JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 38, NO. 6 AMERICAN WATER RESOURCES ASSOCIATION DECEMBER 2002

ASSESSMENT USING GIS AND SEDIMENT ROUTING OF THE PROPOSED REMOVAL OF BALLVILLE DAM, SANDUSKY RIVER, OHIO[1]

James E. Evans, Norman S. Levine, Sheila J. Roberts, Johan F. Gottgens, and Diane M. Newman[2]

ABSTRACT: The proposed removal of Ballville Dam was assessed by (1) using a new Geographic Information Systems (GIS) based method for calculating reservoir sediment storage, (2) evaluating sediment properties and contamination from core data, and (3) assessing downstream impacts from sediment routing calculations. A 1903 (pre-dam) map was manipulated using GIS to recreate the reservoir bathymetry at time of dam construction and used in combination with a detailed 1993 bathymetric survey to calculate sediment volumes and thickness. Reservoir sediment properties and geochemistry were determined from 14 sediment vibracores. Annual sedimentation rates varied from 1.7 to 4.3 g/cm^2/yr based on Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) geochronology and dated flood layers. The pore fluid geochemistry (Ba, Co, Cu, Mn) of four cores showed surficial enrichments in Cu, while Co and Mn show secondary peaks within the sediments. GIS calculations showed that a designed channel through the former reservoir able to accommodate the 10 percent Probable Maximum Flood (PMF) would require removing approximately 0.35 million m^3 of sediment (27 percent of the reservoir fill), either by dredging at a cost of up to $6.3 million or by releasing fine grained sediment downstream. A sediment routing model was applied for the critical 6 km downstream using four cross sections. The sediment routing model predicts that, for flows exceeding minimum Mean Daily Flow (1924 to 1998 data), greater than 90 percent of this sediment would be transported through downstream reaches into Lake Erie (Sandusky Bay).
(KEY TERMS: dams and dam removals; erosion and sedimentation; Geographical Information Systems; surface water hydrology; watershed management.)

INTRODUCTION

This paper reports the results of evaluating the options, costs, and impacts of removing the Ballville Dam, a structure constructed in 1911 on the Sandusky River in northwestern Ohio. This would be the first large dam deliberately removed in Ohio, and thus this report is a necessary first step in educating the public and public policy makers regarding the scientific basis for making these decisions.

There are several reasons why dam removals challenge public understanding. First there is the perception that the "typical" dam is one of the large, relatively new, federal hydropower dams in the western United States (U.S.). The facts are the opposite of these perceptions. There are 75,561 "major" dams in the U.S. (taller than 7.6 m or impounding more than 61,650 m^3). Most of these are smaller and older structures, and about 90 percent are privately owned (Costa, 1988; Shuman, 1995; FEMA, 2002). In addition, few people are aware that dams, like all public works, have design life expectancies. The design life expectancy of a dam can be extended by regular maintenance (including sediment removal from the reservoir), yet this is often not done. The Federal Emergency Management Agency (FEMA) found that about 9200 dams in the U.S. are classed as high hazard because of inadequate spillway design, lack of emergency spillways, inadequate dam maintenance, and/or lack of active sediment management (FEMA 2002). About 35 percent of these hazardous dams have not had safety inspections in over 10 years (FEMA, 2002). For a more detailed review of this subject, see Shuman (1995) and Doyle *et al.* (2000).

The concept that dams and reservoirs can change from assets to liabilities is a recent and contentious public perception. In northern Ohio public attention was drawn to the "involuntary dam removal" (i.e., dam failure) of IVEX dam on the Chagrin River in

[1]Paper No. 01158 of the *Journal of the American Water Resources Association.* **Discussions are open until June 1, 2003.**
[2]Respectively (Evans, Levine, and Roberts), Department of Geology, 190 Overman Hall, Bowling Green State University, Bowling Green, Ohio 43403; Department of Earth, Ecological, and Environmental Sciences, University of Toledo, 2801 West Bancroft Street, Toledo, Ohio 43606; and Graduate Student, Department of Geology, Bowling Green State University, Bowling Green, Ohio 43403 (E-Mail/Evans: evansje@bgnet.bgsu.edu).

northeastern Ohio (Evans *et al.,* 2000a; Evans *et al.,* 2000b,c). This dam, constructed in 1842, had suffered 86 percent storage capacity loss due to sedimentation over its 152 year history. The dam failed catastrophically on August 13, 1994, following a 70 year rainfall event (13.5 cm of rainfall within 24 hours). Because of inadequate spillway design, lack of an emergency spillway, and loss of reservoir storage capacity, the reservoir pool level swiftly rose to the top of the dam. Prior to overtopping, the dam failed from seepage piping failure, probably due to poor dam maintenance (growth of trees on the earth fill dam may have provided piping pathways). The reservoir dewatered within two to three minutes, releasing 38,000 m^3 (about 10 million gallons) of impounded sediment and water, and causing significant damage downstream (Evans *et al.,* 2000b). Regardless of the potential for science and engineering to maintain any given dam into perpetuity, the realities of funding and regulatory oversight are such that thousands of dams are now liabilities for communities that may be unaware of the risk.

Ballville Dam became an issue because of four significant health and safety issues. First, the existing spillway capacity is inadequate for flows exceeding the 25 percent Probable Maximum Flood (PMF) flows (USACE, 1981). This flow level was exceeded in 1913, when an earlier version of the dam failed (USACE, 1981). Cost estimates for modifying the existing dam are currently about $700,000 (Brice, 2000). Second, the primary use of the Ballville Reservoir as public water supply for about 20,500 people (Overmyer and Brown, 1990) is threatened by degraded water quality. The upstream watershed is approximately 85 percent agricultural. Water chemistry data for limited time periods are available from a U.S. Geological Survey (USGS) gaging station (No. 04198000) located immediately upstream of the Ballville Reservoir. These data show pesticide Alachlor values up to 36 µg/l between 1988 and 1994, and fertilizer nitrate plus nitrite concentrations up to 23 mg/l between 1979 and 1995. For these reasons, the City of Fremont has recently purchased 60 ha of land for an off stream water storage facility to operate during nitrate alerts. In addition, there have been two recent hazardous waste spills on upstream tributaries: a 1988 toluene leak of 757,000 liters from a pipeline, and runoff from a 1999 fire that consumed over 5 million tires at a recycling facility (Bates, 2000a,b). Third, bathymetry data show that the reservoir has lost 78 percent storage capacity to sedimentation over the interval 1911 to 1993 (the latest available bathymetric data). Projections of water capacity need (Feller *et al.,* 1987) versus storage capacity loss indicate an inadequate water supply within three to five years. Finally, the dam is a barricade to fisheries habitat. Historical fisheries data for the Sandusky and Maumee Rivers in northwestern Ohio indicate over 100 native fish species existed prior to land clearance for agriculture in the late 1800s (Trautman, 1975). Since the 1940s, about 40 percent of these have suffered significant declines or have been extirpated due to increased turbidity and siltation related to agricultural runoff. A current concern is the status of walleye pike, a major game fish. The ideal walleye habitat is fast flowing water with a pebble to boulder substrate. These conditions existed upstream on the Sandusky River for about 40 km prior to dam construction in 1911 and prior to river channelization and floodwall construction in the City of Fremont during 1972 [approximately river kilometer (RK) 10 to RK 13]. After these modifications, useful walleye habitat has been reduced to a 3 km reach (approximately RK 13 to RK 16) between the dam and the 1972 channelization and floodwall project (Pollick, 1993). State agencies [Ohio Department of Natural Resources (ODNR)-Wildlife] have advocated removing the dam to restore a larger walleye run (Tressler, 2000).

BACKGROUND

Ballville Dam is located adjacent to the City of Fremont, on the Sandusky River, in northwestern Ohio (Figure 1). The Sandusky River has a total drainage area of 3,680 km^2, of which 3,240 km^2 is located upstream of the Ballville Reservoir. The drainage basin is about 97 km north south by 77 km east west. Most major tributaries are located upstream of the reservoir. The total stream length is 210 km, and the Ballville Dam is at RK 16. The Sandusky River has a rectangular drainage pattern due to both structural control of NW/NE fractures and joint sets in the underlying bedrock (Silurian and Devonian carbonate and shale), and north trending glacial buried valleys (Forsyth, 1975). The bedrock surface is only exposed in a few stream cuts or in quarries, typically being buried beneath clay rich glacial tills or glacial, lacustrine silts and clays about 15 m thick (Forsyth, 1975). The Sandusky River has a relatively smooth longitudinal profile, with a mean gradient of 0.74 m/km. One important exception is at the site of Ballville Dam, where shallow bedrock created a 2.5 m waterfall with rapids and gravel bars that extends for several kilometers downstream. Below this, the Sandusky River is estuarine in character, due to flooding of the mouth of the river as glacial isostatic rebound raised the outlet of Lake Erie (Forsyth, 1975).

Flood records are available from USGS gaging station No. 04198000 at RK 19.4, at the upstream end of

