indicate 31 fish species moving upstream of the former dam within the 24 mo after the dam removal, and at least one fish species extending its range downstream (J.F. Gottgens, 2 October 2009, 19 November 2010, written communs.).

Remediation Following Dam Removal

As previously discussed, the successful removal of Secor Dam involved multiple agency partners and funding sources. Throughout the process of designing for and removing the dam, restoration planning became complicated, with the different participants

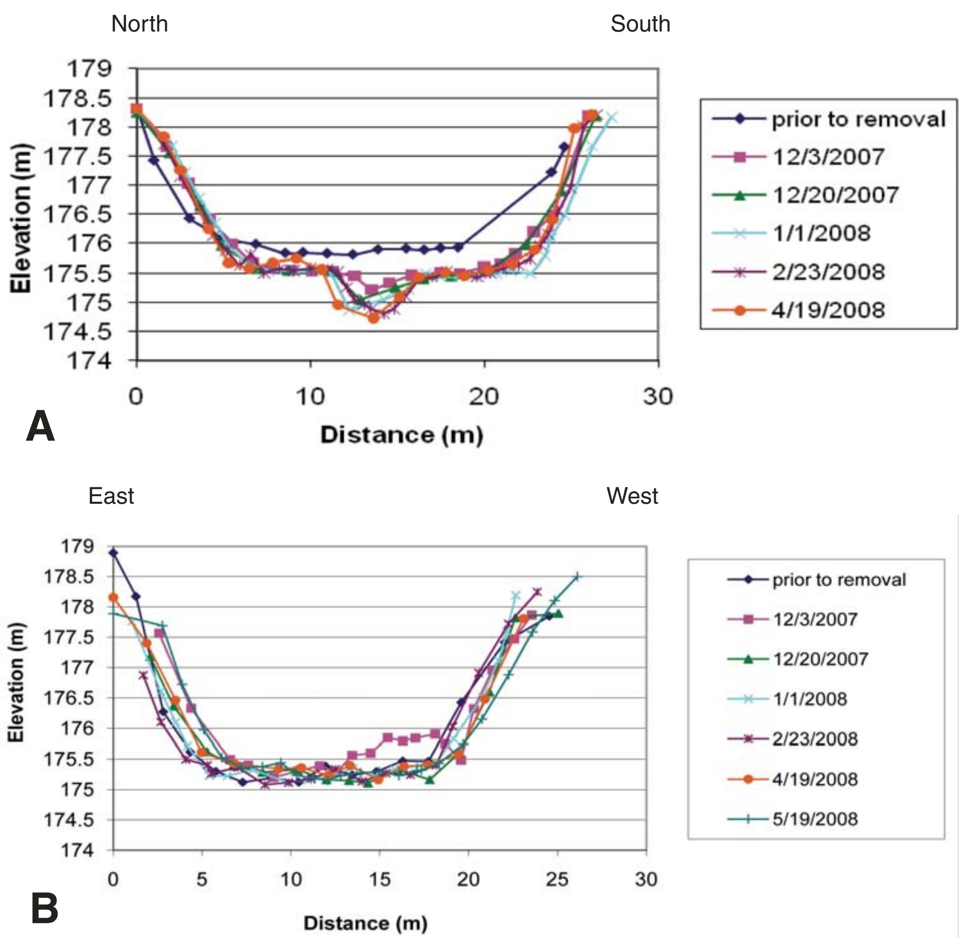

Figure 6. Surveyed channel cross sections showing sequential changes in bed elevation from prior to the removal of Secor Dam until approximately 6 mo after removal. (A) Sequential changes over 6 mo after removal of the Secor Dam at cross section 6 upstream of the dam. (B) Sequential changes over 6 mo after removal of the Secor Dam at cross section 12 downstream of the dam.

each having distinctive goals. For example, ODOT made it clear that its goal was to remove the dam by the most economical manner possible, regardless of restoration goals or concerns. In addition, COE made it clear that restoration meant stream-bank stabilization, although the COE staff members connected with the project were strong advocates for a mix of soft- and hard-stabilization structures instead of entirely hard stabilization structures. Meanwhile, the scientists involved with monitoring the hydrological, sedimentological, and ecological effects of the removal were interested in maintaining the integrity of their studies in the face of unpredictable management and construction activities. These concerns included possible construction zone impact on several species of state-listed freshwater mussels. Finally, the Village of Ottawa Hills and other government entities were concerned with protection of infrastructure components.

In retrospect, it becomes clear that the various consultants were divided into two basic philosophies. The dividing line that was articulated involved perceived threats to infrastructure, although these threats were never quantified to any degree. One infrastructure concern was potential bank failure undermining the Secor Road causeway and bridge (Fig. 1). Another was potential hillslope failure along Edgevale Road near the junction of the Ottawa River and Hill Ditch (downstream of the former dam). Finally, there was concern about buried sewer lines, the locations of which were not well documented. One group of consultants wished to anticipate all potential infrastructure problems with a combination of hard and soft bank-erosion structures. The other group of consultants wished for this river to have the opportunity to adjust to changing conditions, including lateral migration of the channel through the largely undeveloped floodplain in this stretch of the river.

Ultimately, the decisive factor in these discussions was not the science or policy, but the availability of funding resources for the restoration efforts. There were time constraints on spending the available funds, thus bolstering the argument that any potential threats to infrastructure had to be anticipated and addressed immediately. Accordingly, the meander bend upstream of the former dam was remediated as a longitudinal peaked stone-toe protection structure (Derrick and Jones, 2010), one of the former bulkhead walls of the former dam was retained, and the hillslope below Edgevale Road was extensively riprapped. Subsequent vegetative plantings were designed to help reduce any other sites of potential bank erosion (Village of Ottawa Hills, 14 August 2008, personal commun.). The process by which these decisions were made led to the follow-up studies discussed next.

POST-DAM-REMOVAL PALEOGEOMORPHIC ANALYSIS

Historical Changes in Channel Substrate

The Ottawa River was diverted in 1928 to facilitate the construction of the Secor Dam. Today, the former channel is buried beneath 0.8–1.4 m of floodplain sediments adjacent to the existing channel (Fig. 1). Historical engineering plans and existing low areas in the modern topography were used in a successful attempt to locate and vibracore the pre-1928 Ottawa River channel. In six attempts, five vibracores recovered pre-1928 channel substrates, and four of these cored entirely through the channel sediments (Fig. 7). Inspection of the vibracores reveals that the pre-1928 channel was incised into underlying proximal floodplain deposits (inundite facies; see descriptions in Harris, 2008) and that the channel was then partially infilled by fining-upward point-bar deposits, prior to the engineered infilling of the former channel in 1928.

There is a significant contrast in channel substrates between the pre-1928 channel and modern channel (Fig. 8). The pre-1928 substrates are normally distributed (i.e., nearly symmetrical skewness between +0.10ϕ and –0.10ϕ), while the modern channel substrates are either strongly coarsely skewed (<–0.30ϕ), representing fluvial pavements, or strongly finely skewed (>+0.30ϕ), representing mud-infilled pools at low-stage flow conditions (note: ϕ refers to Udden-Wentworth grain-size class intervals). The most striking contrast is that fluvial pavements (channel armoring) are common in the modern channel but entirely lacking in the pre-1928 channel (Fig. 9). Channel armoring is evidence of incision (Julien, 2002). This historical change is interpreted as one of the impact of urbanization of the watershed, which was most significant after the late 1940s, as discussed previously. Specifically, urbanized drainage systems are contributing more storm runoff to the Ottawa River, and channel degradation is the response to this increase in transport conveyance capacity.

Channel Lateral Migration Rates

A vibracore from the upstream portion of the study area cored through a complete point-bar sequence. This information was used to track the changing location of one of the upstream point bars. From the core location, it is likely that this point bar was active prior to the diversion of the Ottawa River channel in 1928, but it was not part of the diversion itself. The distance between the core location and the base of the modern bar is ≥25 m, representing a minimal mean channel migration rate of ≥0.32 m yr^{-1} over the past 79 yr (Evans and Harris, 2008). Evidence of continued lateral migration at this location, both prior to and subsequent to dam removal, includes undercut banks, slumps, toe-of-slope deposits, small colluvial fans, soil avalanches, and tree-fall at the outer bank. The outer bank is ~2.5 m tall at this location, and it exposes the stratigraphy of legacy sediments discussed in a later section.

Evidence for Post-Dam-Removal Sinuosity Changes

There were two unexpected results of the dam removal that occurred at the first meander bend upstream of the former dam. These included erosion at the upstream end of the outer bank and erosion of the downstream end of the inner bank. This is a counterintuitive pattern from the behavior of meandering

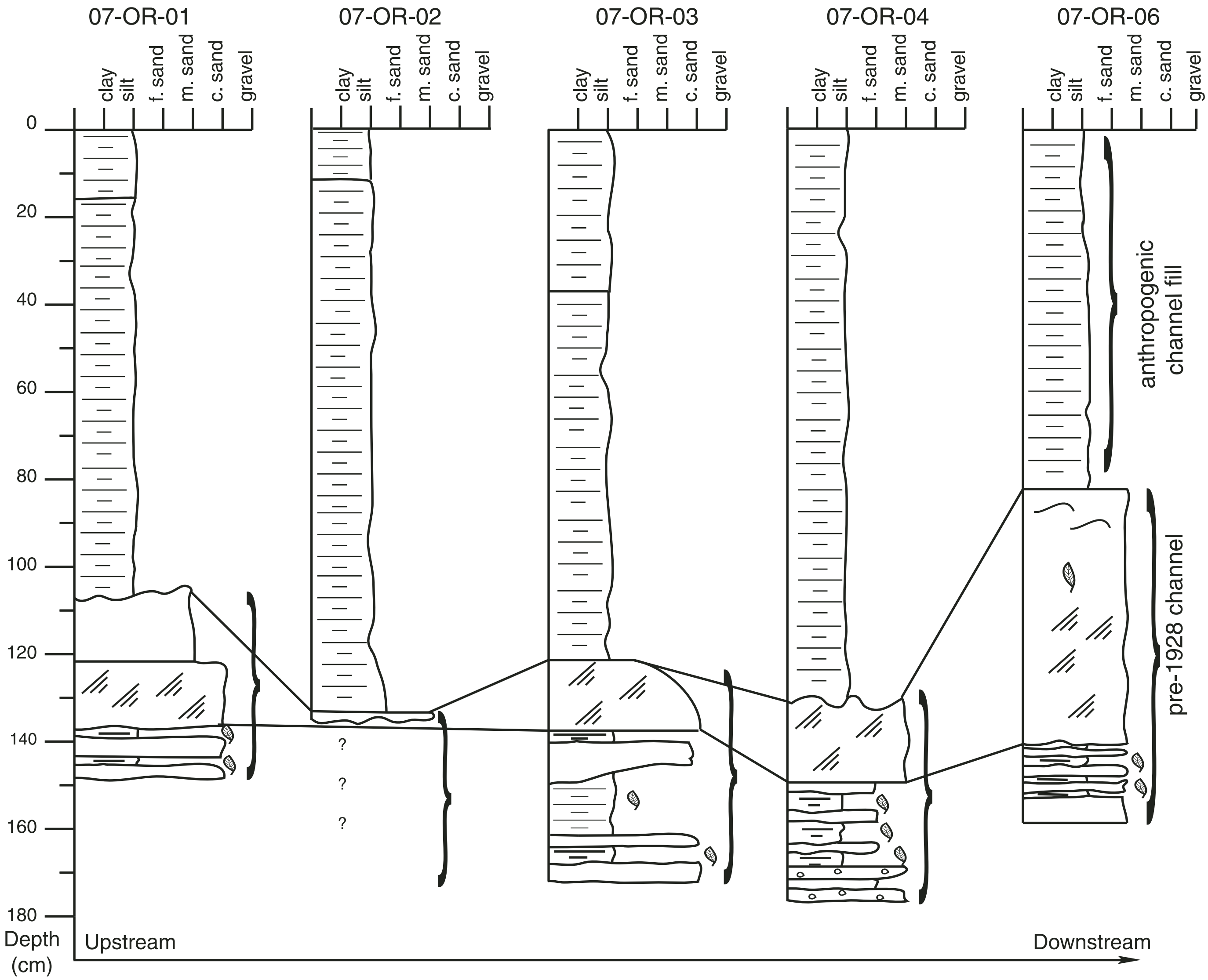

Figure 7. Stratigraphy of the pre-1928 Ottawa River channel from vibracores. The channel was artificially infilled after the river was rerouted to the Secor Dam. The cores are hung from the present ground-level datum, without showing minor variations in topography.

streams, where the zone of maximum boundary shear stress should cross from the upstream side of the point bar on the inner bank to the downstream side of the pool on the outer bank (Dietrich and Smith, 1984). In fact, there was significant erosion on the inner bank, where a point bar would be expected to form in the restored river channel (Figs. 5E and 5F). It appears that the meander wavelength was changing, adjusting the position of the point bar and cutbank.

The meander wavelength (*P*) is defined as the river path length divided by the valley axis path length for specific reaches of the river. Between RK18 and RK30, the meander wavelength of the Ottawa River varies from 1.2 to 2.1. Prior to dam removal, the reach encompassing Secor Dam (RK18 to RK19) had a meander wavelength of 1.3. However, an evaluation of historical documents shows that the pre-1928 Ottawa River in this reach had a much higher meander wavelength (*P* = 2.0). It is possible that the changes in height and position of the pre-1928 dam and the Secor Dam (between 1928 and 2007) affected the stability of the meander wavelength in this reach (resulting in an historical change from *P* = 2.0 to *P* = 1.3), and that the recent Secor Dam removal is driving recent changes. However, these changes were not permitted to develop naturally and were halted or at least inhibited by bank stabilization structures imposed in 2008, approximately 9 mo after the dam was removed.

Recognition of Presettlement Soil Horizon

As discussed previously, the erosional knick zone created at the time of dam removal migrated upstream until it stalled on a peat horizon exhumed in the bed of the stream (Fig. 10).

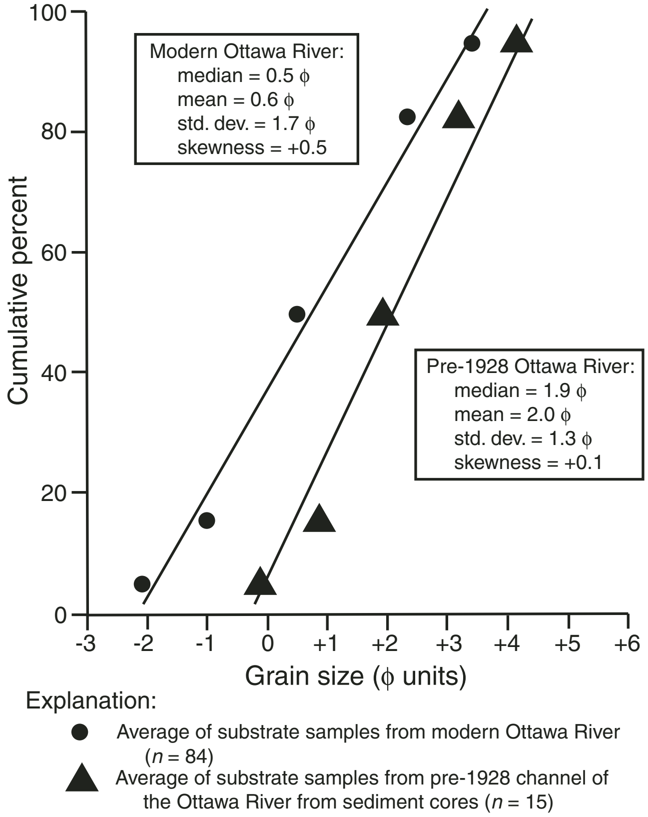

Figure 8. Comparison of average substrate grain-size distributions between the pre-1928 channel and the modern channel. The modern channel data are averaged from 84 surface samples. The pre-1928 channel data are averaged from 15 samples obtained by vibracoring the pre-1928 channel. The comparison highlights the increased grain size and skewness resulting from post-1928 channel armoring, which is attributed to an effect of urbanization.