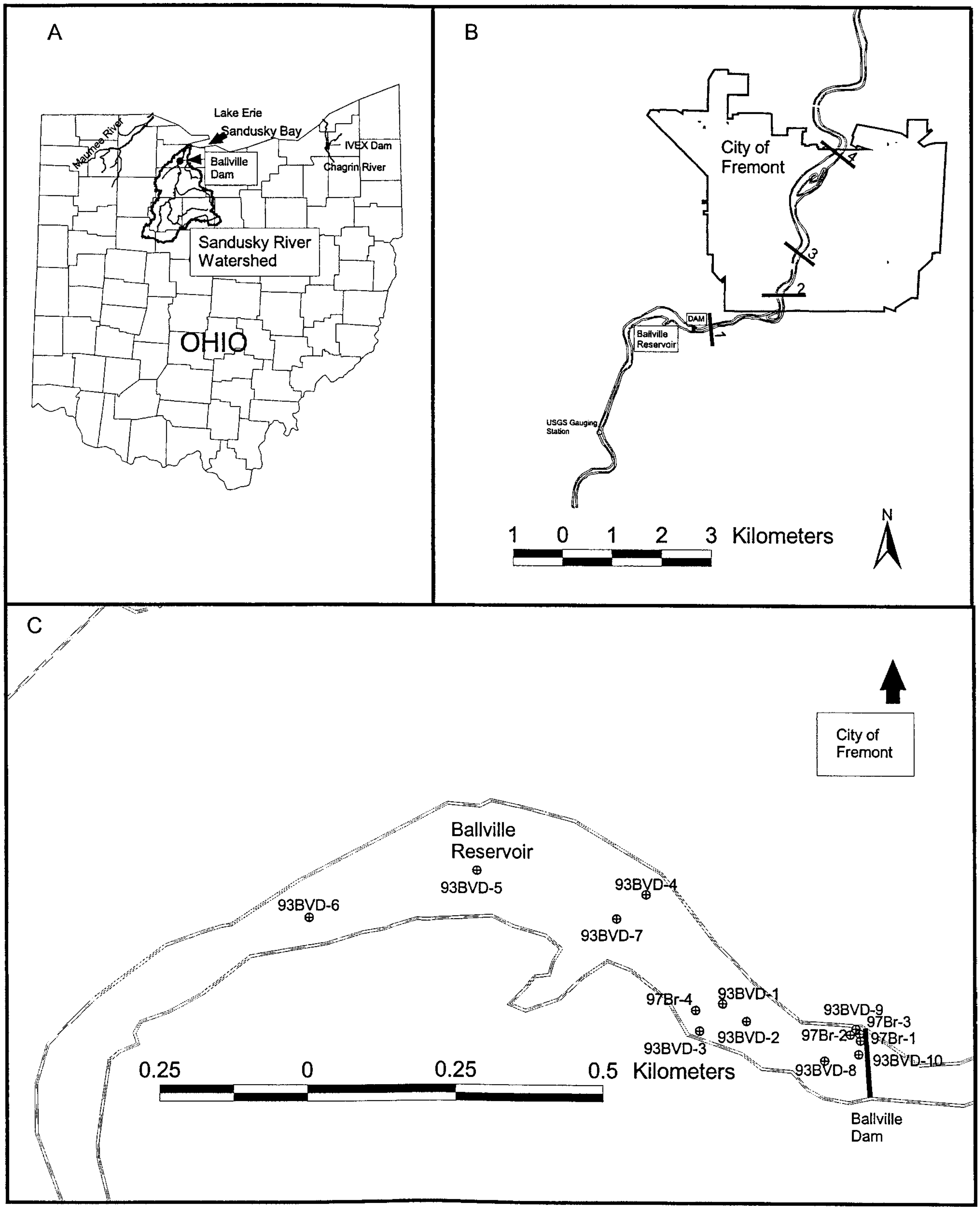

Figure 1. Location Maps Showing: (A) Location of the Sandusky River Watershed in Northwestern Ohio; (B) Location of the Ballville Reservoir, Ballville Dam, City of Fremont, Four Downstream Cross Sections, and the USGS Gaging Station; and (C) Location of Cores in the Ballville Reservoir.

the Ballville Reservoir. Gage records exist for 1924 to the present, including suspended sediment data for 1978 to the present (USGS, 2002). Data indicate that bedload transport on this river is less than 5 percent of total sediment load (Hindall, 1991). The mean annual discharge between 1924 and 1998 is 29 m^3/sec (USGS, 2001). The highest recorded discharge was 1022 m^3/sec in 1978, although the peak discharge of the (ungaged) 1913 flood is estimated at 1,798 m^3/sec (USACE, 1981). The 1913 flood was probably a greater than 200 year recurrence interval event (Figure 2). Other significant floods occurred in 1927, 1930, 1933, 1950, 1959, 1963, 1971, 1979, 1981, 1984, 1985, 1990, and 1997 (USGS, 2002).

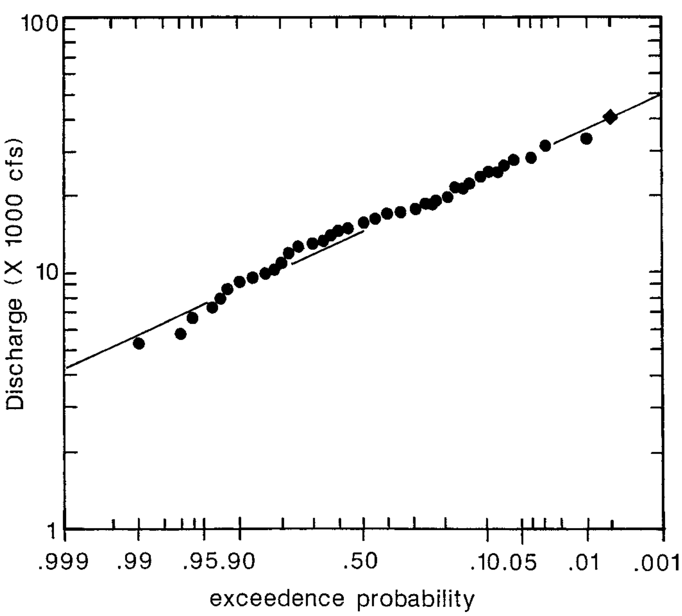

Figure 2. Lognormal Plot of Exceedence Probabilities for Annual Series Data From the Sandusky River From 1924 to 1998. The diamond shows the projected 25 percent PMF (approximately 200 year recurrence interval). The 1913 flood is not shown (recurrence interval greater than 200 years). Data is from the USGS gaging station at the upstream end of the Ballville Reservoir (USGS 04198000).

The region around the Ballville Reservoir was originally prairie, wet prairie, wetland, oak savanna, and riparian forest (Sears, 1926; Gordon, 1966, 1969; Forsyth, 1975) representing the easternmost extent of the "Prairie Peninsula" region of North America (Transeau, 1935). Settlement goes back to the early 1800s, mostly by hunters or trappers (Howe, 1908; Kaatz, 1955). Poor drainage prevented significant land clearance in this region until the late 1800s, with the advent of large scale agriculture, tile drains, and major ditching projects (Kaatz, 1955; Noble, 1975; Pyle, 1975; Wilhelm, 1984).

The Ballville Dam was constructed in 1911 by the Ohio Power Company for hydroelectric generation. The original dam was severely damaged in the 1913 flood, and was enlarged when reconstructed to its present configuration (Figure 3). The existing dam is 10.5 m tall, with two spillways (69.5 m and 26.4 m long) separated by a nonoverflow central section (28.2 m long) for a total length of 124 m (USACE, 1981). The dam is anchored about 1.5 m into bedrock along the bed and south bank, and by a 214 m long concrete floodwall along the north bank. The reservoir is long (about 3.4 km) and narrow (typically less than 150 m), reflecting flooding and widening of the river upstream of the dam. The facility ceased hydroelectric generation in 1946 and was purchased by the City of Fremont for water supply in 1959 (Dobson-Lindbloom Associates, 1983). Maintenance of the structure has been relatively minor – debris removal around the penstock intakes during the 1940s and 1950s, and drawdown to repair the dam and modify the intake structures in 1969 (USACE, 1981). Safety inspections were conducted in 1981 and 1998 by the ODNR. Finally, there was a recent application to the Federal Energy Regulatory Commission to restore the hydroelectric generating capacity of the structure (Universal Electric Power Corporation, 1999).

METHODS

Sediment Cores

Ten 8 cm-diameter vibracores were collected in 1993, and four additional vibracores were collected in 1997 (Figure 1). The 1993 cores were split lengthwise, one half was archived and the other half was cleaned, photographed, and extensively sampled for grain size analysis and geochronology. The 1997 cores were extruded in sections for pore water chemistry (described later). Cores were collected in water up to 4.4 m deep. The vibracorer penetrated through the reservoir sediments until hitting bedrock in all situations, as verified by multiple cores within a limited area at most core sites. The maximum sediment thickness was 3.2 m just upstream of the dam. The thickness of each sediment core was affected by the vibracorer, and was corrected by a comparison of the mud line on the outside of the core with the actual thickness of the core (average correction was 28 percent).

The stratigraphy of the 1993 cores allowed the recognition of historical flood layers. Flood horizons were recognized as fining upward sequences, often with basal erosion surfaces and/or an organic rich

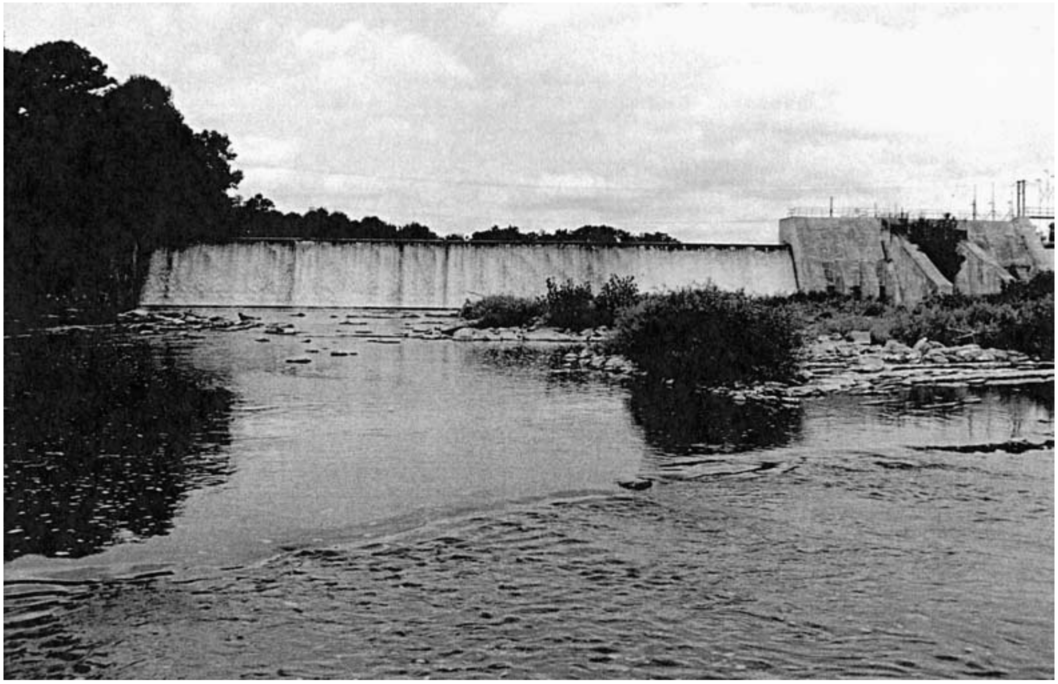

Figure 3. Photograph Showing the Southern Overflow Section of the Ballville Dam and Old Penstock in the Central (nonoverflow) Portion.

(leaf litter) capping layer. The ages of the flood horizons was calculated using geochronology (described later) and by using anthropogenic materials found in some cores (such as aluminum foil, plastic, and construction debris). For example, construction debris from the 1969 dam repairs is found above the 1963 flood horizon, as determined by the peak concentrations of ^{137}Cs (Figure 4). Apparently aluminum foil and certain plastic products arrived in the sediments of Ballville Reservoir soon after they became commercially introduced to this region, according to product information available from their manufacturers (personal communication, Reynolds Aluminum Company, June 26, 1987).