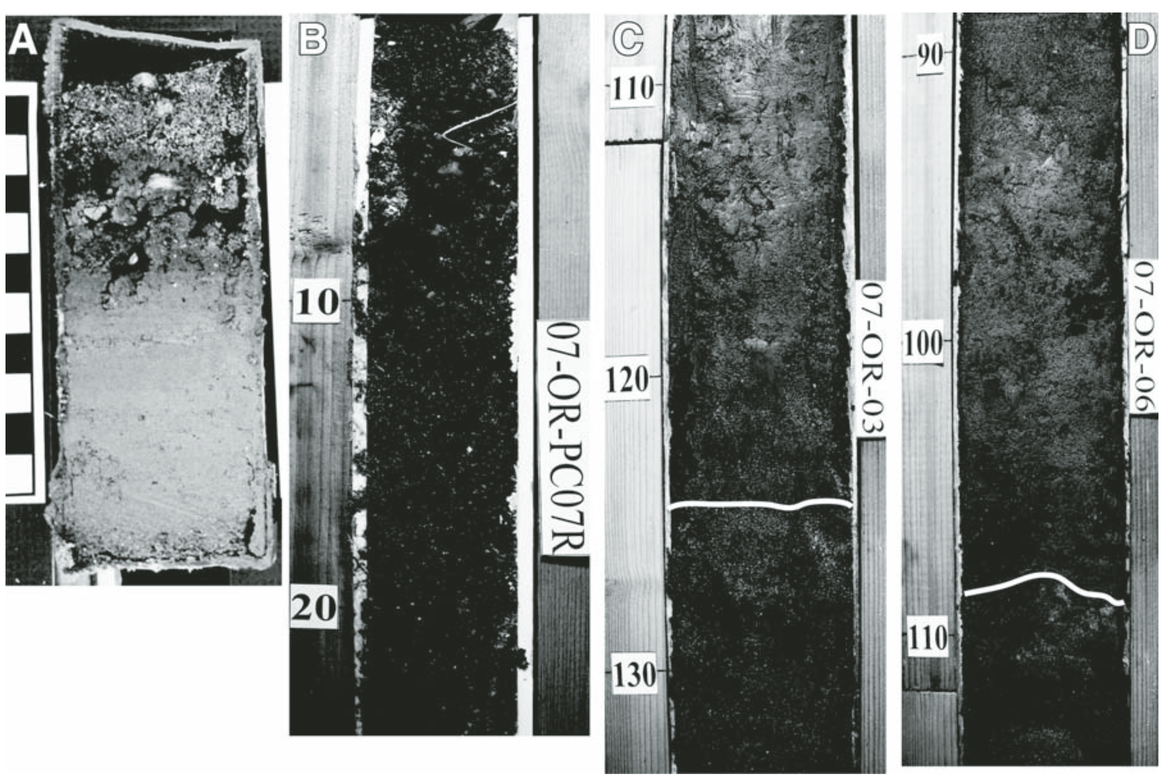

Figure 9. Photographs comparing shallow cores from the modern channel (showing fluvial pavements) with the pre-1928 channel substrate from cores (scales in centimeters). (A–B) Push cores showing modern fluvial pavements from channel armoring. (C–D) Portions of vibracores from the pre-1928 channel. The white line is the contact between the natural channel substrate pre-1928 and the artificial infilling material after the Ottawa River was rerouted to the Secor Dam. Note the lack of fluvial pavement in the pre-1928 substrates.

This peat horizon was the focus of detailed study, with geochemical profiles and textural relationships showing that it is consistent with a prehistorical wetland soil or paleo-Histosol (Webb, 2010). The peat layer is laterally continuous and could be traced throughout the study area between all three trenches and numerous cores. Based upon its lateral and vertical facies associations and geochemical profile, the peat layer can be interpreted as a riparian wetland adjacent to the Ottawa River (Evans and Harris, 2008). The peat layer has a suite of ^{14}C and OSL ages between 4889 ± 179 cal. yr B.P. to 231 ± 15 cal. yr B.P. (Fig. 11), indicating that it spans the age from mid-Holocene age until shortly before initial European land settlement in the region (Webb, 2010).

The 4.5 m composite stratigraphic record shows that the peat horizon overlies fluvial point-bar sequences ("pre–wetland fluvial stage" in Fig. 11). The transition from clastic-rich fluvial deposits to riparian wetlands about (5000 yr) coincides chronologically with a rise to the highest lake levels of Lake Erie (Nipissing I and II stages) that lasted from ca. 5.5 ka to 3.5 ka (Coakley, 1992; Holcombe et al., 2003). Thus, this peat horizon can be interpreted as the result of rising groundwater tables in the region due to the base-level rise of Lake Erie at this time, and the appearance of these wetlands along the Ottawa River can be linked to the formation of the Great Black Swamp throughout northwestern Ohio and portions of southeastern Michigan.

Overlying the peat, there is a succession of carbonaceous muds, silts, and sands, with abundant woody debris. The carbonaceous muds with thin interbedded silt and sand layers are interpreted as deposits from overbank flooding into the riparian wetland, diluting the organic content of the wetland soils. The transition stratigraphically upward from organic-rich sediment to mineral-rich sediment suggests that the riparian wetland was sequentially buried beneath clastic sediment. Other studies interpret similar changes as the transition from "blackwater" (organic-rich) streams to "brownwater" (mineral-rich) streams (Kroes and Hupp, 2010). Although such a transition could be the result of channel migration of the Ottawa River over time, it is suggestive that the uppermost sand layer has an OSL age of 231 ± 15 cal. yr B.P., which is approximately the time of arrival of European settlers in the region. It is likely that land clearance at this time was responsible for fluvial aggradation and infilling of adjacent riparian wetlands.

Within the "channel instability stage" (Fig. 11) and stratigraphically superimposed on these older interbedded clastic and organic deposits are two prominent sand layers that can be traced laterally through all three trenches and numerous cores. The first

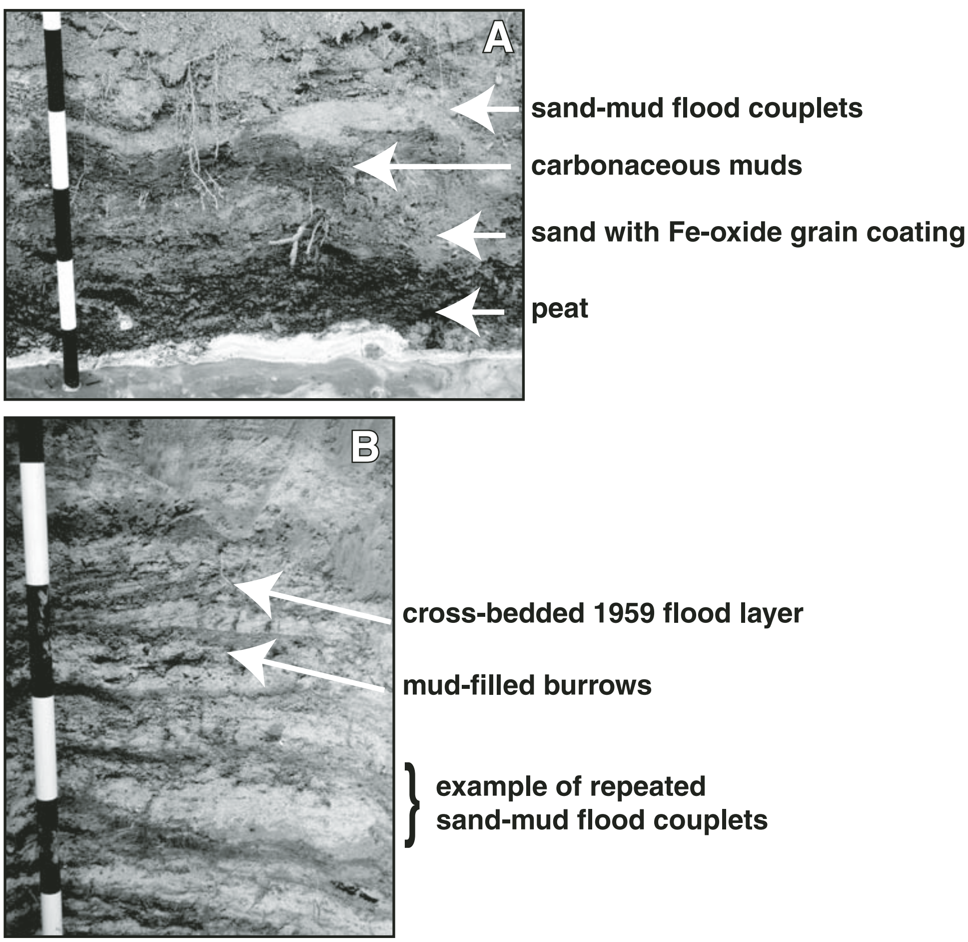

Figure 10. Field photographs of the stratigraphy of one of the trenches. (A) Peat (hydromorphic paleosol) overlain by sand with Fe-oxide grain coatings and carbonaceous muds. The upstream knick-zone migration after the dam was removed stalled on this resistant layer, and it formed a riffle. The presence of the peat is interpreted to represent the transition from blackwater (organic-sediment rich) streams prior to land clearance to brownwater (mineral-sediment rich) streams after land clearance. (B) Flood couplets representing floodplain aggradation. The cross-bedded sand layer has optically stimulated luminescence (OSL) ages indicating it is the historic 1959 flood. Overlying this sand is 1.7 m of silty sediment representing high rates of vertical accretion during watershed urbanization. Scale bars are 10 cm increments.

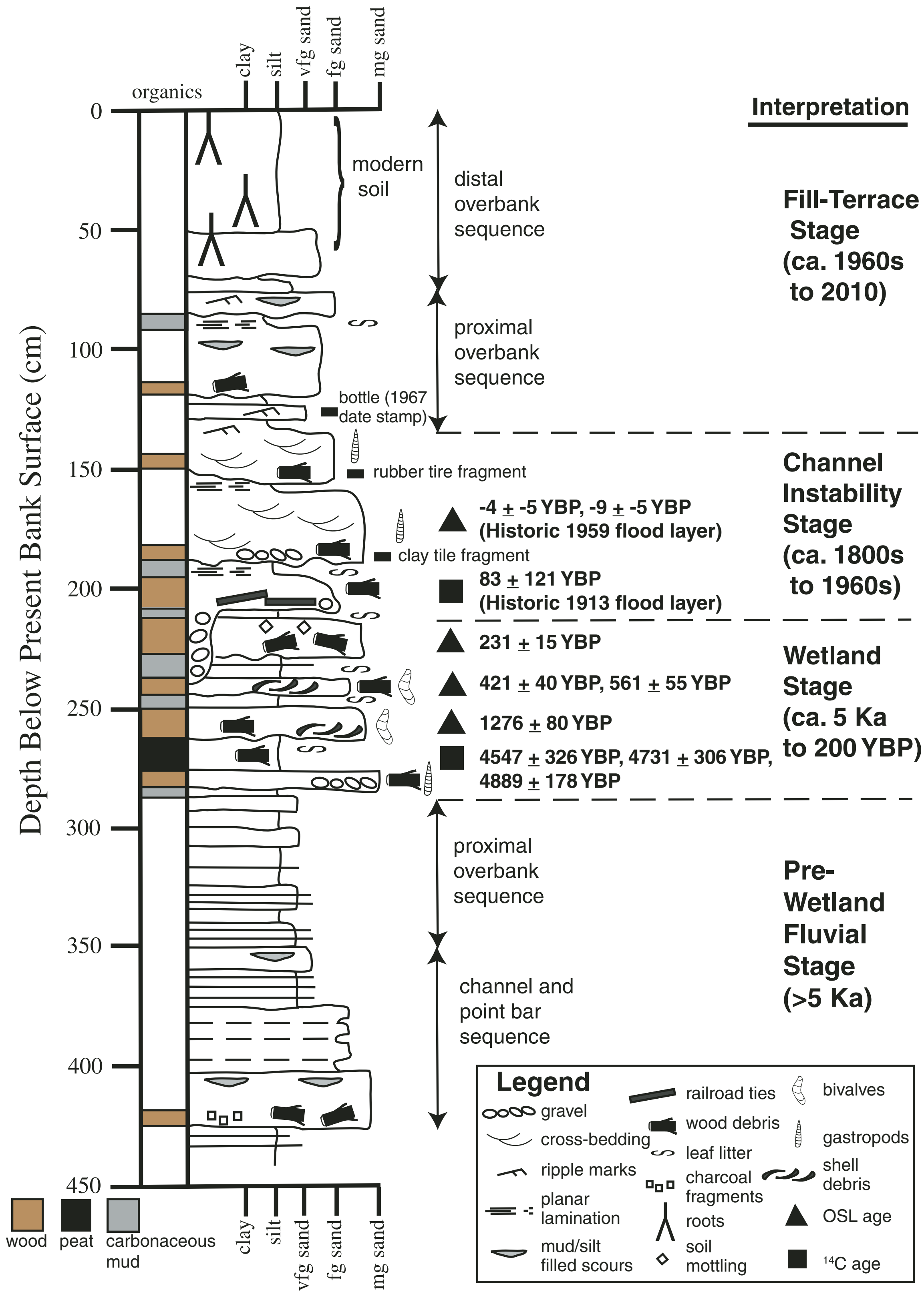

Figure 11. Composite stratigraphic section created from adjacent vibracore (09OR-11) and trenches (09OR-5 and 09OR-6). Geochronology data are matched to specific sample horizons. See text for discussion. YBP—yr B.P.; OSL—optically stimulated luminescence; vfg—very fine grained; fg—fine grained; mg—medium grained.

sand layer scours approximately 40 cm into the underlying deposits, contains pebbles, and contains anthropogenic debris including a layer of railroad ties (Fig. 11). Organic debris in this sand has a ^{14}C age of 83 ± 121 cal. yr B.P. This sand layer is interpreted as the flood layer from the historic flood of 1913, which devastated much of the region. The second sand layer has a suite of OSL dates ranging from –4 ± 5 cal. yr B.P. to –9 ± 5 cal. yr B.P., in other words between calendar years 1954 and 1959. Historical flood records point to a major flooding event that occurred during January 1959, after a storm that involved 3.7 cm rainfall on frozen ground. The historic 1959 flood submerged floodplains, roads, the decking of major highway and railroad bridges, and caused significant flood damage throughout the region (*Toledo Blade*, 21 January 1959).

Overlying the historic 1959 flood horizon, there is a 1.3–1.7-m-thick interval of mostly yellowish silts that are organized into repetitive fining-upward sequences of thin sands, silts, and thin capping muds ("fill-terrace stage" in Fig. 11). These deposits are interpreted as post-1959 historical flood horizons. The flood horizons contain anthropogenic materials, including a glass bottle with a 1967 date stamp and plastic debris consistent with post-1970s ages (Webb, 2010). We interpret this upper package of clastic floodplain sediment to represent vertical accretion of the floodplains, creating the present fill-terrace morphology. The minimum floodplain sedimentation rates for this section are between 2.85 cm yr^{-1} and 3.15 cm yr^{-1}, which are approximately three orders of magnitude higher than presettlement rates (Webb, 2010). Indirect evidence in support of these extraordinarily high floodplain aggradation rates includes the multiple sets of adventitious roots of floodplain trees that are now exposed in channel cutbanks.