Each sediment horizon in the cores had to be corrected for differential sediment compaction due to the mass of the overlying sediment. This was accomplished by using porosity data obtained by sampling discrete intervals from each core, and accurately obtaining the mass of each sample before and after oven drying at 105°C. By assuming 100 percent initial saturation, porosity for each interval can be obtained as

$$\phi_i = [M_w / \rho_w] / [(M_w / \rho_w) + (M_s / \rho_s)] \quad (1)$$

where ϕ_i is the porosity of some core interval i; M_w is the mass of water in that core interval; M_s is the mass of solids in that core interval; ρ_w is the density of water (assumed to be 1.00 g/cm^3); and ρ_s is the density of solids (assumed to be 2.60 g/cm^3)

The actual thickness of each sediment layer (t_i) is the *in situ* thickness (t_i') times the ratio of the final compaction porosity (ϕ') to the interval porosity (ϕ_i).

$$t_i = t_i' (\phi' / \phi_i) \quad (2)$$

The actual depth from the surface down to any interval in the core, as corrected for compaction, is the summation of the overlying interval thickness, or

$$z = \Sigma_0^x t_i \quad (3)$$

where z is the depth to the xth sediment layer.

Geochronology

^{137}Cs is a bomb fallout isotope having a 30.2 year half life and strongly adsorbs to fine grained sediments. As ^{137}Cs does not occur naturally, its presence in sediments can be correlated to the historical hydrogen bomb tests. The oldest sediments containing detectable levels of ^{137}Cs are generally interpreted as 1952 ± 2 years (e.g., McCall *et al.,* 1984). Subsequent peaks correspond to intervals of significant testing in 1957 to 1958 and 1962 to 1963, with lower values between 1959 and 1961 due to a moratorium on testing, and after 1963 due to the Limited Test Ban Treaty (sediment ages are typically about one year younger than testing intervals due to cesium atmospheric residence time). Exceptions include slightly higher values in 1971 and 1974 (due to open air tests by nontreaty nations) and in 1985 (due to the Chernobyl accident). ^{137}Cs has been used to calculate soil erosion rates and sediment accumulation rates within drainage basins (Pennington *et al.,* 1973; Ritchie *et al.,* 1973; Ritchie *et al.,* 1975; Oldfield *et al.,* 1980; Campbell *et al.,* 1982, 1988; McCall *et al.,* 1984; Walling and Bradley 1988; Ritchie and McHenry 1990; Evans *et al.,* 2000a; Evans *et al.,* 2000b).

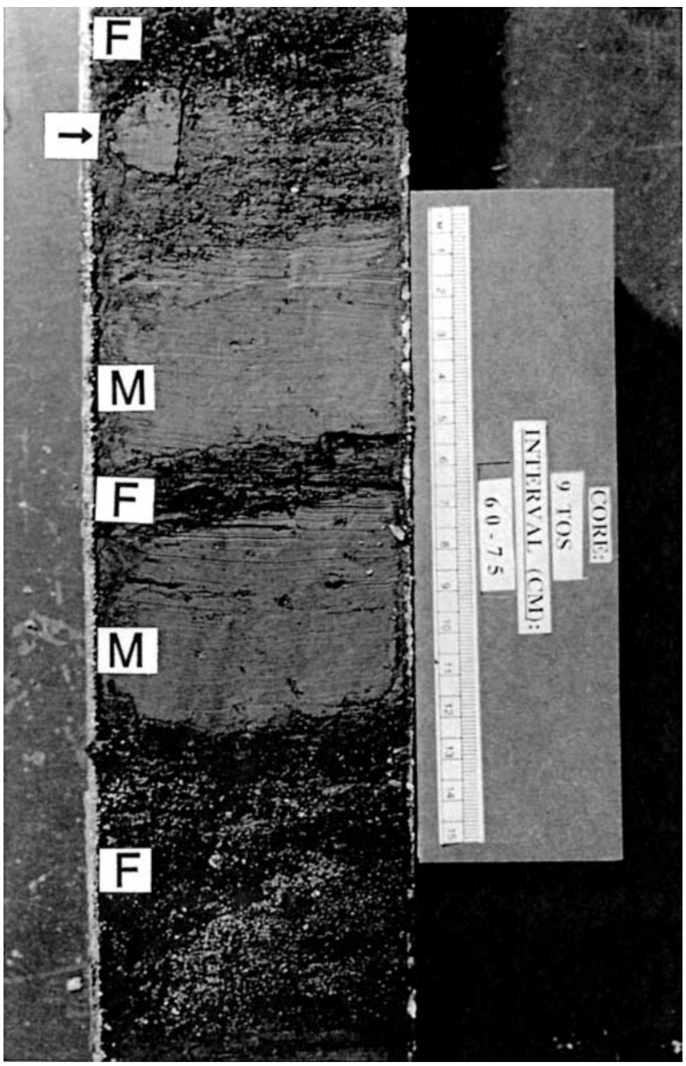

Figure 4. Photograph of Part (60 to 75 cm) of a Sediment Core (93BVD-9) From Near the Ballville Dam. This core shows coarse grained flood layers (F), separated by silty mud intervals (M). Note construction debris from 1969 dam repairs (arrow points at piece of a brick) above the 1963 flood horizon (as determined from geochronology).

^{210}Pb geochronology makes use of the natural decay of atmospheric Radon-222 (^{210}Rn) to ^{210}Pb, which is subsequently deposited as dry fallout on land and water surfaces. In lake sediments, the decay of "unsupported" ^{210}Pb (i.e., delivered by dry fallout, as opposed to produced within the sediments by decay of *in situ* ^{222}Rn) allows calculation of sedimentation rates (Krishnaswamy and Lal, 1978; Evans *et al.,* 1981).

One core (93BVD-8) was utilized for ^{210}Pb and ^{137}Cs analysis. Twenty-five samples representing 1 cm intervals in the core were collected, dried at 95°C for 24 hours, pulverized, weighed, and placed in low density polypropylene tubes of 4 ml capacity. The tubes were then sealed and stored a minimum of 21 days to allow for the equilibration of Radium-226 (^{226}Ra) to ^{222}Rn. Radioisotope activities were determined using low background, high purity, germanium gamma counting in a 14.5 mm by 40.0 mm well detector (EPRI, 1996). The detector operates at a positive bias of 1800V and at a temperature of liquid nitrogen provided by a high vacuum cryostat dewar system. Counts were obtained with a 4096 channel analyzer calibrated at 0.186 keV/channel. Samples were generally counted for 24 hours, but variable times were used for lower sample weights. Counts were corrected for Compton scattering by subtracting the areas below the peak from the total counts. Calibration and determinations of background are discussed elsewhere (Gottgens *et al.,* 1999). The stratigraphic resolution of the ^{137}Cs peak in this core was determined to be ±1.75 years, using the methods of Miller and Heit (1986).

Sediment Geochemistry

Trace metal analyses for barium, cobalt, copper, and manganese were conducted on pore waters squeezed from four vibracores collected in 1997. These cores were promptly cut into 10-cm sections, and the sediment extracted with a plunger. The pore waters were separated from the sediment by centrifuging or by squeezing with a special device (Newman, 1998). Additional centrifuging was used to remove fine grained particulates from pore water samples. Sample contamination was addressed by evaluating pure water samples after prolonged contact with core tubes or other sampler materials. Graphite furnace, atomic absorption spectroscopy (AAS) was used for determining metals concentrations. Three replicates of each metal were done for each sample and standard. Calibration of samples and standards are discussed in detail elsewhere (Newman, 1998).

Sediment Thickness Maps (GIS Analyses)

GIS analysis used ArcInfo version 8.0®. A surrogate 1911 bathymetric map (when the reservoir was first flooded) was created by scanning the 1903 USGS topographic map, then flooding that topography to the depth of the spillway of the Ballville Dam. The 1993 bathymetric map was created by digitizing field data from the Ohio Geological Survey (15 to 20 depth soundings from each of 19 transects, as mapped in the field using a total station). The 1993 data were contoured to create a bathymetric map. The 1911 and 1993 bathymetric maps were then coregistered into the 1983 WGS Ohio North State Plane. An isopach map showing the sediment thickness in the reservoir was created by subtracting the 1911 bathymetry from the 1993 bathymetry at the nodes of one foot square grid cells. The isopach map was then contoured using a nearest neighbor, inverse distance weighing method which preserves the integrity of the original data.

Hydrology and Sediment Transport

Four channel cross sections were established downstream of the dam (Figure 1) at changes in substrate type and channel slope (Table 1). At each cross section, channel width and depth were surveyed, substrate materials were collected and described, and water surface slopes were measured with a transit. Roughness (Manning's n) was calculated using the method of Cowan (1956). To verify the quality of the measured cross sections, discharge was calculated at each cross section and compared to USGS data from that day. In addition, boundary shear stress was calculated from cross section and slope data using

$$\tau_b = \rho g h \sin \theta \tag{4}$$

and from vertical velocity profiles, using

$$\tau_b = \rho U_*^2 \tag{5}$$

where τ_b is the boundary shear stress (dynes/cm^2); ρ is the fluid density (g/cm^3); g is the acceleration due to gravity (980 cm/sec^2); h is the flow depth (cm); θ is the water surface slope (dimensionless); and U^* is the shear velocity (cm/sec), which is obtained from the slope of the vertical velocity profile (velocity versus the natural log of depth).

The critical or entrainment shear stress (the imposed boundary shear stress necessary to transport grains of a certain size class) was obtained from

$$\tau_c = \tau_{*c} (\rho_s - \rho) g D_n \tag{6}$$

where τ_c is the critical shear stress (dynes/cm^2); τ_{*c} is the Shields Number (dimensionless); ρ_s is the density of the sediment grains (g/cm^3); and D_n is the nominal grain diameter (cm). The Shields Number can be obtained from plots of the Shields Number versus the sedimentation parameter (ζ_*) based upon assumptions about sorting and grain shape (Wiberg and Smith, 1987). The sedimentation parameter is obtained by

$$\zeta_* = [(\rho_s - \rho)g]/\rho \, (D_n^3/\nu^2) \tag{7}$$

where ν is the kinematic viscosity (cm^2/sec).

TABLE 1. Sediment Routing Calculations Downstream of Ballville Dam.