DISCUSSION

Historical Changes in Rivers

Numerous previous studies have considered human impacts on rivers in eastern North America. Generally speaking, there are at least three and possibly four partly overlapping phases in the historical development of these human impacts: (1) a phase that began in the early 1600s on the East Coast and by the mid-1800s had reached the Upper Mississippi Valley region, consisting of the effects of land clearance for agriculture and other development activities such as constructing milldams by European settlers; (2) a phase that began in the mid-1900s consisting of the effects of soil conservation practices on stream sediment loads; and (3) a phase that saw its greatest effects after the mid-1900s, consisting of the effects of urbanization on watershed hydrology and stream sediment budgets. The fourth component, which remains poorly understood, would have preceded all of these, and consists of the way in which the "presettlement" land management practices of Native Americans affected rivers and/or how variations in the populations of beavers affected watershed hydrology. Each will be considered in the following.

The arrival of European settlers in eastern North America starting in the 1600s had two effects: (1) significant increases in watershed sediment supply due to upland deforestation and land clearance for agriculture (Jacobson and Coleman, 1986), and (2) the concurrent increase in intrabasinal sediment storage (alluvium and colluvium) from a variety of processes including the relative base-level rise from construction of large numbers of milldams (Walter and Merritts, 2008) and/or the accelerated subsidence and infilling of impacted riparian wetlands (Kroes and Hupp, 2010). It has been argued that the result was inundation, burial, and sequestration of presettlement riparian wetlands, leading to the development of silt-rich, broad floodplains with incised, laterally migrating channels, i.e., the classical meandering form (Walter and Merritts, 2008), although disagreements exist (Bain et al., 2008; Wilcock, 2008). From a sediment budget viewpoint, sediment input overwhelmed the transport conveyance capacity of the fluvial system, causing the accumulation of sediment volumes within the drainage basin (i.e., as intrabasinal storage in the form of alluvium or colluvium). Intrabasinal storage due to such anthropogenic causes has also been termed "legacy sediments."

Sediment budgets have been further impacted by recent (generally <50 yr) land-use changes, driven by both economic and social factors. In some regions, watershed sediment inputs have significantly declined due to abandonment of agricultural fields and subsequent reforestation (Wolman, 1967; Costa, 1975; Jacobson and Coleman, 1986). In other areas, agricultural soil erosion has declined as a result of improved soil conservation practices (Trimble and Lund, 1982; Kuhnle et al., 1996). While these changes in agricultural land use have profound impacts on sediment supply, recent studies have shown that these have been accompanied by minimal changes in streamflow (Cruise et al., 2010). However, these reductions in watershed-scale sediment inputs are not necessarily matched by reductions in stream sediment loads or sediment yield (Knox, 1987). The implication is that these streams are maintaining sediment loads and compensating for reduced upland soil erosion inputs by eroding or reworking intrabasinal storage. Examples include the decoupling of reservoir sedimentation rates from current land-use practices (Evans et al., 2000c) and the persistence of high sediment yields despite significant soil conservation efforts (Faulkner and McIntyre, 1996). These studies highlight the need to apply sediment budget concepts to understanding watershed changes (Evans et al., 2000c; Allmendinger et al., 2007).

Finally, urbanization represents a special case for sediment budgets. During the urbanization of a drainage basin, the initial soil erosion effects of land clearance and housing construction can produce sediment input rates that are orders of magnitude higher than the equivalent effect from agricultural fields (Wolman and Schink, 1967; Gellis et al., 1996; Allmendinger et al., 2007). Coinciding with increased sediment inputs in urbanizing watersheds are hydrologic modifications such as construction of impermeable surfaces and routing of runoff through urban storm-drain networks that increase runoff (Carter, 1961; Wolman, 1967; Booth and Jackson, 1997), increase peak streamflow discharge (Beighley and Moglen, 2002; Meierdiercks et al., 2010), and change channel morphology (Pizzuto et al., 2000; Segura and Booth, 2010). However, unlike the continued, long-term impact of agriculture (as long as the fields are farmed), sediment inputs in urbanized areas should decline over time as disturbed ground such as new housing developments becomes revegetated. Thus, unlike the long-term continuous sediment inputs from agricultural drainages, sediment inputs from urbanized drainages can be expected to be more episodic (related to historical intervals of peak urbanization or suburbanization in a region), and may be masked to some extent by increases in transport capacity (related to increased storm runoff in urbanized drainages). Thus, after the initial pulse of sediment from land clearance, the long-term effect of urbanization may be an increase in transport conveyance capacity, which will be manifested by bank erosion, incision, and reworking of sediment held in intrabasinal storage.

In summary, in any particular drainage basin in eastern North America, human impacts on fluvial systems generally include: (1) initially high sediment input rates related to land clearance, followed by (2) reductions in sediment input due to the abandonment and revegetation of farm fields, or improved soil conservation practices on currently farmed fields, or the revegetation of disturbed urbanized areas. During the initial phase, sediment input rates tended to vastly exceed conveyance capacity and lead to increased intrabasinal storage of legacy sediment as alluvium or colluvium. During the later phase, reduced sediment input rates lead to erosion (remobilization and reworking of previously stored legacy sediment). In other words, according to sediment budget concepts, reductions in watershed sediment input rates (often a consequence of public policy to improve soil conservation practices) *inevitably* leads to enhanced rates of incision or bank erosion. This will continue until such time as the fluvial system has adjusted sediment supply to transport conveyance capacity, which in all likelihood means until the legacy sediments are reworked and removed from the drainage basin—regardless of whether or not this was part of public policy, or an intended or unintended consequence of such policy.

Historical Changes of the Ottawa River

Historical changes in the Ottawa River, in northwestern Ohio, are an important link between studies in the Piedmont area of the East Coast of North America (Leopold, 1956; Wolman, 1967; Costa, 1975; Jacobson and Coleman, 1986; Allmendinger et al., 2007; Walter and Merritts, 2008; deWet et al., 2011) and studies in the Upper Mississippi Valley region (Knox, 1977, 1987; Trimble 1981, 1983). This study confirms earlier findings about an initial phase of increased sediment inputs resulting in burial of presettlement soils, sediment storage in presettlement wetlands, and vertical aggradation of floodplains, followed by a phase of reduced sediment inputs resulting in incision and bank erosion. These observations are interpreted conceptually using sediment budgets.

Today, the Ottawa River is a meandering stream with typical features such as point bars, confluence bars, cutbanks, and meander-loop cutoffs. However, for much of its length, the stream is deeply incised, with ≤2.0-m-tall banks hydraulically separating the channel from its floodplain except under very limited high-stage flow conditions. The high banks are sites of erosional undercutting, slumping, and tree-fall, creating erosion problems faced by land managers. It was a natural thought progression to try to address these problems as part of the river restoration effort that included removal of the Ottawa Dam.

The problem is that certain assumptions underlying this restoration approach are incorrect. The presently existing river is not in equilibrium, is demonstrably unstable, and looked fundamentally different in presettlement times. The picture that emerges is that this was a blackwater stream flanked by extensive riparian wetlands (sites of peat formation), with relatively small sediment loads, and apparently low-relief channel banks (allowing floodwaters to carry in silt and particulate organic matter). Among other values, these wetlands provided extensive flood storage capacity. After arrival of European settlers, high sediment loads associated with land clearance changed the Ottawa River to a brownwater stream. At first, the wetlands provided significant accommodation space for storage of excess sediment supply, until the wetlands were infilled, buried, and evolved into clastic floodplains. The evidence also shows that change (sediment vertical accretion in floodplains) accelerated during urbanization after World War II. Thus, the resulting clastic floodplains and fill-terrace morphology presently flanking the modern incised channel are relatively recent features. Whether or not those banks should be defended is both questionable and possibly counterproductive. Using a sediment budget approach to this situation, one could argue that this river is going to continue to attempt to erode and rework legacy sediments until they are either removed from the fluvial system or at least until the sediment supply and transport conveyance capacity are balanced. It may or may not be practical to allow this to happen, depending upon the need to defend or move infrastructure or the effect on property boundaries. However, these issues should at least be openly debated as part of any "river restoration" plan.

Setting aside the historical changes caused by land clearance and urbanization, there are still the more recent hydrological changes that are very directly related to urbanization of the watershed. These include: (1) the fairly recent transition from natural substrates to fluvial pavements (armored surfaces), (2) the measured rate of lateral channel migration of 0.32 m yr^{-1} subsequent to diverting the channel of the river during the 1928 construction of the dam, and (3) the evident attempt of the river to adjust meander wavelength in response to the dam removal in 2007. All of these are evidence of ongoing channel instability and should also be addressed in formulating any river restoration plan. Certainly, it should be a last-resort option to stabilize the channel in place when it is so clearly in the process of adjusting to changes operating over both decadal and centennial time scales.

Public Policy Aspects of This Case Study

The Secor Dam removal and related river restoration efforts for the Ottawa River in northwestern Ohio are an example of a "passive" river restoration project in an urban watershed, and they provide some important insights about these types of projects and about river restoration efforts in general. The first is the importance of understanding the magnitude and rate of historical changes in any project river. This study confirms other findings showing that there has been a two-phase impact of human activity on stream sediment budgets: (1) There was an initial phase of significant intrabasinal storage of legacy sediments due to high sediment input rates from land clearance, disturbance, and soil erosion from agriculture or housing construction in urbanized areas, and (2) there was a more recent phase of incision, bank erosion, lateral channel migration, and riparian tree-fall into channels due to subsequent reductions in sediment inputs (from farm field abandonment, or improved soil conservation practices, or from revegetation of urban construction sites, and combinations thereof) and reworking of legacy sediments. An understanding of sediment budget concepts is critical. For example, these occurrences of localized bank erosion issues are better explained to the general public not as "problems" but as "manifestations of a problem," where that broader underlying problem consists of ongoing, long-term adjustments to sediment budgets.

Second, urban river restoration projects are likely, as this project was, to involve numerous agencies and various constituencies, and might, as this project did, have a complicated funding mechanism reliant on multiple funding sources with different criteria and expectations. In these instances, communication is a key factor, and a unified restoration plan agreed upon by all parties should be the most important first task. The alternative is a more ad hoc approach of decision making, where decisions made by one party, and not necessarily agreed to by others, inevitably limit available choices down the road. An important component of this is the realities of actions and decisions permitted by the different funding agencies. In retrospect, there was a gap in understanding the difference between issues directly controlled by the removal of the dam and more systemic issues that transcended the spatial extent of the dam's influence.

Third, the easiest choice is not necessarily the best choice or even the least expensive choice (in terms of time, money, or effort). Particularly in a project with multiple agencies and constituencies, it was easier to arrive at some operational level of agreement with a "passive" restoration approach (remove the dam and let the river adjust) while targeting specific "hotspots" of bank erosion. There are multiple problems with this approach. First, it effectively ignored all of the advances in scientific understandings of historical changes in rivers. Second, it will require scrambling to constantly repair local problems. Third, it may eventually lead to an engineered solution where much of the banks are protected, raising the question of what constitutes success in river restoration projects (Florsheim et al., 2008). Certainly, it would be hard to advocate that a riprapped ditch is a successful restoration. Countering the arguments for engineered solutions requires hard data to document the rates and magnitude of change in a particular river. This should not be oversimplified to mean there was some pristine predisturbance state that can be reattained, a statement that would not only be theoretically incorrect but practically impossible to achieve (Bain et al., 2008; Wilcox, 2008).

What could have been done in this particular project? Given the evidence that this river transitioned from a blackwater stream flowing through low banks adjacent to riparian wetlands, an interesting active river restoration effort in this case might have been to scale back the anthropogenic fill terraces, confine the low-stage flow between low berms, and restore riparian wetlands outboard of those low berms. The restored riparian wetlands would have provided important habitat, acted to increase floodwater storage, and improved water quality due to natural filtration. Boardwalks or other access points with explanatory signage could have provided a public education function.

That did not happen in this project, but it could have. We propose that hydrologists have a particular role to play in such projects of educating public policy decision makers, the general public, and possibly other involved scientists or engineers about the evidence for, and implications of, long-term anthropogenic impacts on a river system using a sediment budget approach. In projects such as this one, focusing on the removal of a low-head dam, the resulting incision, bank erosion, substrate changes, and lateral migration of the channel are inevitable consequences of manipulations of the stream sediment budget. Failure to understand these key concepts will result in restored rivers that are highly engineered and do not serve the functions of natural river systems.

SUMMARY AND CONCLUSIONS

For a project focusing on removal of a low-head dam, the removal of the Secor Dam on the Ottawa River was relatively unusual because of the wealth of both pre- and post-dam-removal scientific studies. Such studies predicted and then measured the hydrological and sedimentological response of the dam removal (Evans and Harris, 2008; Harris, 2008; Roberts et al., 2007), and looked at synoptic issues of historical changes in the Ottawa River due to urbanization and land clearance (Webb, 2010). The paleohydrological evidence, including data from the pre-1928 paleochannel, showed that the effect of urbanization of the watershed was creation of fluvial pavements in the channels, lateral channel migration rates of 0.32 m yr^{-1}, and rapid floodplain aggradation rates (>1.7 m of aggradation since 1959). The removal of the dam resulted in incision, channel widening, and the start of channel aggradation (and channel narrowing), as anticipated from models and previous case studies (Doyle et al., 2003; Cui et al., 2006; Evans, 2007; Harris, 2008). Incipient changes in meander sinuosity (erosion at the upstream end of the outer bank and erosion at the downstream end of the inner bank) were not anticipated, but they are consistent with overall channel instability. In other words, the conclusion, well supported by the science, is that the Ottawa River has been in a prolonged (both decade- and century-scale) state of channel instability linked to drainage-basin scale anthropogenic activities.

Geomorphic changes related to channel instability have been the focus of numerous studies. One approach is to contrast sediment supply (ratio of available sediment below the dam to available sediment above the dam) with transport conveyance capacity (ratio of the frequency of sediment-transporting flows after dam removal to before dam removal) (Grant et al., 2003). Prior to dam removal, the Ottawa River showed evidence for sediment supply less than transport capacity, such as incision, armoring, and bank erosion. The Ottawa River returned to this condition approximately 3 mo after the dam removal. The intervening ~3 mo interval immediately after dam removal was characterized by sediment supply greater than transport capacity, such as pool infilling by fine-grained sediment, infiltration of fines into gravel matrices, bar construction and migration, and overall channel aggradation. These changes indicate channel instability over decadal time scales that preceded removal of the dam and may continue. Already, the Ottawa River is attempting to outflank or undermine the imposed bank stabilization structures that were the outcome of this river restoration project.

Looking further back in time, paleohydrologic analysis makes it clear that the Ottawa River has been in a status of channel instability over at least the past 60 yr (post-1950), specifically related to urbanization of the drainage basin. These changes included episodic inputs of sediment supply in excess of transport capacity, leading to extraordinarily high rates of floodplain aggradation, lateral channel migration, and flashy discharge associated with higher runoff volumes and frequency related to urbanization of drainage networks. There is no indication that these driving causes of channel instability will not persist for many decades to come. Accordingly, significant incision, armoring, and bank erosion are highly probable outcomes. Even further back in time, operating over a time scale of several centuries, land clearance associated with the arrival of European settlers in this region changed blackwater (organic-sediment rich) streams flowing through riparian wetlands to brownwater streams where wetlands were infilled by clastic sediment and evolved to silt-rich floodplains.

None of this is surprising. However, the evidence for prolonged channel instability raises significant hurdles for any river restoration project. First, there is a need to evaluate whatever baseline model is to be used to guide river restoration, given the likelihood the river has been in a long-term state of channel instability. This is the key step where paleohydrologic and paleogeomorphic analyses can provide necessary data. Second, there is a need to recognize that removing a dam is not synonymous with river restoration. Removing a dam is better stated as a societal decision to replace one aquatic ecosystem with another (Thornton, 2003), or (in our words) to replace one case of channel instability with another. The ramifications are significant—management of a restoration project must be understood as a long-term commitment. Third, rivers should be evaluated as systems and given sufficient lateral space to erode, deposit, and adjust sediment loads, in contrast to the prevailing policy of defending the arbitrary location at which an unstable channel happened to find itself at a particular time. Even in this highly urbanized setting, there was room for active and creative solutions. For example, the fill terraces could have been scaled back, a low berm could have been constructed to channel the river at low-flow stage, and the floodplain could have been replaced with reconstructed riparian wetlands. In this particular case, there was too much emphasis on removing the dam (which was the easiest and least complicated part of the entire project) and neither the patience nor the funding viability to deal with the complex fluvial response that followed. In other words, the true goal of river restoration was lost in the decision-making process.