Stream Reach	Manning's n (roughness)	Slope of Reach	Substrate Type	Bankfull Width (m)	Overbank Width (m)	Minimum Flow of Record (Q=0.14 m^3/s) τ_b (dynes/cm^2)	Minimum Mean Daily Flow (Q=4.0 m^3/s) τ_b (dynes/cm^2)	Minimum Mean Annual Flow (Q=7.0 m^3/s) τ_b (dynes/cm^2)	Mean Bankfull Flow (Q=370 m^3/s) τ_b (dynes/cm^2)
1	0.070	6.19×10^{-3}	Bedrock	43	72	18.2	136	194	2,038
2	0.068	2.94×10^{-3}	Cobbles	53	119	8.6	70	98	1,060
3	0.054	8.33×10^{-4}	Cobbles	93	107	2.4	18	25	272
4	0.054	3.85×10^{-4}	Sand	139	180	1.1	8.2	11.5	125

RESULTS

Sediment Properties

The ten vibracores recovered in 1993 were evaluated for sediment properties. Sediment textural properties ranged from clay (< +8ϕ) to 8 cm cobbles (-7ϕ). The cores typically consisted of silt-sized grains (+4ϕ to +8ϕ) with thin (1 to 6 cm thick) layers or lenses of sand and gravel. Coarser grained layers that had basal erosion features, fining-upward sequences, and capping organic-rich (leaf litter) layers were interpreted as flood event layers, and were matched to historical flood data, as calibrated using geochronology (Figure 5). The sediment texture changes from a gravel:sand:silt ratio of 20:20:60 at the upstream end of the reservoir to 5:10:85 near the dam.

Sedimentation Rates

The average sedimentation rate for each core was obtained by dividing the core thickness (corrected for vibracorer compaction) by the total age of the reservoir. The long term average sedimentation rate for this reservoir from 1911 to 1993 was about 3.9 cm/yr.

Although average sedimentation rates are useful, sedimentation in a reservoir is actually episodic (related to floods), and therefore varies over intervals within a core. To determine interval sedimentation rates and to determine the age of sediment horizons, ^{137}Cs and ^{210}Pb geochronology was used on core 93BVD-8. This core was selected because of its overall fine-grained, homogeneous nature and lack of unconformities. Twelve flood layers of coarse grained silt to very fine grained sand were identified in this core (Figure 6). The ^{137}Cs data shows multiple peaks that

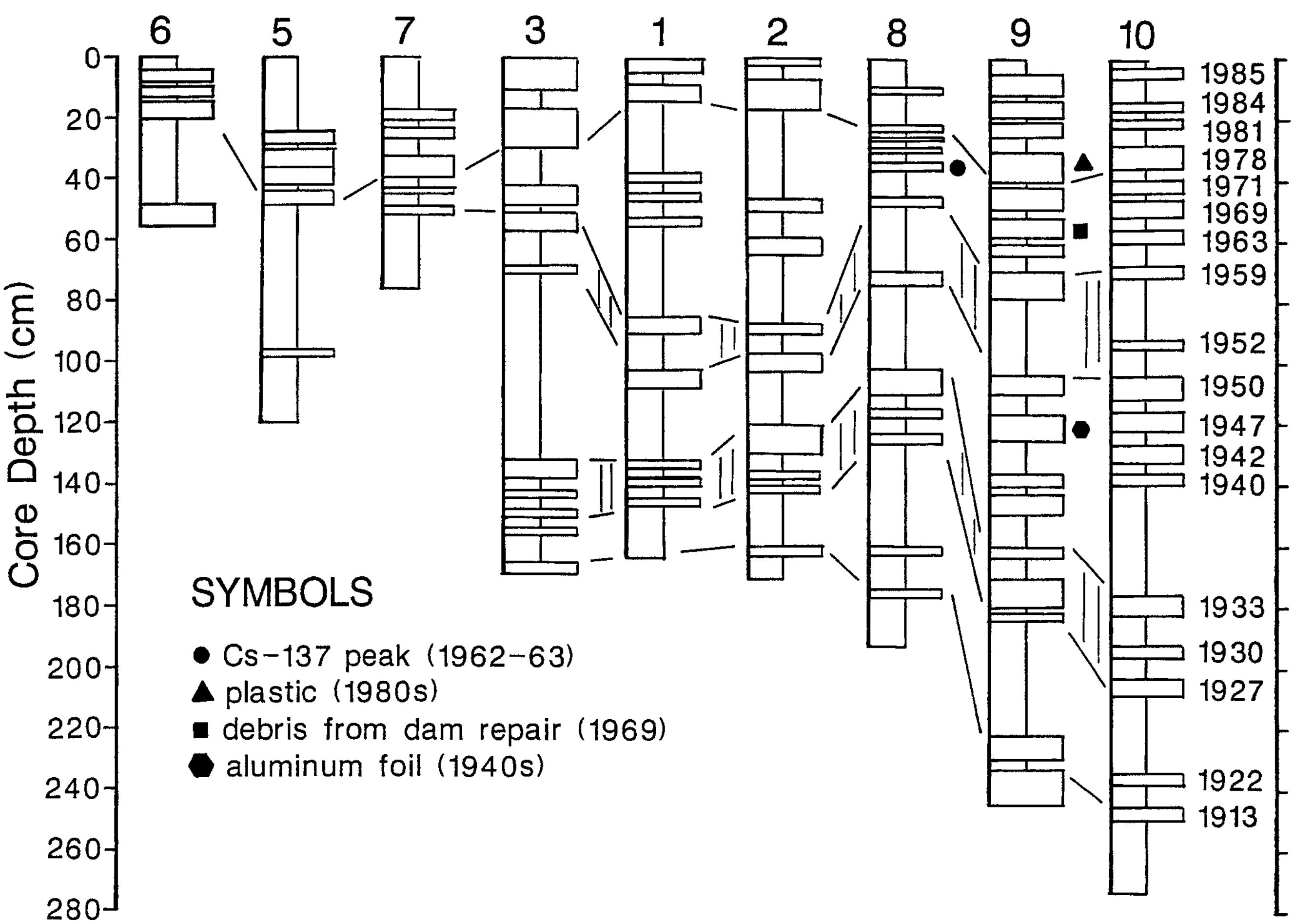

Figure 5. Correlation Diagram of the 1993 Set of Vibracores From the Ballville Reservoir. Core 8 (93BVD-8) was analyzed for ^{137}Cs and ^{210}Pb geochronology. Ages were assigned by matching historical floods to flood horizons in the cores, as calibrated by geochronology data and/or the presence of anthropogenic materials.

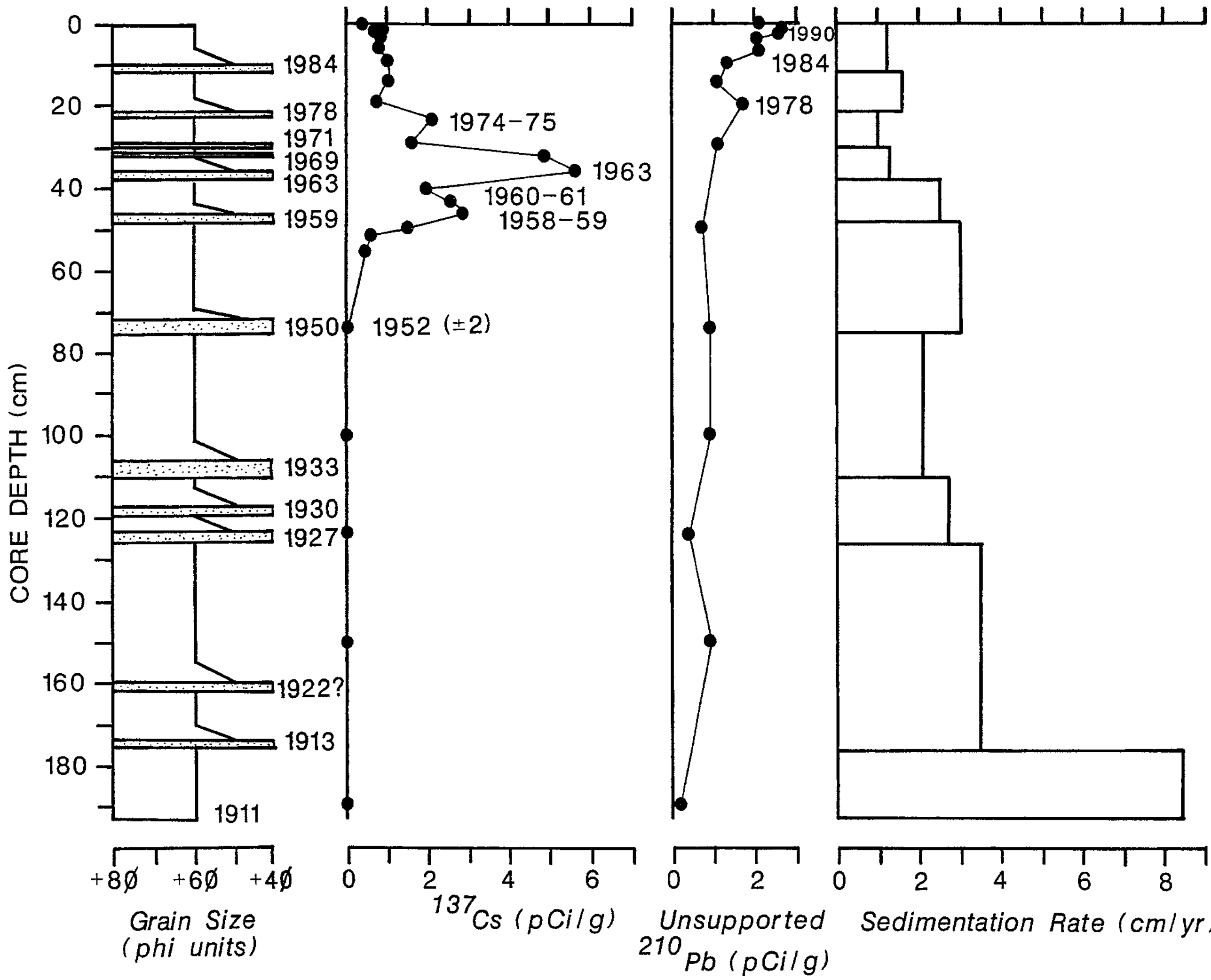

Figure 6. Detailed ^{137}CS and ^{210}Pb Geochronology and Sedimentation Rates From Core 93BVD-8.

are interpreted as follows. The first appearance of ^{137}Cs (1952 ± 2 years) is in fine grained sediment that overlie a flood horizon matched to the flood of 1950. ^{137}Cs peak concentrations match floods of 1959 and 1963, while a 1974 to 1975 ^{137}Cs concentration peak falls between the floods of 1971 and 1978. A small ^{137}Cs concentration peak above the 1984 flood horizon might correspond to the 1985 Chernobyl event.

In this sediment core, the typical use of ^{210}Pb profiles to calculate sedimentation rates was complicated by the variations in the rate of supply (Appleby and Oldfield, 1978), probably due to episodic flood events and related soil erosion (e.g., Bloesch and Evans, 1982; Binford and Brenner, 1986). Because of this problem, ^{210}Pb geochronology was useful because the ^{210}Pb concentration peaks can be used consistently with the ^{137}Cs data to identify the three largest recent (1924 to 1993) flood events occurring in 1978, 1984, and 1990.

Older flood layers are identified by other means. For example the 1927, 1930, and 1933 flood horizons were identified because they were three major flood events occurring within a short time interval and separated by significant time intervals from other major floods (Figure 6). The 1913 flood and dam failure created a prominent, gravel rich flood horizon in several cores near the dam (Figure 5), and is most likely the lowest flood horizon in this core. In contrast a flood horizon at about 162 cm depth (Figure 6) can only be tentatively assigned an age of 1922, based on hydrograph data from the nearby Maumee River (there was not a gage station on the Sandusky River until 1924). This horizon was not used in sedimentation rate calculations.

Interval sedimentation rates were calculated based upon the sediment thickness over certain time intervals. The sediment thickness was corrected twice: (1) the entire core was corrected for shortening due to the vibracorer, and (2) each individual sediment horizon was corrected for sediment compaction using the porosity data. Interval sedimentation rates show initially very high values (8.5 cm/yr), generally declining to rates of about 1.0 cm/yr (Figure 6). This decline in sedimentation rates is interpreted as the effect of sediment bypassing as the reservoir shallows.

The sediment dynamics of the reservoir appears somewhat different when all cores are used to calculate average sediment accumulation rates. Correlation of dated horizons between cores necessitated somewhat cruder time demarcations (Figure 7). Mass sedimentation rates (Evans *et al.,* 2000a) range from 1.7 to 4.3 g/cm^2/yr. Intervals of the highest sedimentation rates in the reservoir can be seen to correlate to sediment conveyance rates. For example, the high sediment accumulation rates of 1978 to 1993 correspond to six of the largest ten floods of record, while the high rates of 1927 to 1933 correspond to two of the largest ten floods of record. The implications of sediment conveyance rates on reservoir sediment dynamics is discussed elsewhere (Evans *et al.,* 2000a).

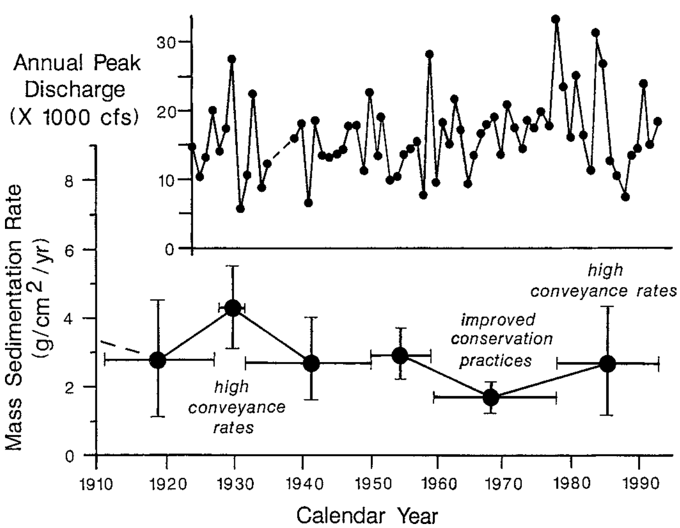

Figure 7. Comparison of Sandusky River Annual Peak Discharge (from USGS Gage Station 04198000) to Mass Sedimentation Rate Values, Calculated by Averaging Interval Values From All of the Sediment Cores. Crosses indicate range of sedimentation rate values (vertical) and time intervals (horizontal). The data are interpreted to show intervals of higher sedimentation rates are related to intervals of greater sediment conveyance.

Reservoir Sediment Volumes

As stated earlier, the procedure involved GIS based conversion of the 1903 (pre-dam) USGS topographic map into a 1911 bathymetric map, by flooding the valley to the depth of the spillway of the dam (Figure 8A). The 1993 bathymetric map (created from bathymetric surveys conducted by the Ohio Geological Survey) was converted to GIS format (Figure 8B), and the two coregistered GIS bathymetric maps were superimposed to create an isopach map of the sediment fill in the reservoir as of 1993 (Figure 8C). Then this map was compared to the actual sediment thicknesses obtained at the sediment core sites.

The use of GIS allowed easy calculation of the reservoir surface area, sediment volume, and water volume. The produced 1911 bathymetric map suggests that the original volume storage capacity of the reservoir was 1.68 million m^3 (about 444 million gallons), which is somewhat higher than previous estimates (e.g., Feller *et al.,* 1987). By 1993, the accumulation of a decompacted sediment volume of 1.31 million m^3 (due to compaction, the actual sediment volume was 0.95 million m^3) left a water storage capacity of 0.73 million m^3 (about 99 million gallons). Figure 9 shows that this historical reconstruction of the original storage volume is consistent with data from the bathymetric surveys of 1959, 1966, and 1985 (Feller *et al.,* 1987) and 1993 (this study).

The GIS database can be used to illustrate a problem with assessing the accuracy of sediment volume calculations based upon core data, which are typically obtained from randomly selected locations. If the core data from this study were used to construct Thiessen polygons (Figure 10), then this method would have substantially underestimated the volume of sediment in the reservoir (0.41 million m^3 of sediment, or only about 32 percent of what was calculated using the isopach map method). The random location of cores does not reliably measure actual sediment thickness in this case because prior to construction of the dam and reservoir the Sandusky River followed a relatively narrow, bedrock floored channel.

The GIS database can be used to show that the Sandusky River, although now a reservoir, has retained many characteristics of a meandering stream. Differences in 1903 and 1993 bathymetry indicate deposition at the downstream end of the prominent bend in the middle of the reservoir, which has produced an emergent point bar and island (Figure 8B). In contrast, channel scour is indicated where 1993 bathymetry has increased with respect to 1903 bathymetry (Figure 11). As is typical of meandering streams (e.g., Dietrich and Smith, 1984), higher boundary shear stresses produce localized scour at

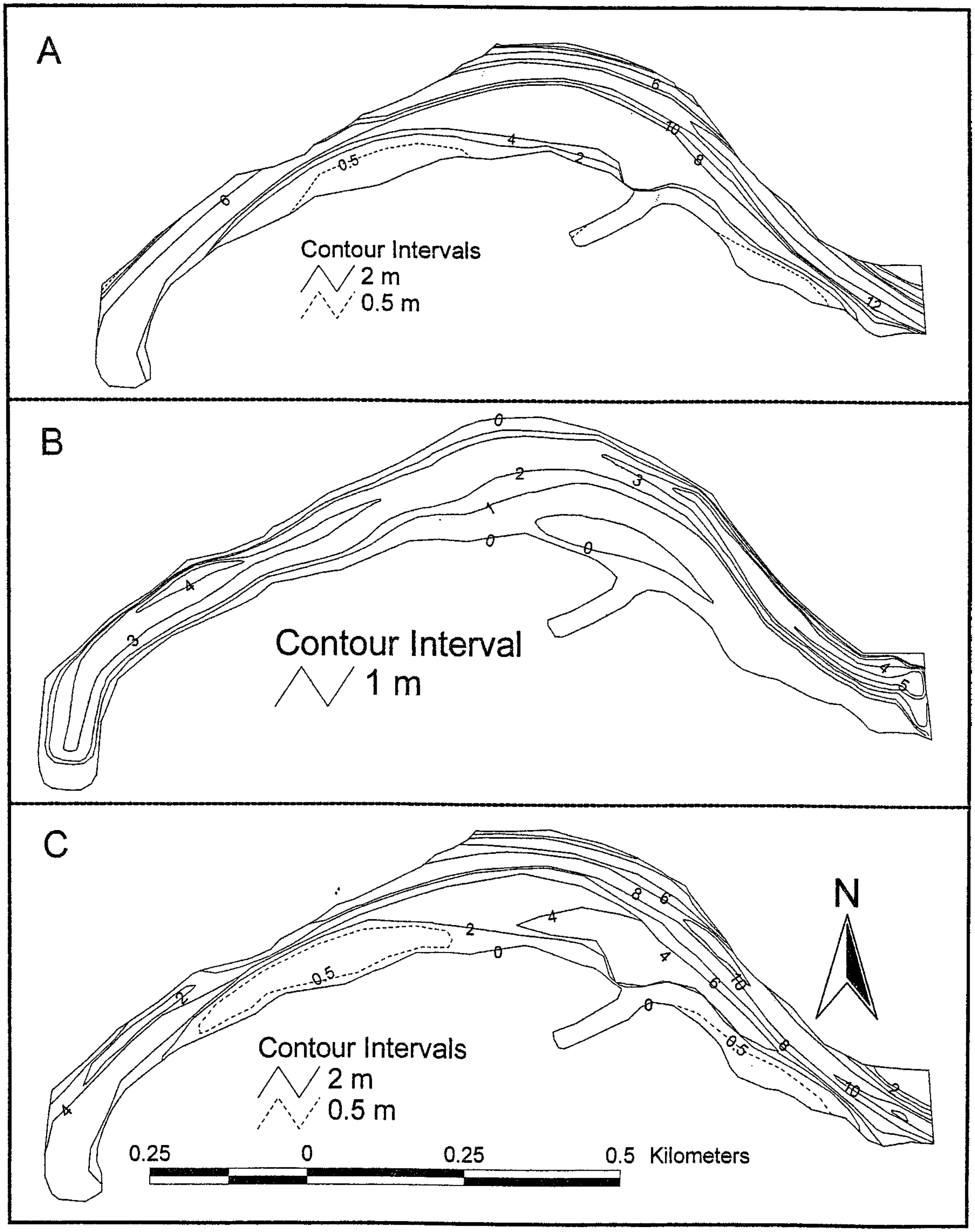

Figure 8. The 1911 Ballville Reservoir Bathymetric Map (A), Created by Flooding the 1903 (pre-dam) Topographic Contour Map to the Depth of the Spillway of the Ballville Dam; the 1993 Ballville Reservoir Bathymetric Map (B) Created From a Detailed Bathymetric Survey (Ohio Geological Survey data); and the Resulting Isopach Map (C) Showing Reservoir Sediment Fill.

the upstream end of the point bar, then this band of higher shear stress shifts across the channel to scour the downstream end of the pool. The location of this localized scour may threaten the integrity of the 214 m long floodwall that anchors the north abutment of the dam.