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REFERENCES CITED

Allmendinger, N.E., Pizzuto, J.E., Moglen, G.E., and Lewicki, M., 2007, A sediment budget for an urbanizing watershed 1951–1996, Montgomery County, Maryland, U.S.A.: Journal of the American Water Resources Association, v. 43, p. 1483–1498.

Anderhalt, R., Kahle, C.F., and Sturgis, D., 1984, The sedimentology of a Pleistocene glaciolacustrine delta near Toledo, Ohio, *in* Carter, C.H., and Guy, D.E., Jr., eds., Field Guidebook to the Geomorphology and Sedimentology of Late Quaternary Lake Deposits, Southwestern Lake Erie: 14th Annual Field Conference of the Great Lakes Section of SEPM: Tulsa, Oklahoma, SEPM, p. 59–90.

Bain, D.J., Smith, S.M.C., and Nagle, G.N., 2008, Reservations about dam findings: Science, v. 321, p. 910, doi:10.1126/science.321.5891.910a.

Baker, D.B., Richards, R.P., Loftus, T.T., and Kramer, J.W., 2004, A new flashiness index: Characteristics and applications to Midwestern rivers and streams: Journal of the American Water Resources Association, v. 40, p. 503–522, doi:10.1111/j.1752-1688.2004.tb01046.x.

Bednarek, A.T., 2001, Undamming rivers: A review of the ecological impacts of dam removal: Environmental Management, v. 27, p. 803–814, doi:10.1007/s002670010189.

Beighley, R.E., and Moglen, G.E., 2002, Assessment of stationarity in rainfall-runoff behavior in urbanizing watershed: Journal of Hydrologic Engineering, v. 7, p. 27–34, doi:10.1061/(ASCE)1084-0699(2002)7:1(27).

Black Swamp Conservancy, 2009, Black Swamp Conservancy: http://www.blackswamp.org/ (accessed 14 April 2009).

Booth, D.B., and Jackson, C.R., 1997, Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation: Journal of the American Water Resources Association, v. 33, p. 1077–1090, doi:10.1111/j.1752-1688.1997.tb04126.x.

Carter, R.W., 1961, Magnitude and Frequency of Floods in Suburban Areas: Washington, D.C.: U.S. Geological Survey Professional Paper 424-B, p. 9–11.

Coakley, J.P., 1992, Holocene transgression and coastal-landform evolution in northeastern Lake Erie, Canada, *in* Quaternary Coasts of the United States, Marine and Lacustrine Systems: Tulsa, Oklahoma, SEPM (Society for Sedimentary Geology) Special Publication 48, p. 416–426.

Coogan, A.H., 1996, Ohio's surface rocks and sediments, *in* Feldman, R.M., and Hackathorn, M., eds., Fossils of Ohio: Ohio Division of Geological Survey Bulletin 70, p. 31–50.

Costa, J.E., 1975, Effects of agriculture on erosion and sedimentation in the Piedmont province, Maryland: Geological Society of America Bulletin, v. 86, p. 1281–1286, doi:10.1130/0016-7606(1975)86<1281:EOAOEA>2.0.CO;2.

Cruise, J.F., Layman, C.A., and Al-Hamdan, O.Z., 2010, Impact of 20 years of land-cover change on the hydrology of streams in the southeastern United States: Journal of the American Water Resources Association, v. 46, no. 6, p. 1159–1170, doi:10.1111/j.1752-1688.2010.00483.x

Cui, Y., Parker, G., Braudrick, C., Dietrich, W.E., and Cluer, B., 2006, Dam removal express models (DREAM): Part I. Model development and validation: Journal of Hydraulic Research, v. 44, p. 291–307, doi:10.1080/00221686.2006.9521683.

Derrick, D.L., and Jones, M.M., 2010, Innovative Streambank Protection in an Urban Setting, Accotink Creek, VA: U.S. Army Corps of Engineers Report ERDC/CHL CHETN-VII-10, August 2010, 22 p.

deWet, A., Williams, C.J., Tomlinson, J., and Loy, E.C., 2011, Stream and sediment dynamics in response to Holocene landscape changes in Lancaster County, Pennsylvania, *in* LePage, B.A., ed., Wetlands, Integrating Multidisciplinary Concepts: New York, Springer Science + Business Media B.V., doi:10.1007/978-94-007-0551-7_3.

Dietrich, W.E., and Smith, J.D., 1984, Bed load transport in a river meander: Water Resources Research, v. 20, p. 1355–1380, doi:10.1029/WR020i010p01355.

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2002, Geomorphic analogies for assessing probable channel response to dam removal: Journal of the American Water Resources Association, v. 38, p. 1567–1579, doi:10.1111/j.1752-1688.2002.tb04365.x.

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2003, Channel adjustments following two dam removals in Wisconsin: Water Resources Research, v. 39, p. 1011–1026, doi:10.1029/2002WR001714.

Evans, J.E., 2007, Sediment impacts of the 1994 failure of IVEX dam (Chagrin River, NE Ohio): A test of channel evolution models: Journal of Great Lakes Research, v. 33, Special issue 2, p. 90–102.

Evans, J.E., and Harris, N., 2008, Preliminary study of the sediment impacts of the 2007 removal of the Secor Dam (Ottawa River, Ohio), *in* Davenport, T., Gibson, R., Bonnell, J., and D'Ambrosio, J., eds., Conference Proceedings of the 16th National Nonpoint Source Monitoring Workshop, 14–18 September 2008: Columbus, Ohio, U.S. Environmental Protection Agency/Ohio Environmental Protection Agency/Ohio State University Extension Service, p. 57–58.

Evans, J.E., Mackey, S.D., Gottgens, J.F., and Gill, W.M., 2000a, From reservoir to wetland: The rise and fall of an Ohio dam, *in* Schneiderman, J.A., ed., The Earth around Us: Maintaining a Livable Planet: San Francisco, W.H. Freeman, p. 256–267.

Evans, J.E., Mackey, S.D., Gottgens, J.F., and Gill, W.M., 2000b, Lessons from a dam failure: The Ohio Journal of Science, v. 100, p. 121–131.

Evans, J.E., Gottgens, J.F., Gill, W.M., and Mackey, S.D., 2000c, Sediment yields controlled by intrabasinal storage and sediment conveyance over the interval 1842–1994, Chagrin River, northeast Ohio: Journal of Soil and Water Conservation, v. 55, p. 263–269.

Evans, J.E., Levine, N.S., Roberts, S.J., Gottgens, J.F., and Newman, D.M., 2002, Assessment using GIS and sediment routing of the proposed removal of Ballville Dam, Sandusky River, Ohio: Journal of the American Water Resources Association, v. 38, p. 1549–1565, doi:10.1111/j.1752-1688.2002.tb04364.x.

Faulkner, D., and McIntyre, S., 1996, Persisting sediment yields and sediment delivery changes: Water Resources Bulletin, v. 32, p. 817–829, doi:10.1111/j.1752-1688.1996.tb03479.x.

Florsheim, J.L., Mount, J.F., and Chin, A., 2008, Bank erosion as a desirable attribute of rivers: Bioscience, v. 58, p. 519–529, doi:10.1641/B580608.

Folk, R.L., and Ward, W.C., 1957, Brazos River bar: A study on the significance of grain-size parameters: Journal of Sedimentary Petrology, v. 27, p. 3–26.

Forsyth, J.L., 1973, Late-glacial and postglacial history of western Lake Erie: Compass, v. 51, p. 16–26.

Gallagher, R.E., 1978, Ottawa River (Tenmile Creek) Hydrology: Streamflow Quantity and Erosion at Toledo, Ohio [M.S. thesis]: Toledo, Ohio, University of Toledo, 187 p.