Suspended sediment data for the Sandusky River over the interval 1978 to 1993 (USGS, 2002) were compared to the decompacted volumes of the sediment that accumulated in the reservoir over this same time period. Between 1978 and 1993 the Ballville Dam had an average trapping efficiency of 4.3 percent. These results are comparable to national studies of reservoirs based upon drainage basin size (e.g., Brune, 1953). The relatively low trapping efficiency of the Ballville Dam can be attributed to: (1) the mostly clay rich source materials in the drainage basin (Forsyth, 1975), (2) the short residence time of water in the reservoir, as indicated by phytoplankton studies (P. A. Kline, 1975, unpublished M.S. Thesis), and (3) the increasing effect of sediment bypassing as the reservoir shallowed.

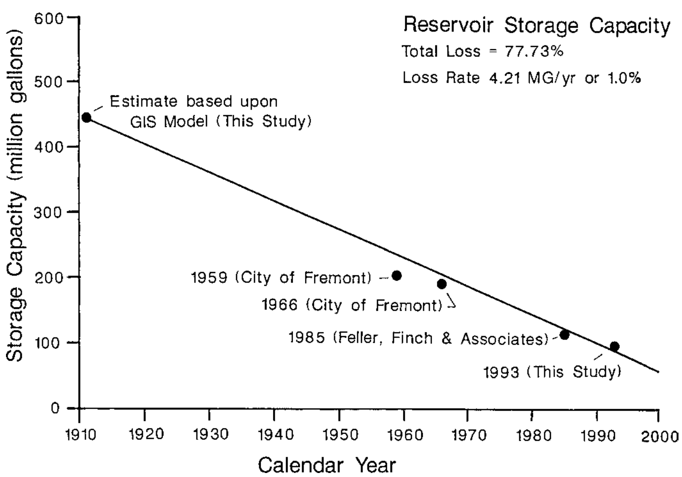

Figure 9. Historical Loss of Storage Capacity of the Ballville Reservoir, Based Upon Bathymetric Surveys by the City of Fremont (1959 and 1966), Feller *et al.* (1987), and the Ohio Geological Survey (1993). Initial (1911) value calculated from the created 1911 bathymetric map (this study).

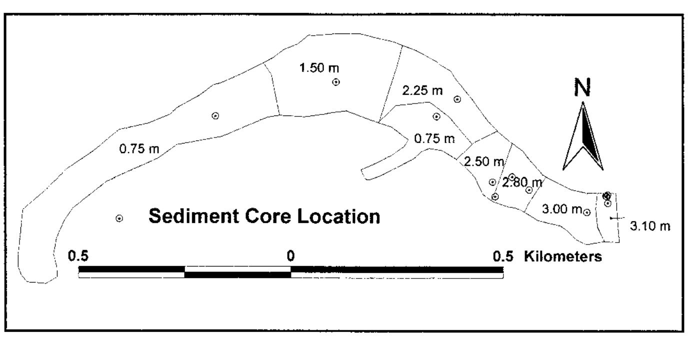

Figure 10. GIS-Based Calculation of Sediment Volumes in the Ballville Reservoir Based Upon a Thiessen Polygon Model. Core locations and average polygon values shown.

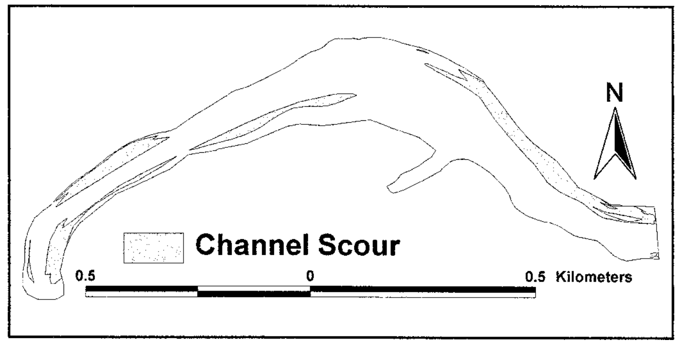

Figure 11. GIS-Based Map Showing Places Where 1993 Bathymetry is Deeper Than 1911 Bathymetry. These areas of scour show that the Sandusky River, although a reservoir, is behaving like a meandering stream, with scour upstream of the point bar on the inside bend and downstream of the pool on the outside bend.

Sediment Routing Calculation

Sediment routing involved two separate calculations. The first determined how much reservoir sediment would need to be removed (either by dredging before removing the dam, or by simultaneous dam removal and release downstream) in order to reestablish the channel of the Sandusky River across the reservoir. In this situation, the shape of a designed channel is constrained by the bedrock floored channel and bedrock controlled slope. The channel sides, however, are only locally controlled by bedrock (notably, one side of the channel at the site of the dam). Therefore the upstream reservoir was modeled as a series of trapezoid shaped channel cross sections that diminished in depth upstream. At the present site of the dam, the bedrock floored channel, bedrock controlled slope, thickness of sediment fill, and Manning's roughness prescribe a trapezoid shaped channel 130 m wide at the top, 120 m wide at the base, 3 m deep, and having a 30° side slope. Such a channel could accommodate flows of approximately 800 m^3/sec (28,000 ft^3/sec), which is roughly an exceedence probability of 0.05 (20 year recurrence interval). The width and depth of upstream cross sections were modified by changes in sediment thickness and depth to bedrock. The total volume of sediment that must be removed is about 0.35 million m^3 (0.46 million yd^3), which is 27 percent of the sediment fill of the reservoir. The estimated cost of dredging this volume of sediment would be up to $6.3 million (Whipkey, 1998), excluding on land disposal costs.

If the sediment were released downstream, the concern would be degradation of critical fisheries habitat in the 3 km reach immediately downstream of the dam (RK 13 to RK 16). The boundary shear stress (τ_b)

is a property of the fluid flow, and changes both spatially and temporally. To account for spatial and temporal effects, τ_b was calculated at each of the four downstream cross sections for four different minimal flow conditions (Table 1). The selected flow conditions are: (1) the minimum flow of record (which was October 20 to 21, 1963); (2) the 1924 to 1993 minimum mean-daily flow; (3) the 1924 to 1993 minimum mean annual flow; and (4) the 1924 to 1993 mean bankfull flow (this is equivalent to the 1.5 year recurrence interval, or $Q_{1.5}$). In contrast to τ_b, the critical shear stress (τ_c) is a property of the sediment, and depends on grain size, grain shape, sorting, and grain density. Although not shown here, τ_c is easily calculated from each grain size class. Next, an initial motion calculation is made, which in simple terms is a comparison of the boundary shear stress imposed by the flow (τ_b) to the shear stress needed to move the grains (τ_c), under assumed conditions of excess shear stress [$(\tau_b - \tau_c)/\tau_c$] close to unity (Wiberg and Smith, 1987). The results show that flows exceeding minimum mean daily flow would cause greater than 90 percent of the sediment (all of the silt and clay) to be transported through the critical fisheries habitat on the Sandusky River, and into Sandusky Bay on Lake Erie (Table 2).

Sediment Contamination

The concentrations of barium, cobalt, copper, and manganese in the sediments of the Ballville Reservoir indicate significant sediment contamination. The concentration of barium in sediment pore waters varies from 25 to 675 ppb, and generally increases with depth (Figure 12). Cobalt concentration ranges from 0 to 40 ppb, and shows significant enrichments between 120 and 200 cm. Copper concentration ranges from 1 to 40 ppb, and shows peaks at the surface and between 50 and 100 cm depth in cores. Finally, manganese concentration ranges from 4 to 850 ppb, and increases sharply below about 100 cm. These trace element concentrations are comparable to other studies of sediment pore water from Lake Erie (Matisoff *et al.,* 1980; Azcue *et al.,* 1996) and adjacent wetlands (C. M. Mancuso, 1986, unpublished M.S. Thesis). Azcue *et al.* (1996) analyzed both sediment and sediment pore water in Lake Erie and found that concentrations in sediments are typically an order of magnitude higher than in pore water. If this is true, the concentration of copper could be as high as 400 ppb, and manganese could be as high as 10 ppm in the core sediment.

The vertical trends in trace element concentrations can be explained as follows. Barium is present as a trace element in carbonate rocks, so its profile through the reservoir sediments may be due to weathering of the underlying bedrock and diffusion upward through the overlying sediments. Surficial enrichments in copper and manganese may be an artifact of wastewater treatment effluent (Nriagu and Pacyna, 1988; Nriagu *et al.,* 1996) or because copper sulfate was used for aquatic weed control in the reservoir. Manganese enrichments at depth within sediments have been related to changing redox conditions or the position of the oxidized microzone (Callender *et al.,* 1974). Certain concentration peaks may indicate changes in influx rates (i.e., historical periods of significantly greater pollution).

DISCUSSION

There are few empirical studies of impacts of dam removals (e.g., Doyle *et al.,* 2000, Stanley *et al.,* 2002, Doyle *et al.,* 2002). The available studies suggest downstream impacts depend on whether the released sediment moves as a sediment wave (e.g. Wohl and Cenderelli, 2000) or is more gradually dispersed (Doyle *et al.,* 2002). Within the reservoir, initial incision mobilizes fine grained sediment, typically silts and muds, which tend to have localized and transient effects downstream, such as temporary filling of pools (Wohl and Cenderelli, 2000). Larger impacts downstream can result from headcut incision into the coarse grained sediment at the upstream end of the

TABLE 2. Anticipated Size Class Deposited in Given Reach, Under Given Flow Conditions.

Flow Conditions	Discharge	Reach 1	Reach 2	Reach 3	Reach 4
Minimal Flow of Record	0.14 m^3/sec	granules	v. coarse-gr. sand	medium-gr. sand	coarse-gr. silt
Minimum Mean Daily Flow	4.0 m^3/sec	pebbles	pebbles	granules	v. coarse-gr. sand
Minimum Mean Annual Flow	7.0 m^3/sec	pebbles	pebbles	granules	v. coarse-gr. sand
Mean Bankfull Flow	370 m^3/sec	cobbles	cobbles	pebbles	pebbles

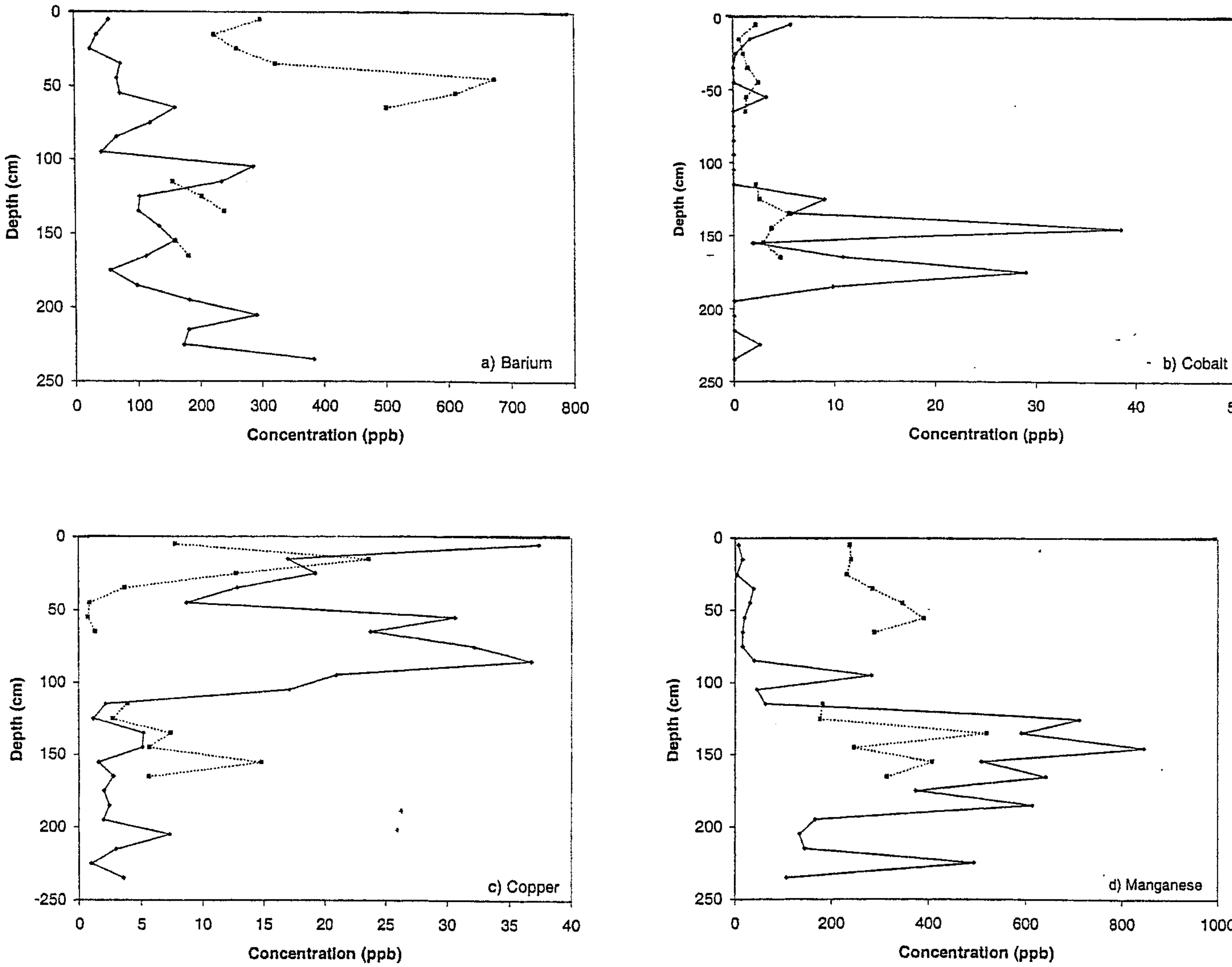

Figure 12. Sediment Profiles for Pore Fluid Concentrations of (A) Barium, (B) Cobalt, (C) Copper, and (D) Manganese From Cores 97BR-1 (solid line) and 97BR-4 (dashed line). For core 97BR-4, a gap is due to problems extracting pore water from one interval of the core.

reservoir (i.e., the former delta). Some of these effects can be mitigated by dewatering the reservoir by phased drawdown (e.g., Harbor, 1993), and by using accompanying methods to stabilize the banks of the incised channel in the reservoir. Shields *et al.* (1995) showed that the latter is most effectively done by a combination of stabilization of the structural toe of the bank (i.e., riprap) and revegetation methods.

In this case, several factors would act to simplify the mitigation process. The former (and future) channel of the Sandusky River through the reservoir is bedrock floored. When the IVEX dam failed, the Chagrin River downcut to its bedrock surface, with nickpoint migration rates of tens of meters per hour. For IVEX reservoir, incision completely crossed the reservoir (over 500 m) within approximately 24 hours. Similar high rates have been observed in other dam removals (Doyle *et al.*, 2002). In the case of Ballville Reservoir, the assumed rapid incision to the bedrock surface, and subsequent stabilization of vertical downcutting, makes designed cross sectional shape and bank heights more predictable.

Finally, if the dam is removed, the construction of the dam as two separate spillway sections would easily accommodate a phased drawdown of the structure. After opening the sluice gates to lower the pool elevation, a cofferdam could be constructed to permit one spillway to be reduced in height. Subsequently, that cofferdam would be removed (the reservoir pool would drop to the height of the modified first spillway). A second coffer dam would be constructed (using debris from the first spillway and first cofferdam) to allow complete removal of the second spillway. When this second coffer dam is removed, the original dam will cease to exist. As part of the phased drawdown of the dam, the exposed parts of the former reservoir would be reseeded and stabilized in stages. Material from the final spillway and cofferdam removal could be used to remediate the site, as riprap toes along the banks.

SUMMARY AND CONCLUSIONS

The Ballville Dam may need to be removed because: (1) safety inspections indicate that the dam is hazardous due to inadequate spillway capacity (UDACE, 1981; ODNR, 1998); (2) the primary use of the reservoir for municipal water supply is threatened by degraded water quality; (3) the storage capacity of the reservoir has declined greater than 78 percent due to sedimentation, approaching action levels for dredging (Feller *et al.,* 1987); and (4) the dam is a barrier to fisheries habitat. While one state agency (ODNR-Wildlife) has publicly advocated removing the dam, a local citizen group (Citizen's Committee to Save the Ballville Dam) opposes removal because of the potential loss of the reservoir for recreation, fishing, migratory bird habitat, and other concerns (Tressler, 2000).

To assist public policy decision makers evaluate these competing interests, this study has shown that the reservoir has filled with a decompacted volume of 1.31 million m^3 of mostly silt sized sediment, of which about 27 percent (0.35 million m^3) would have to be removed to reestablish the channel of the Sandusky River across the former reservoir site. If dredged prior to dam removal, this would cost up to $6.3 million, not including on land disposal costs. Pore fluid geochemistry data suggest that the sediments are contaminated, which would greatly increase these costs. If the sediment were released as part of dam removal, a sediment routing calculation has shown that at flows greater than minimum mean daily discharge more than 90 percent of the released sediment would move through downstream reaches and be deposited in Sandusky Bay (Lake Erie). Damage to downstream fish habitat on the Sandusky River would likely be minimal.

Sedimentation rates in the reservoir have varied both temporally and spatially. At present (1978 to 1993), the dam has a trapping efficiency of about 4.3 percent, indicating that most fine grained sediment already bypasses the structure. Such low trapping efficiency is the collective result of the fine grained sediment eroded from the drainage basin, the low residence time of water in the reservoir, and shallowing of the reservoir over time.

ACKNOWLEDGMENTS

This manuscript was improved significantly by the comments of three anonymous reviewers. We wish to acknowledge and thank Scudder D. Mackey and the Ohio Geological Survey for assistance with sediment coring operations and for providing bathymetric survey data. We also thank Kenneth Myers (City of Fremont), David Davies (ODNR-Wildlife), Ken Krieger (Heidelberg College), Mark Ogden (ODNR-Water), Harold Schindel (U.S. Geological Survey), and Jim Rickenberg (Wood County Soil and Water Conservation District) for their assistance and advice. Aaron Svitana assisted with descriptions of sediment cores. Finally, this study was supported by a grant from the Center for Policy Analysis and Public Service at Bowling Green State University.

LITERATURE CITED

Appleby, P. G. and F. Oldfield, 1978. The Calculation of ^{210}Pb Dates Assuming a Constant Rate of Supply of Unsupported ^{210}Pb to the Sediments. Catena 5:1-18.

Azcue, J. M., F. Rosa, and A. Mudroch, 1996. Distribution of Major and Trace Elements in Sediments and Pore Waters of Lake Erie. Journal of Great Lakes Research 22: 389-402.

Bates, K., 2000a. Throngs Await Suit Settlement 12 Years After Chemical Spill. The Toledo Blade, December 18, 2000, p. B1-B2.

Bates, K., 2000b. Canoes Give Officials a Gander at the Sandusky. The Toledo Blade, July 19, 2000, p. B1-B2.

Binford, M. W. and M. Brenner, 1986. Dilution of ^{210}Pb by Organic Sedimentation in Lakes of Different Trophic States, and Applications to the Studies of Sediment-Water Interactions. Limnology and Oceanography 31:584-595.

Bloesch, J. and R. D. Evans, 1982. ^{210}Pb Dating of Sediments Compared to Accumulation Rates Estimated by Natural Markers and Measured with Sediment Traps. Hydrobiologia 92:579-586.

Brice, M., 2000. City Officials Say Safe, Adequate Water Supply Key in Final Decision. The Fremont News-Messenger, January 12, 2000, p. A1.

Brune, G. M., 1953. Trap Efficiency of Reservoirs. Transactions of the American Geophysical Union 34:407-418.

Callender, E., C. J. Bowser, and R. Rossman, 1974. Geochemistry of Ferro-Manganese and Manganese Carbonate Crusts From Green Bay, Lake Michigan. Transactions of the American Geophysical Union 54:340.

Campbell, B. L., R. J. Loughran, and G. L. Elliott, 1982. Caesium-137 as an Indicator of Geomorphic Processes in a Drainage Basin System. Australian Geographical Studies 20:49-64.

Campbell, B. L., R. J. Loughran, and G. L. Elliott, 1988. A Method for Determining Sediment Budgets Using Caesium-137. *In:* Sediment Budgets, M. P. Bordas and D. E. Walling (Editors). International Association of Hydrological Sciences Publication 174:171-179.

Costa, J. E., 1988. Effects of Agriculture on Erosion and Sedimentation in the Piedmont Province, Maryland. Geological Society of America Bulletin 86:1281-1286.

Cowan, W. L., 1956. Estimating Hydraulic Roughness Coefficients. Agricultural Engineering 37:473-475.

Dietrich, W. E. and J. D. Smith, 1984. Bed Load Transport in a River Meander. Water Resources Research 20:1355-1380.

Dobson-Lindbloom Associates, 1983. Ballville Dam Detailed Safety Study. Dobson-Lindbloom Associates, Columbus, Ohio.