Gellis, A.C., Webb, R.M.T., Wolfe, W.J., and McIntyre, S.C.I., 1996, Land use, upland erosion, and reservoir sedimentation, Lago Loiza, Puerto Rico: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 79.

Gerwin, K., 2003, Land-Use Changes in the Ottawa River Watershed: http://www.utoledo.edu/as/geography/pdfs/research_gerwin2.pdf (accessed 14 April 2009).

Gottgens, J.F., Evans, J.E., Levine, N.S., Roberts, S.J., and Spongberg, A.L., 2004, Dam Removal in the Ottawa River, Ohio: A Feasibility Study: Toledo, Report to the Ohio Department of Natural Resources, Office of Coastal Management, 72 p.

Grant, E.G., Schmidt, J.C., and Lewis, S.L., 2003, A geological framework for interpreting the downstream effect of dams on rivers: American Geophysical Union, Water Science and Application, v. 7, p. 203–219.

Harris, N., 2008, Sedimentological Response of the 2007 Removal of a Low-Head Dam, Ottawa River, Toledo, Ohio [M.S. thesis]: Bowling Green, Ohio, Bowling Green State University, 228 p.

Heinz Center, 2002, Dam Removal: Science and Decision Making: Washington, D.C., The Heinz Center for Science, Economics, and the Environment, 221 p.

Holcombe, T.L., Taylor, L.A., Reid, D.F., Warren, J.S., Vincent, P.A., and Herdendorf, C.E., 2003, Revised Lake Erie postglacial lake level history based on new detailed bathymetry: Journal of Great Lakes Research, v. 29, p. 681–704, doi:10.1016/S0380-1330(03)70470-5.

Jacobson, R.B., and Coleman, D.J., 1986, Stratigraphy and recent evolution of Maryland Piedmont floodplains: American Journal of Science, v. 286, p. 617–637, doi:10.2475/ajs.286.8.617.

Julien, P.Y., 2002, River Mechanics: Cambridge, UK, Cambridge University Press, 434 p.

Knox, J.C., 1977, Human impacts on Wisconsin stream channels: Annals of the Association of American Geographers, v. 67, p. 323–342, doi:10.1111/j.1467-8306.1977.tb01145.x.

Knox, J.C., 1987, Historical valley floor sedimentation in the Upper Mississippi Valley: Annals of the Association of American Geographers, v. 77, p. 224–244, doi:10.1111/j.1467-8306.1987.tb00155.x.

Kroes, D.E., and Hupp, C.R., 2010, The effect of channelization on floodplain sediment deposition and subsidence along the Pocomoke River, Maryland: Journal of the American Water Resources Association, v. 46, p. 686–699, doi:10.1111/j.1752-1688.2010.00440.x.

Kuhnle, R.A., Binger, R.L., Foster, G.R., and Grissinger, E.H., 1996, The effect of land use changes on sediment transport in Goodwin Creel: Water Resources Research, v. 32, p. 3189–3196.

Larson, G., and Schaetzl, R., 2001, Origin and evolution of the Great Lakes: Journal of Great Lakes Research, v. 27, p. 518–546, doi:10.1016/S0380-1330(01)70665-X.

Leopold, L.B., 1956, Land use and sediment yield, *in* Thomas, W.L., Jr., ed., Man's Role in Changing the Face of the Earth: Chicago, University of Chicago Press, p. 639–647.

Mannik-Smith Group, Inc., 2008, Ottawa River Habitat Restoration Inventory: http://www.tmacog.org/Environment/Ottawa_River_Habitat/Ottawa_River_Habitat_Restoration_Inventory.pdf (accessed 5 May 2009).

Meierdiercks, K.L., Smith, J.A., Baeck, M.L., and Miller, A.J., 2010, Heterogeneity of hydrologic response in urban watershed: Journal of the American Water Resources Association, v. 46, no. 6, p. 1221–1237, doi:10.1111/j.1752-1688.2010.00487.x.

Murray, A.S., and Wintle, A.G., 2000, Luminescence dating on quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, p. 57–73, doi:10.1016/S1350-4487(99)00253-X.

Pizzuto, J.E., 2002, Effects of dam removal on river form and process: Bioscience, v. 52, p. 683–692, doi:10.1641/0006-3568(2002)052[0683:EODROR]2.0.CO;2.

Pizzuto, J.E., Hession, W.C., and McBride, M., 2000, Comparing gravel-bedded rivers in paired urban and rural catchments of southeastern Pennsylvania: Geology, v. 28, p. 79–82, doi:10.1130/0091-7613(2000)028<0079:CGRIPU>2.0.CO;2.

Roberts, S.J., Gottgens, J.F., Spongberg, A.L., Evans, J.E., and Levine, N.S., 2007, Assessing potential removal of low-head dams in urban settings: An example from the Ottawa River, NW Ohio: Environmental Management, v. 39, p. 113–124, doi:10.1007/s00267-005-0091-8.

Segura, C., and Booth, D.B., 2010, Effects of geomorphic setting and urbanization on wood, pools, sediment storage, and bank erosion in Puget Sound streams: Journal of the American Water Resources Association, v. 46, p. 972–986, doi:10.1111/j.1752-1688.2010.00470.x.

Selle, A., Burke, M., Melchior, M., and Koonce, G., 2007, Active versus passive channel recovery following dam removal: A comparison of approaches, *in* Kabbes, K.C., ed., Proceedings of the 2007 World Environmental and Water Resources Congress, Restoring Our Natural Habitat, May 15–19, 2007, Tampa, Florida: Washington, D.C., American Society of Civil Engineering, Environmental and Water Resources Institute, p. 3856–3865.

Simons, R.K., and Simons, D.B., 1991, Sediment problems associated with dam removal—Muskegon River, Michigan, *in* Shane, R.M., ed., Proceedings of the 1991 National Conference of the American Society of Civil Engineers: New York, American Society of Civil Engineers, p. 680–685.

Stuiver, M., and Reamer, P.J., 1993, Radiocarbon calibration program—Calib rev5.0.2: Radiocarbon, v. 35, p. 215–230.

Thornton, J.A., 2003, Discussion of "Geomorphic analogies for assessing probable channel response to dam removals," by Martin W. Doyle, Emily H. Stanley, and Jon M. Harbor: Journal of the American Water Resources Association, v. 38, p. 1567–1579.

Trimble, S.W., 1981, Changes in sediment storage in the Coon Creek basin, Driftless Area, Wisconsin, 1853–1975: Science, v. 214, p. 181–183, doi:10.1126/science.214.4517.181.

Trimble, S.W., 1983, A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853–1977: American Journal of Science, v. 283, p. 454–474, doi:10.2475/ajs.283.5.454.

Trimble, S.W., and Lund, S.W., 1982, Soil Conservation and the Reduction of Erosion and Sedimentation in the Coon Creek Basin, Wisconsin: U.S. Geological Survey Professional Paper 1234, 35 p.

Walter, R.C., and Merritts, D.J., 2008, Natural streams and the legacy of water-powered mills: Science, v. 319, p. 299–304, doi:10.1126/science.1151716.

Webb, L.D., 2010, Historical Changes in the Geomorphology of the Ottawa River (NW Ohio, U.S.A.) due to Urbanization and Land Clearance [M.S. thesis]: Bowling Green, Ohio, Bowling Green State University, 169 p.

Whitten, D., 2010, Glass Factory Marks on Bottles: http://www.myinsulators.com/glass-factories/bottlemarks.html (accessed 12 May 2010).

Wilcock, P., 2008, What to do about those dammed streams: Science, v. 321, p. 910–912, doi:10.1126/science.321.5891.910b.

Wilhelm, P.W., 1984, Draining the Black Swamp: Henry and Wood Counties, Ohio, 1870–1920: Northwest Ohio Quarterly, v. 56, p. 79–95.

Wolman, M.G., 1967, A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler, v. 49A, p. 45–62.

Wolman, M.G., and Schink, A.P., 1967, Effects of construction on fluvial sediment: Water Resources Research, v. 3, p. 451–464, doi:10.1029/WR003i002p00451.

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