Doyle, M. W., E. H. Stanley, and J. M. Harbor, 2002. Geomorphic Analogies for Assessing Probable Channel Response to Dam Removal. JAWRA 38(6):1567-1579.

Doyle M. W., E. H. Stanley, M. A. Luebke, and J. M. Harbor, 2000. Dam Removal: Physical, Biological, and Societal Considerations. Proceedings of the American Society of Civil Engineers, Joint Conference on Water Resources Engineering and Water Resources Planning and Management, Minneapolis, Minnesota, 10 pp.

Electric Power Research Institute (EPRI), 1996. Protocol for Estimating Atmospheric Mercury Deposition. EPRI Corporation, Palo Alto, California, Technical Report 106768.

Evans, J. E., T. C. Johnson, E. C. Alexander, Jr., R. S. Lively, and S. J. Eisenreich, 1981. Sedimentation Rates and Depositional Processes in Lake Superior from ^{210}Pb Geochronology. Journal of Great Lakes Research 7: 299-310.

Evans, J. E., J. F. Gottgens, W. M. Gill, and S. D. Mackey, 2000a. Sediment Yields Controlled by Intrabasinal Storage and Sediment Conveyance Over the Interval 1842-1994: Chagrin River, Northeast Ohio, U.S.A. Journal of Soil and Water Conservation 55(3):264-270.

Evans, J. E., S. D. Mackey, J. F. Gottgens, and W. M. Gill, 2000b. Lessons From a Dam Failure. Ohio Journal of Science 100(5):121-131.

Evans, J. E., S. D. Mackey, J. F. Gottgens, and W. M. Gill, 2000c. From Reservoir to Wetland: The Rise and Fall of an Ohio Dam. *In:* The Earth Around Us: Maintaining a Livable Planet, J.S. Schneiderman (Editor). W. H. Freeman and Company, New York, New York, pp. 256-267.

FEMA (Federal Emergency Management Agency), 2002. National Dam Safety Inspection Program. *Available at* http://www.fema.gov/fima/damsafe/resources.shtm. *Accessed on* November 12, 2002.

Feller, Finch, and Associates, 1987. Ballville Dam Reservoir Capacity Study. Consultant's Report to the City of Fremont, 18 pp.

Forsyth, J. F., 1975. The Geologic Setting of the Sandusky River Basin. *In:* Sandusky River Basin Symposium, D. B. Baker and B. L. Prater (Editors). International Joint Commission on the Great Lakes, Tiffin, Ohio, pp. 15-60

Gordon, R. B., 1966. Natural Vegetation of Ohio, at the Time of the Earliest Land Surveys. Ohio Biological Survey Map and Description, Columbus, Ohio.

Gordon, R. B., 1969. The Natural Vegetation of Ohio in Pioneer Days. Ohio Biological Survey Publication, Columbus, Ohio, 109 pp.

Gottgens, J. F., B. E. Rood, J. F. Delfino, and B. S. Simmers, 1999. Uncertainty in Paleoecological Studies of Mercury in Sediment Cores. Water, Air, and Soil Pollution 110:313-333.

Harbor, J. M., 1993. Proposed Measures to Alleviate the Environmental Impacts of Hydroelectric Dams on the Elwha River, Washington, U.S.A. *In:* Industrial and Agricultural Impacts on the Hydrologic Environment, Y. Eckstein and A. Zaporozec (Editors). Proceedings of the Second Joint Conference on Environmental Hydrology and Hydrogeology, American Institute of Hydrology.

Hindall, S. M., 1991. Temporal Trends in Fluvial-Sediment Discharge in Ohio, 1950-1987. Journal of Soil and Water Conservation 46: 311-313.

Howe, H., 1908. Historical Collections of Ohio. Krehbiel and Company, Publishers, Cincinnati, Ohio, Vol. 2, 911 pp.

Kaatz, M. R., 1955. The Black Swamp: A Study in Historical Geography. Annals of the Association of American Geographers 45:1-35.

Kline, P. A., 1975. A Survey of the Phytoplankton of the Sandusky River at Fremont, Sandusky County, Ohio. M.S. Thesis, Bowling Green State University, Bowling Green, Ohio, 123 pp.

Krishnaswamy, S. and D. Lal, 1978. Radionuclide Limnochronology. *In:* Lakes: Chemistry, Geology and Physics, A. Lerman (Editor). Springer-Verlag, New York, New York, pp.153-177.

Mancuso, C. M., 1986. Distribution of Trace Elements in the Interstitial Waters and Sediments of a Freshwater Estuary. M.S. Thesis, Bowling Green State University, Bowling Green, Ohio, 138 pp.Matisoff, G., A. H. Lindsay, S. Matis, and F. M. Soster, 1980. Trace Element Mineral Equilibria in Lake Erie Sediments. Journal of Great Lakes Research 6: 353-366.

McCall, P. L., J. A. Robbins, and G. Matisoff, 1984. ^{137}Cs and 210Pb Transport and Geochronologies in Urbanized Reservoirs With Rapidly Increasing Sedimentation Rates. Chemical Geology 44: 33-65.

Miller, K. M. and M. Heit, 1986. A Time Resolution Method for Assessing the Quality of Lake Sediment Cores That are Dated With ^{137}Cs. Limnology and Oceanography 31: 1292-1300.

Newman, D. M., 1998. Concentrations of Barium, Chromium, Cobalt, Copper, and Manganese in the Pore Water of Sediments in the Ballville Reservoir. M.S. Thesis, Bowling Green State University, Bowling Green, Ohio, 57 pp.

Noble, A. G., 1975. Ohio's Physical Landscape. *In:* Ohio – An American Heartland, A. G. Noble and A. J. Korsok (Editors). Ohio Geological Survey Bulletin 65:27-53.

Nriagu J. O. and J. M. Pacyna, 1988. Quantitative Assessment of Worldwide Contamination of Air, Water and Soils by Trace Metals. Nature 333:134-139.

Nriagu, J. O., G. Lawson, K. T. W. Henry, and V. Cheam, 1996. Dissolved Trace Metals in Lakes Superior, Erie, and Ontario. Environmental Science and Technology 30:178-187.

Oldfield, F., P. G. Appleby, and R. Thompson, 1980. Palaeoecological Studies of Lakes in the Highlands of Papua New Guinea: I. The Chronology of Sedimentation. Journal of Ecology 68:457-477.

ODNR (Ohio Department of Natural Resources), 1998. Dam Inspection Report, Ballville Dam, Sandusky County. Ohio Department of Natural Resources, Division of Water, File No. 1231-003, 6 pp.

Overmyer, R. L. and L. C. Brown, 1990. Sandusky County Water Resources. AEX-480.72, Ohio Cooperative Extension Service, Columbus, Ohio, 4 pp.

Pennington, W., R. S. Cambray, and E. M. Fisher, 1973. Observations on Lake Sediments Using Fallout 137Cs as a Tracer. Nature 242:324-326.

Pollick, S., 1993. Walleye Run on Sandusky Not What It Used To Be. The Toledo Blade, March 25, 1993, p. C10.

Pyle, G., 1975. The Population of Ohio – Past, Present, and Future Distribution. *In:* Ohio – An American Heartland, A. G. Noble and A. J. Korsok (Editors). Ohio Geological Survey Bulletin 65:19-26.

Ritchie, J. C., J. R. McHenry, and A. C. Gill, 1973. Dating Recent Reservoir Sediments. Limnology and Oceanography 18:254-263.

Ritchie, J. C., P. H. Hawks, and J. R. McHenry, 1975. Deposition Rates in Valleys Determined Using Fallout Caesium-137. Geological Society of America Bulletin 86:1128-1130.

Ritchie, J. C. and J. R. McHenry, 1990. Application of Radioactive Cesium-137 for Measuring Soil Erosion and Sediment Accumulation Rates and Patterns: A Review. Journal of Environmental Quality 19:215-233.

Sears, P. B., 1926. The Natural Vegetation of Ohio. II. The Prairies. Ohio Journal of Science 26: 28-146.

Shields, F. D., A. J. Bowie, and C. M. Cooper, 1995. Control of Streambank Erosion Due to Bed Degradation With Vegetation and Structure. Water Resources Bulletin 31:475-489.

Shuman, J. R., 1995. Environmental Considerations for Assessing Dam Removal Alternatives for River Restoration. Regulated Rivers: Research and Management 11:249-261.

Stanley, E. H., M. A. Luebke, M. W. Doyle, and D. W. Marshall, 2002. Short-Term Changes in Channel Form and Macroinvertebrate Communities Following Low-head Dam Removal. Journal of the North American Benthological Society 21:172-187.

Transeau, E. N., 1935. The Prairie Peninsula. Ecology 16:205-218.

Trautman, M. B., 1975. The Fishes of the Sandusky River System, Ohio. *In:* Sandusky River Basin Symposium, D. B. Baker and B. L. Prater (Editors). International Joint Commission on the Great Lakes, Tiffin, Ohio, pp. 233-241.

Tressler, M., 2000. Fremont's Dam Blocks State's Vision of River. The Toledo Blade, January 3, 2000, pp. 9-10.

USACE (U.S. Army Corps of Engineers), 1981. Phase 1 Inspection Report: Ballville Dam, Sandusky County, Ohio. U.S. Army Engineer District, Pittsburgh, Report OH-809, 78 pp.

U.S. Geological Survey, 2002. Streamflow Data: Sandusky River at Station 04198000. *Available at* waterdata.usgs.gov/oh/nwis/uv?04198000. *Accessed on* November 12, 2002.

Universal Electric Power Corporation, 1999. Application for Preliminary Permit for the Ballville Dam Hydroelectric Project. Federal Energy Regulatory Commission, Washington D.C., Application P11668-000.

Walling, D. E. and S. B. Bradley, 1988. The Use of Caesium-137 Measurements to Investigate Sediment Delivery From Cultivated Areas in Devon, U.K. *In:* Sediment Budgets, M. P. Bordas and D. E. Walling (Editors). International Association of Hydrological Sciences Publication 174:325-335.

Whipkey, S. L., 1998. Costs of Dredging Dog River. *Available at* http://www.southalabama.edu/geography/fearn/480page/98Steve/Steve.html. *Accessed on* July 14, 2000.

Wiberg, P. L. and J. D. Smith, 1987. Calculations of the Critical Shear Stress for Motion of Uniform and Heterogeneous Sediments. Water Resources Research 23:1471-1480.

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

Wohl, E. E. and D. A. Cenderelli, 2000. Sediment Deposition and Transport Patterns Following a Reservoir Sediment Release. Water Resources Research 36:319-333.